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Deliverable 6.4

Assessment of environmental risks exerted upon, and by, low-trophic aquaculture in the Atlantic Region

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30/6/2022

Executive summary

The main objective of AquaVitae's (AV) work package 6 *Environmental monitoring, risk assessment and sustainability* is to develop recommendations on how to increase low trophic species (LTS) aquaculture production with a net positive impact on sustainability in the Atlantic Region. It is well recognized that aquaculture, including LTA, is highly interconnected to the ecosystem in which it occurs and that aquaculture practices can have both negative and positive impacts on the surrounding environment, and thus on its sustainability performance. The recommendations must consequently recognize the changing conditions for low trophic aquaculture (LTA), hence justifying assessment of environmental risks exerted upon, and by, LTA. According to ISO31000, the term "risk" is defined as "effect of uncertainty on objectives", which includes both negative and positive events.

The study was done through a combination of bottom-up and top-down approaches to cover a wide enough scope. The bottom-up approach focused on current acknowledged risks, and was structured around three online stakeholder workshops with representatives from seven industry and industry-oriented research organizations held during summer and fall 2021. Each participant worked through step 1-3 of the risk assessment process defined by ISO 31000: defining the context, identifying risk, and analyzing the risks. The process and the assessment were guided by an Excel tool partly developed in the project.

These results were complemented by a top-down approach focusing on future foreseeable risks. To investigate how risks exerted upon and by LTA might develop in the foreseeable future, forecasting scenarios based on identified trends were applied. Relevant large-scale societal trends and assessment frameworks, together with global aquaculture trends, were identified using literature reviews. To outline the trends' conceptual cause-effects relations, they were structured according to the DAPSI(W)R(M) approach. Change in demand (continued increase vs. slowdown) and operational prioritisation (maximising output of produced food and other ecosystem services vs. minimized input of utilized energy and other resources) were selected from these trends as strategic uncertainties from an AV perspective. The strategic uncertainties were combined to give four forecasting scenarios. By using different selections of the remaining trends, each scenario was elaborated to provide more depth and detail. The aim was for each scenario to be at the same time sufficiently thought-provoking to inspire reflection over future risks for LTA in the Atlantic Region yet also possible, consistent, credible, and relevant for the scope. The likelihood of all events described did not have to be equal for the four scenarios.

The major conclusions from this study, were that:

1. LTA will be increasingly challenging to conduct despite rising demand and new opportunities.
2. Changing conditions present exploitable opportunities both for LTA and society at large.
3. Stakeholders' risk awareness focuses on operations-related threats exerted upon LTA.
4. Scale is an important aspect in risk identification and analysis.
5. There is an apparent need to strengthen the LTA sectors' risk management capacity

More specifically, ongoing climate change, loss of biodiversity and pollution, including eutrophication, will, if left unmitigated, fundamentally change the environmental conditions for world food production (and arguably all biologically dependent activities) on every level and in every environment, making LTA more challenging. At the same time, it is very likely that the demand for LTS will continue to increase in the foreseeable future. These interactions between opportunities and threats in a dynamic environment justify a systematic risk management process, which includes continuous monitoring and capacity adaptation on both operational and societal levels.

Major threats (negative risks) include LTA contributing to **deterioration of surrounding ecosystems** by pollution (e.g, organic enrichment of sediment and benthic impacts, nutrient pollution, faeces, antifouling), release or escape of farmed stock (non-native/invasive species and pathogens), spurring intensified global fisheries (LTA demanding fish meal and fish oil as feed) and entanglement of marine mammals in LTA infrastructure, as well as LTA suffering **loss of production** due to predation or grazing, mortality from diseases or seawater quality, red tides/toxic algal blooms, unpredictable access to offshore production and epiphyte outbreak competing for resources, and **material damage** due to extreme weather conditions. Many of these threats will be exacerbated by the on-going ecological crisis of climate change and biodiversity loss.

Major opportunities (positive risks), on the other hand, include LTA contributing to **improved ecosystems** by reducing global fisheries (LTA replacing fish meal and fish oil as feed), providing biodiversity and other ecosystem services and replacing food items with high carbon footprint with lower carbon footprint, and experiencing **increased production** due to rising sea temperature and eutrophication, and favourable conditions for cultivation of new species. As the threats, opportunities may arise or grow as a consequence of climate change effects.

Results from the series of stakeholder workshops indicate a striking discrepancy between these potentially drastic changes to LTA in a near future, and stakeholders' focus on mitigating threats on a day-by-day or short-term basis. Thus, there is an apparent need to strengthen the LTA sector's risk management capacity to properly and sustainably mitigate threats and exploit opportunities under changing conditions. In brief, overall knowledge level of risk assessments and how to conduct them should be improved by both industry actors and governmental representatives. Risk assessment can also be facilitated by development of efficient tools, particularly to assess the dynamic risks of intermediate climate change states. The obvious benefits of strengthening the LTA sector's/stakeholders' risk management capacity must, however, be balanced against the effort and costs.

Table of content

Abbreviations

AV	AquaVitae
AD	Assessment domain
Chl-a	Chlorophyll a
CSF	Challenge-structuring framework
D6.1	Deliverable 6.1
DAPSI(W)R(M)	Drivers, Activities, Pressures, State changes, Impacts (on human Welfare), Responses (as Measures)
EC	European Commission
EEA	European Environment Agency
ESG	Environmental, social, and corporate governance
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GMO	Genetically modified organism
GMT	Global megatrend
IMTA	Integrated multi-trophic aquaculture
IPBES	The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
ISO	International Organization for Standardization
LTA	Low-trophic aquaculture
LTS	Low-trophic species
NGO	Non-governmental organization
RAS	Recirculating aquaculture system
SDG	Sustainable Development Goal
SOFI	The State of Food Security and Nutrition in the World
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
VC	Value chain
WEF	World Economic Forum
WHO	World Health Organization
WP	Work package
WWF	World Wildlife Foundation

1 Introduction

1.1 Synopsis of AquaVitae

AquaVitae (AV) is a research and innovation project, funded by the EU's Horizon 2020 program. The project consortium consists of 35 partners, from 16 different countries spread across four continents. In addition to Europe, partners are situated in countries bordering the Atlantic Ocean, including Brazil, South Africa, Namibia, as well as North America. The overall objective of AV is to introduce new low trophic species (LTS), products and processes to marine aquaculture value chains (VCs) across the Atlantic, in a sustainable way. AV focuses on the VCs for macroalgae production, integrated multi-trophic aquaculture (IMTA) and production of new echinoderm species as well as of underutilised shellfish species and low trophic finfish species.

In addition to research in specific VCs, a significant part of the research activities in AV, directed through a number of work packages (WPs), focuses on aspects of high relevance to the different domains in the sustainability matrix (social, economic and environmental), e.g. consumer attitudes and market potential studied by work package 5 (WP5), environmental monitoring, risk assessment, and sustainability by WP6, profitability and socio-economic aspects by WP7 and policy and governance by WP8.

1.2 Scope and motivation of WP6, T6.3 and D6.4

WP6 is one of AV's four cross-cutting scientific work packages. Its main objective is to develop recommendations on how to increase low-trophic aquaculture (LTA) production with a net positive impact on sustainability in and around the Atlantic Ocean. To achieve AV's objective to sustainably increase LTA production, opportunities must be exploited, and threats mitigated. Thus, risks must be properly managed.

It is well recognized that aquaculture, including LTA, is highly interconnected to the ecosystem in which it occurs and that aquaculture practices can have both negative and positive impacts on the surrounding environment. The major areas of environmental concerns for aquaculture are well documented and include organic enrichment of sediment and benthic impacts, nutrient pollution, introduction of non-native/invasive species and pathogens and dispersal of such agents into local ecosystems, genetic and ecological impacts on wild populations, chemical contamination, human health concerns and social issues related to resource utilization and access (Black 2008, Phillips & Subasinghe 2008, Serpa & Duarte 2008, Salin & Arome Ataguba 2018).

Aquaculture can, however, be considered not only a consumer of goods and services, but also a provider. This is especially true for LTA, in particular for extractive species (organisms such as mussels, oysters and macroalgae which depend on natural available sustenance, e.g., microalgae or nutrients). Common services include biodiversity enhancement, nutrient extraction and water quality improvement, enhancement of wild populations throught larval spillover, as well as provisioning and cultural services (Langton et al. 2019, Alleway et al. 2019, Schatte Olivier et al. 2020, Gentry et al. 2021, Mascorda Cabre et al. 2021, Theuerkauf et al. 2021, The Nature Conservancy 2021). Extractive aquaculture can also be considered to be restorative when it provides net-positive environmental outcomes (Nature Conservancy 2021).

The impact of LTA on the environment is very context dependent and will vary with culture species, system used, local conditions and more (Theuerkauf et al. 2021). Although the effects of LTA are highly diverse and context dependent, it should be noted that many of the impacts of aquaculture are subtle

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and cumulative, and hence often insignificant in relation to a single farm but potentially impactfull in terms of a large number of farms and/or large scale production, in particular if crowded in relation to limited resources (Phillips & Subasinghe 2008).

In addition to these perspectives, LTA will also be affected by anthropogenic activities and by the surrounding environment, e.g through contamination and pollution, environmental and oceanographic conditions and through interactions with the surrounding ecosystems (e.g., competition, predation, invasive species and more). As a result of human mediated climate change, increasing exploitation of costal areas, and increasing pressure on both terrestrial and marine ecosystems, the impacts of these factors on earth systems is expected to increase (IPBES 2019, WWF 2020, IPCC 2021). Consequently the interactions between LTA practice and the environment is challenging to discern, especially in the context of uncertainties in future pressures.

In 2020 the Global Risks Report of the World Economic Forum (WEF), for the first time in the history of the survey, placed environmental-related issues in the top 5 places for risks with the highest likelihood of occurring in the next 10 years (WEF 2020). Last year the COVID-19 pandemic placed infectious diseases on the top list, with remaining positions being environmental-related (WEF 2021):

1) Extreme weather
2) Climate action failure
3) Human environmental damage
4) Infectious diseases
5) Biodiversity loss

Given that much of aquaculture, and especially extractive LTA, is conducted in the open environment, one can expect that many of these risks will impact the aquaculture industry.

The risk analysis framework is useful for identifying, evaluating and addressing environmental issues from, and on, aquaculture. However, the understanding of risks associated with aquaculture and ecosystem functions is still limited (Philips and Subasinghe 2008). The term “risk” is often defined as the potential occurrence of unwanted, adverse consequences associated with an activity, yet the international standard definition of risk is “effect of uncertainty on objectives” (ISO 2022) which includes both negative and positive events. Risk analysis is used to determine the likelihood of the occurrence and the consequence of such events. The purpose of risk analysis is to provide a structured way to assess and communicate risks to, or from, a sector (Phillips & Subasinghe 2008).

The importance of risk assessments in different activities, including in aquaculture, is well recognised, and there are many examples where specific issues such as the potential effects of new pharmaceutical tretments and chemicals (Costello et al. 2001, Rico and Van den Brink 2014, de la Casa-Resino et al. 2021), use of alternative components in aquaculture feeds (Glencross et al. 2020), the impact of non-native species (Campbell & Hewitt 2008) and of climate change (Doubleday et al. 2013) on aquaculture practices have been explored using risk assessment. For some specific aspects in aquaculture, i.e. pathogen risks, food safety and public health risks, ecological (pests) risks, genetic risks, environmental risks, financial risks, and social risks, there is even general recommendations on methodology to use (FAO 2008). Risk assessments in general can include effects on many different aspects, but can also be more specific as in e.g. environmental risk assessments or in ecological risk assessments which primarily focuses on the impact on the environment or ecosystem interactions. With the emergence and increase of new challenges (e.g. climate change, new polutants, land and sea use changes, biodiversity loss and invasive species), ecological risk assessment has grown and evolved.

Although risk assessment and management is included in the every day activities in aquaculture practices, most of the risk assessments are performed by experts and are directed towards decision-makers. In fact, the aquaculture industry has been observed to implement systematic risk management to a lesser extent compared to other industries (Holmen & Thorvaldsen 2015). Moreover, the wide range of environmental risks relevant to aquaculture requires a wide range of tools for risk assessment, and it is often difficult to quantify the likelihood of risk events and the consequence of these events. Consequently, many forms of risk analysis are a significant undertaking that requires considerable capacity, both in terms of knowledge and access to suitable information and tools. The limited use of structured risk assessments may consequently be a result of insufficient knowledge level about, and time constraints to execute, structured risk assessments (Holmen et al. 2018). Aditionally, according to Philips and Subasinghe (2008), there are limited experiences and a lack of case studies associated with more complex risk analyses in aquaculture, thereby limiting the posibility of knowledge transfer within the field. These challenges cause a significant knowledge gap related to the actual risks observed during aquaculture operations.

Thus, there is an urgent need to strengthen the aquaculture industry's risk assessment capacity and to assess how global risks and emerging pressures relate to performance of various aquaculture systems. This will be key in national and international development agendas, not only for food security but also for livelihoods, conservation, and restoration of marine ecosystems (Troell et al. 2022). Likewise, sustainable aquaculture requires risk management of culture of non-native species and developed farmed types, as well as expanded culture of native species (Sonesson et al., 2021).

To address the above mentioned challenges, T6.3 in WP6 in AV , including T6.3.1 (Risk Identification and Analysis) and T6.3.2 (Risk Evaluation and Treatment) has the primary objective to produce knowledge to enable prediction, adaptation and resilience to pressures exerted by, and upon, LTA in the Atlantic Ocean, including climate change and emerging pollutants. More specifically, D6.4, the joint and primary output from the two subtasks, aims to:

- Collate insights gained through the industry's' first-hand experience of risks in LTA into general trends or findings (bottom-up approach).
- Forecasting the possible future development of LTA through scenarios based on identified trends (top-down approach) to identify future risks exerted by, and upon, LTA.
- Increase the general knowledge about environmental risks exerted upon, and by, LTA at different geographical scales

D6.4 will be followed by D6.5 (Fact sheets describing environmental effects from and on LTS aquaculture) and D6.6 (Recommendations of the most important mitigation actions to address the major identified threats). Both these deliverables will draw from results from multiple WP6 tasks including T6.3. **Note: risk treatment of identified risks in this report will be discussed in D6.6. and is therefore not included in this deliverable.**

1.3 Data management

AquaVitae is a participant in the H2020 Open Research Data Pilot, aiming at facilitating reuse of research data either collected or generated throughout a project. The Open Research Data Pilot aims to make data FAIR, i.e., Findable, Accessible, Interoperable and Reusable. To achieve this, all AquaVitae WPs, including WP6, have prepared data management plans, in short describing expected data collection/generation, and how it will be curated and preserved. As a rule of thumb, all data is to be made available in an online repository according to the time frames provided by the European Commission (EC). In accordance with the data management plan, T6.3 will deposit external and internal risks affecting the sustainability performance of LTA in the Atlantic region according to the practitioners' workshops in the AquaVitae repository in Zenodo.

1.4 The COVID-19 pandemic's effect on D6.4

The worldwide COVID-19 pandemic has inevitably challenged the original work plan of this task. However, T6.3 is relatively independent of work in other WP/tasks and is thus not affected by any cascading effects. Combined with the acquired experience of adapting to COVID-19 imposed restrictions, such as replacing physical workshops with digital ones, D6.4 was only postponed one month, from month 36 to month 37. The major impact on the task from this change was a reduction in the number of stakeholders that could be engaged in the process, resulting in a smaller dataset compared to what was originally expected.

2 Methodology

2.1 Analytical framework

D6.4 covers the first three steps of the risk management process – establish context, risk identification and risk analysis – as described by ISO 31000 (2021). This is illustrated in Figure 1. The following two steps, risk evaluation and risk treatment, will be covered in D6.6.

The basis for the risk assessment was the challenge-structuring framework (CSF) developed by WP6 and reported in D6.1[1] and in the Assessment Domain (AD) Report (Strand et al. 2022). T6.3 expands the CSF, by adding the temporal dimension to include not only current acknowledged risks but also future foreseeable risks. This **establishes the context** for the following steps and is elaborated in chapter 3. The **risk identification** was carried out through a combination of bottom-up and top-down approaches, drawing from stakeholder workshops, including both industry and academic partners, and forecasting analysis, respectively. This is elaborated in chapters 4 and 5. The **risk analysis** is elaborated in chapter 6.

Note that "risk" is a comprehensive concept, including both risks exerted by, and upon, LTA as well as both negative and positive risks. The former is in line with the AV objective of sustainable LTA. The latter is according to ISO 31073:2022 (ISO 2022), defining **risk** as "effect of uncertainty on objectives", where "effect" can be either positive or negative. Negative risks are referred to as **threats**, and positive risks as **opportunities**. Please refer to the appendix for a summary of the risk management process and the risk terminology used in this report. D6.4 focuses on environmental risks, rather than economic, social, governance and technical risks.

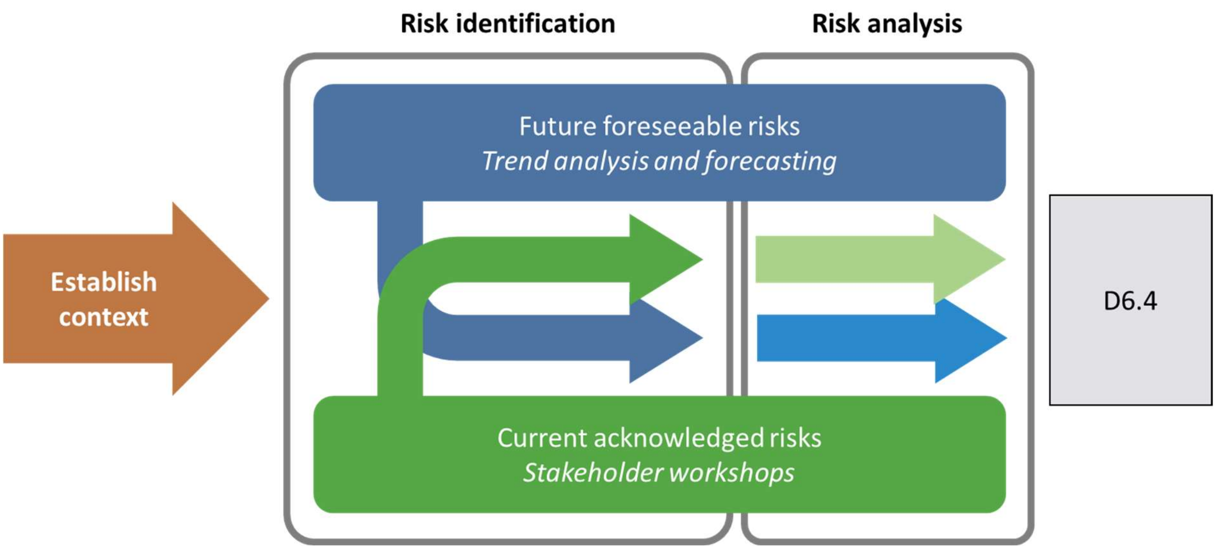


Figure 1. D6.4 encompasses the three steps of Establishing context, Risk identification and Risk analysis, from the risk management process. The risk identification and risk analysis are carried out through a combination of bottom-up and top-down approaches, drawing from stakeholder workshops, including both industry and academic partners, and forecasting analysis, respectively. Risk evaluation and risk treatment will be covered in a later deliverable (D6.6).

[1] D6.1 Recommendation of indicators to be used in sustainability analysis of new and underutilized low-trophic species in aquaculture was presented by WP6 and submitted by AV 11/09/2020.

2.2 Stakeholder workshops on risk identification and risk analysis

The bottom-up approach was structured around three stakeholder workshops during summer and fall 2021. Due to COVID-19 restrictions, all workshops had to be performed online. To somewhat compensate for the limited interaction this imposed, all participants were offered so-called "deep dives", i.e., separate sessions with the WP6 experts. The participants represented industry and research, as summarized in Table 1.

During three workshops, each participant worked through step 1-3 of the risk assessment process defined by ISO 31000 (described in the Appendix). The process steps in the standards are: 1) defining the context, 2) identifying risk events, 3) analyzing risks, 4) evaluating risks and 5) determine how to properly manage the risks. This is also similar to the structure suggested for risk assessment in aquaculture by FAO (2008). The process and the assessment were guided by an Excel tool partly developed in the project. Based on this information, the tool visualises a risk profile for the operator.

The workshop series was the culmination of a data collection process, that was initiated immediately following the submission of D6.1 in September 2020. Preparations included scoping the data collection, development, and validation of the data collection Excel tool, and, at the later stage, workshop planning. The Excel data collection tool was validated in an iterative process, utilising experience from data collection in T6.2.2, and feedback from a small group of test-users. The tool allowed the participants to define risks separated by culture site and process step (e.g., culture structures, harvest, packing, transport).

Table 1. Participating stakeholders in the risk management workshops. Everyone did not attend all three workshops. The structure of the organisations participating in the process is reported according to the assessment domain developed in T6.1 (Strand et al. 2022). All organisations included both the seed production and grow out steps of the value chain in the data recorded. All organisations except #6 also performed their activities in near-shore areas. Most activities were also performed as monoculture.

Stakeholder	Role	VC	Organism group	Production system	Production mode	Geographical sector
#1	Industry	IV (Shell-fish)	Bivalves	Surface systems	Monoculture	Europe
#2	Research	I (Macro-algae)	Green/red macroalgae	Land-based ponds and tanks	Monoculture	Europe
#3	Research*	IV (Shell-fish)	Bivalves	Surface systems	Monoculture	Europe
#4	Industry	II (IMTA)	Abalone	Land-based ponds and tanks	Monoculture	South Africa
#5	Research*	III (Echino-derms)	Echinoderm	Land-based ponds and tanks	Monoculture	Europe
#6	Industry	I (Macro-algae)	Brown macroalgae	Surface systems	Monoculture	Europe
#7	Industry	IV (Shell-fish)	Bivalves	Land-based ponds and tanks		Brazil

**Applied research together with industry partners*

2.2.1 Scales for the evaluation of risk by stakeholders

The stakeholders evaluated each identified risk event with respect to consequences and likelihood against scales with five different levels defined by IVL (Table 2). When defining likelihood and consequences scales, the aim was to create a scale that distributes risk events between all levels. A risk matrix where all risk events end up being placed in the same corner would provide a poor basis for prioritisation. The consequence of a risk event was separated into four dimensions: effects on ecosystems, material damages, the irreversibility of the consequences and the loss of production.

Table 2. Scales used by stakeholders for the evaluation of risk events.

Likelihood	
1 - 1 time per 100 years 2 - 1 time per 10 years 3 - Every year 4 - Every week 5 - Every day	
Consequences	
Effects on ecosystems	***Irreversibility***
5 - Everything dies 4 - Widespread effects outside of the production area or ecosystem replacement 3 - Very impaired/weakened natural ecosystem 2 - Local effects restricted to the production site, impaired/weakened natural ecosystem 1 - No effects	5 - Infinite effect 4 - Recovery within 100 seasons 3 - Recovery within 10 seasons 2 - Recovery within 1 season 1 - No residual effect
Material damages	***Loss of production through harm on farmed species production (estimated yearly)***
5 - Impossible to operate 4 - Severe consequences or harm on important specialised gear 3 - Moderate consequences 2 - Easily replaceable material or mild consequences 1 - Normal wear	5 - 100% or high impact over several seasons 4 - 60% or medium impact over several seasons 3 - 30% or low impact over several seasons 2 - 10% 1 - 0 %

2.3 Expert trend analysis and forecasting scenarios

As stated in the introduction, D6.4 is based on the fact that the conditions for LTA are changing and that LTA, in turn, is changing partly as a response to this. Thus, it is reasonable to assume that the current risks, acknowledged by the stakeholders, will not be the same in the future. To investigate how risks exerted upon and by LTA might develop in the foreseeable future, forecasting scenarios based on identified trends were applied, as outlined in Figure 2.

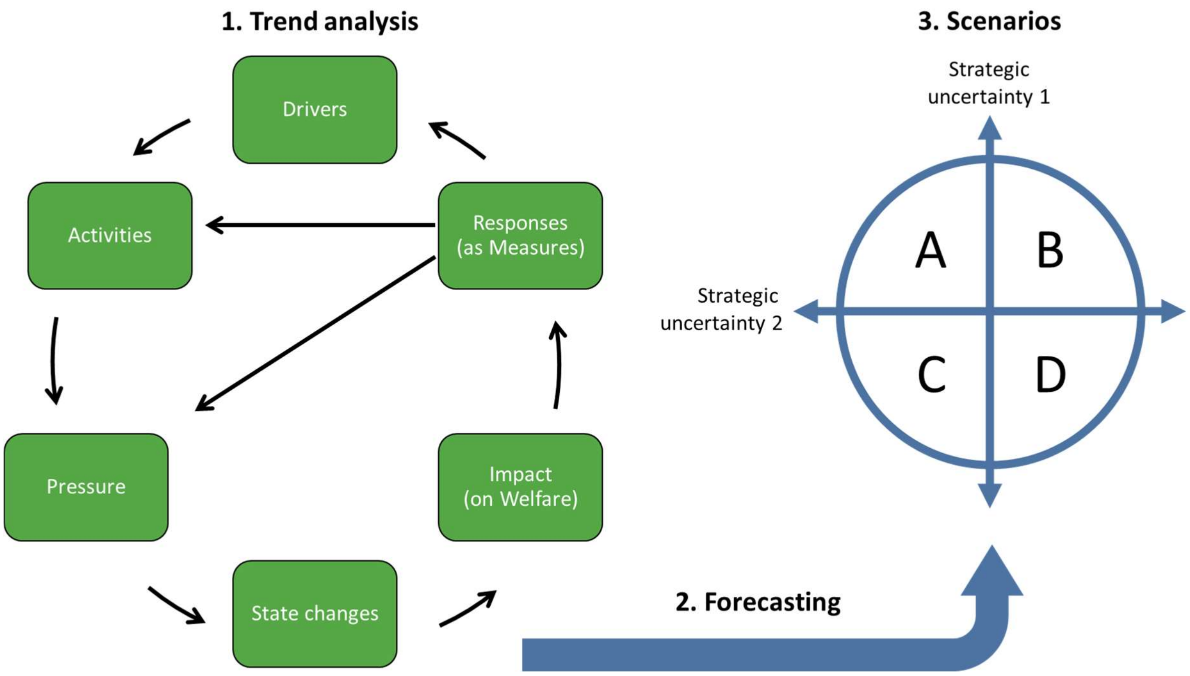


Figure 2. To investigate future risks, trends were analysed and structured with a DAPSI(W)R(M) approach (1). Based on these trends a forecast was done on their possible outcomes and relative importance (2). To provide an overview of the forecasting result, two pairs of possible outcomes were selected as so-called strategic uncertainties with relation to the AV objectives. For each of the four combinations A–D a specific scenario was developed (3).

Relevant trends were identified in a literature review. Literature was identified based on existing knowledge of ongoing processes (FAO Guidelines for Sustainable Aquaculture[2], FAO thematic reviews[3], European Green Deal: Strategic guidelines for sustainable and competitive EU aquaculture[4]), through project clustering (e.g., ClimeFish) and through online literature searches. The review combined large-scale societal trends and assessment frameworks with global aquaculture trends and outlined their interactions. To further explain the conceptual cause-effect relations of the identified trends, they were structured according to the DAPSI(W)R(M) approach. DAPSI(W)R(M) is an abbreviation for its internal logic, where Drivers of basic human needs, such as the need for food, energy, space, movement of goods, security, or recreation, require Activities which lead to Pressures. The Pressures are the mechanisms of State change on the natural system, especially changes in physio-chemical variables (e.g., dissolved oxygen, organic matter, etc.) and changes to the health of individuals, populations, communities, and ecosystems. State changes, in turn, leads to Impacts (on human Welfare), reflecting changes (positive or negative) to the provision of goods and benefits for society. Those then require Responses (as Measures). DAPSI(W)R(M) was presented by Elliott et al. (2017) as a development and clarification of the DPSIR (Driver-Pressure-State-Impact-Response) approach, which has long been a valuable problem-structuring framework used to assess the causes, consequences, and responses to change in a holistic way within an environmental context (EEA 1995).

After trend identification, the information was used in forecasting to structure the major trends into possible developmental paths of LTA around the Atlantic. There are three basic types of **forecasting methods**: qualitative techniques, time series analysis and projection, and causal models (Hyndman and Athanasopoulos 2018, Harvard Business Review 2022). In this case, qualitative forecasting was the most suitable approach as it is not feasible to describe the future state of LTA in the Atlantic Region

[2] https://www.fao.org/in-action/gsa/fr/
[3] https://aquaculture2020.org/thematic/
[4] https://ec.europa.eu/commission/presscorner/detail/en/ip_21_1554

based on numerical information about the past (required for time series analysis) or the assumption that the past patterns will continue (required for causal models, Hyndman and Athanasopoulos 2018). In general, the accuracy of qualitative forecasting improves when the forecaster has important domain knowledge and up-to-date information. It is important, however, to recognise that qualitative forecasting is subjective and thus comes with limitations in terms of replication and in terms of inconsistencies based on explicit or subconscious agendas and as a consequence of anchoring (assigning unproportional weight to the last observation).

Scenarios are descriptions of possible futures. They are not predictions, but forecasts based on various uncertainties and consequently possible development paths. Scenarios developed through qualitative, also called judgmental, forecasting are based on the trends that are significant for the scope at hand, in this case LTA in the Atlantic Region. To provide an overview of the forecasting result, two pairs of possible outcomes were selected as so-called strategic uncertainties with relation to the AV objectives. For each of the four combinations, a specific scenario was developed. By using different selections of the remaining trends, each scenario was elaborated to provide more depth and detail. The scenario development process was based on a combination of the identified trends, identified linkages between different parameters and expert knowledge. The aim was for each scenario to be at the same time sufficiently thought-provoking to inspire reflection over future risks for LTA in the Atlantic Region yet also possible, consistent, credible, and relevant for the scope. Note, however, that the likelihood of all events described does not have to be equal for the four scenarios.

2.4 Comparison of results from stakeholder workshops and expert scenarios

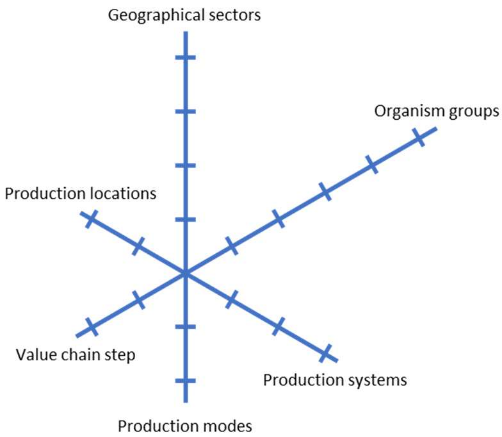
The results from the stakeholder workshops and forecasting scenarios were synthesized into general conclusions. Both approaches result in identified risks. However, due to their differences, these results were not directly compatible. The bottom-up approach was characterised by the stakeholders' experience of LTA operations, their risk perception and understanding of the risk management process. The forecasting scenarios provided a more consistent and general outcome, being the result of the cohesive process from trend analysis to risk identification. The stakeholders' context was much more granular than the forecasting scenarios', looking at risks for a single, specific LTS-system rather than at a global scale. During the workshops, the stakeholders also analysed the identified risks by determining the level of risk in terms of the combination of consequences and their likelihood. This could not be done for the future risks, since their likelihoods are nested with the likelihood for the different scenarios which are not estimated. Thus, the results from the bottom-up and top-down approaches had to be merged to increase the knowledge about environmental risks exerted upon, and by, LTA at different geographical scales. Doing this, details will inevitably be lost for the benefit of consistency and interpretability. To reduce the risk of bias in the synthesis D6.4 was reviewed and anchored by the workshop participants and WP6 core team.

3 Context

The general context for the risk assessment was set by the WP6 CSF, which in turn consists of a desired state for LTA in the Atlantic Region and the five prioritised UN Sustainability Goals (SDGs), as described in D6.1. AV describes the desired state for LTA in the Atlantic Region as follows: *Sustainable LTS aquaculture contributes to fulfilling the needs of the present without compromising the ability of future generations to meet their own needs.* In this context, AV divides sustainability of LTA into four domains; environmental (WPs 1-4 and 6), social (WP 5), economic (WP7) and governance (WP8). The SDGs most directly linked to AV's objectives are SDG 14 *Life below water*, 2 *Zero hunger*, 8 *Decent work and economic growth*, 12 *Responsible consumption and production* and 13 *Climate action*. The CSF is illustrated in Figure 3 and presented in D6.1. The risk assessment focuses mainly on environmental risks only

Figure 3. Schematic illustration of the CSF. At the core is the AV's desired state for LTA in the Atlantic Region, covering four sustainability domains and with the five SDGs most directly linked to the AV objectives highlighted. Figure modified from D6.1.

The material boundaries for the risk assessment are given by the AD, a catalogue of emerging and existing LTS-systems around the Atlantic region (Strand et al. 2022). These systems represent the activities that are exposed to, and pose, risks in this context. In the AD, each LTS-system is described as a unique combination of six characteristics' elements (Figure 4). In brief, the diversity in LTS systems was found to be substantially higher in North America and Europe compared to in South Africa and Namibia, and in Brazil. Currently, bivalves are the most important organism group of LTS produced in the Atlantic Ocean and the group is well represented in all geographical sectors across the Atlantic. Nearshore activities include all organism groups and geographical sectors, while offshore LTA are only present in Europe and North America (Figure 5).



Geographical sectors
- Europe
- North America
- Brazil
- South Africa and Namibia

Organism groups
- Brown macroalgae
- Red/green macroalgae
- Bivalves
- Abalone
- Echinoderms

Production systems
- Land-based ponds and tanks
- Surface systems
- Bottom culture systems

Production modes
- Monoculture
- Polyculture

Value chain steps
- Seed production
- Grow out

Production locations
- Near-shore
- Off-shore

Figure 4. The AD is defined by six characteristics. Each unique combination of the characteristics' different elements represents an LTS-system. From Strand et al. 2022.

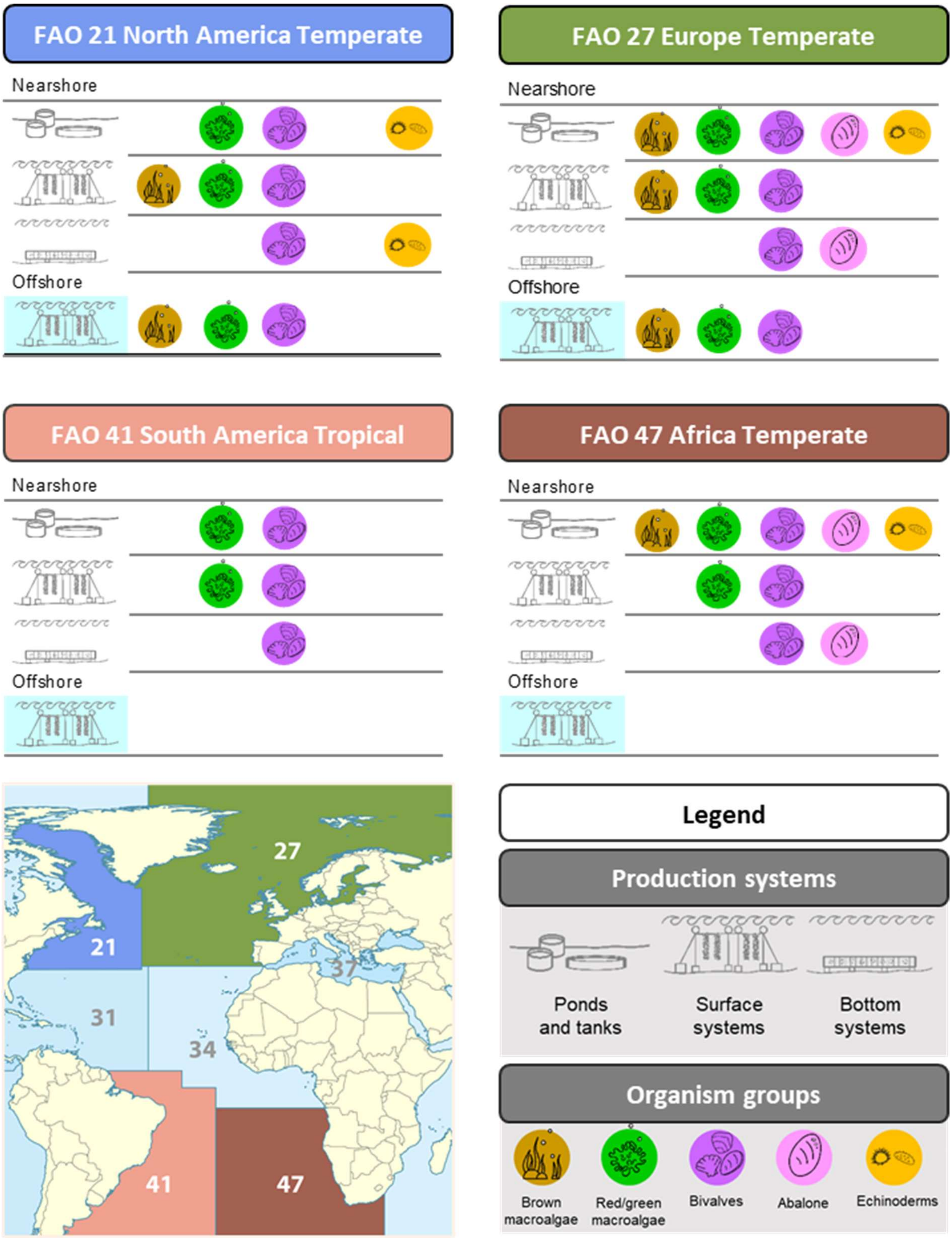


Figure 5. An overview of the AD, illustrated for each of the four geographical sectors. The characteristic value chain step is not represented in the illustration. Figure modified from Strand et al. 2022.

4 Identification of current acknowledged risks

The primary objective of the risk assessment workshops was to gain insights into general trends or findings through the stakeholders' first-hand experience of risks in aquaculture. The secondary objective was to evaluate the general knowledge level of risk assessment methods among the stakeholders and if needed strengthen the stakeholders in their own structured assessment of risks. Consequently, training was an important part of the workshops.

4.1 Example of results for individual stakeholders

On an individual level, the risk assessment work resulted in the identification of farm-specific risks and a prioritisation of what risk events to manage. Examples of risk dashboard outputs are illustrated in Figure 6 and Figure 7. The example is based on a stakeholder operating six different farms and experiencing recurring risk events from various sources. The other stakeholders generated similar results based on their assessments. Please note that the text and numbers in the figures is not critical but the figures are included to illustrate what type of output was obtained by the participants after completing the workshop process.

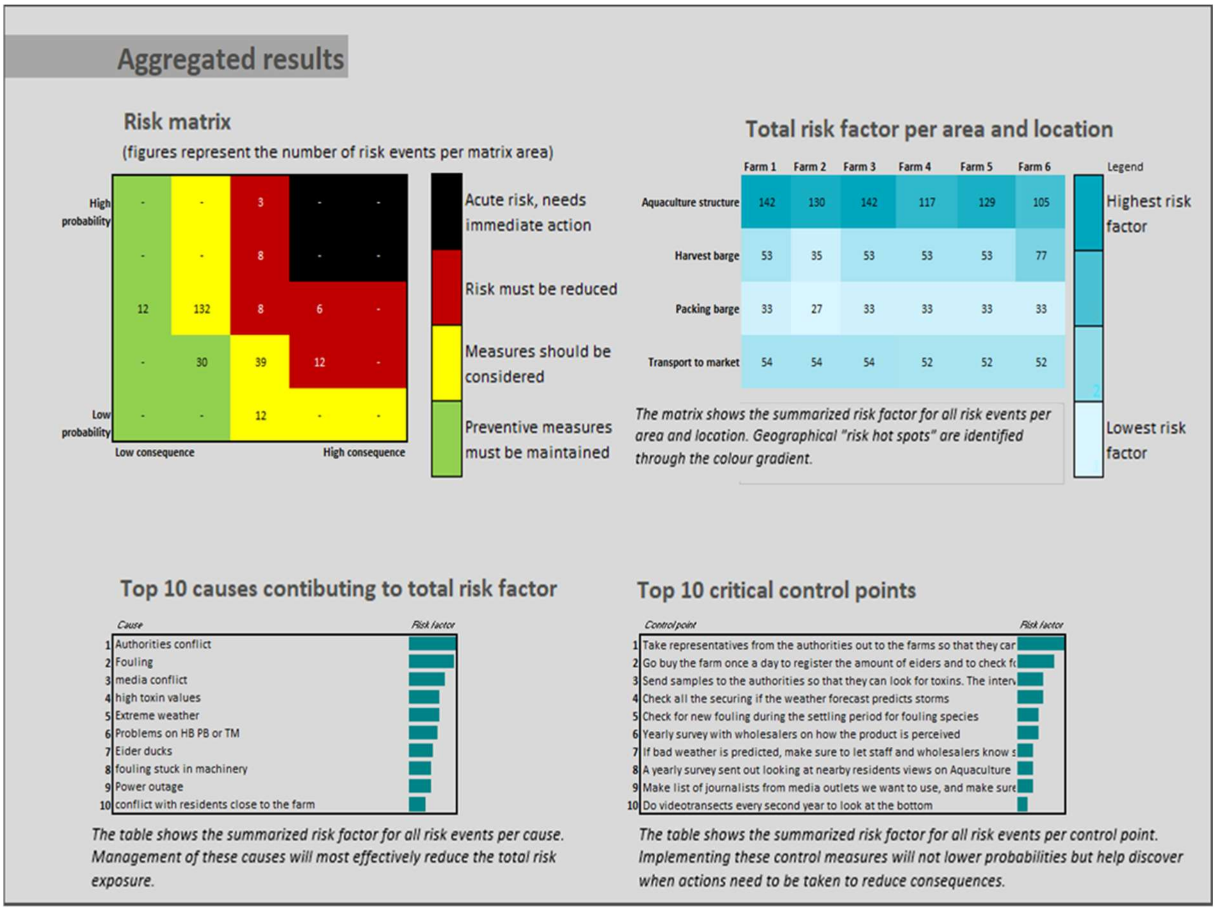


Figure 6. Screenshot from the aggregated results of one of the participating organisations, showing: 1) the distribution of the total number of risk events per risk matrix area, 2) the total risk factor per geographical area and process step, 3) the top 10 causes contributing to the total risk factor and 4) the top 10 critical control points, defined as the control point that controls the largest total risk factor, i.e., the control that would give the most bang for the bucks if implemented.

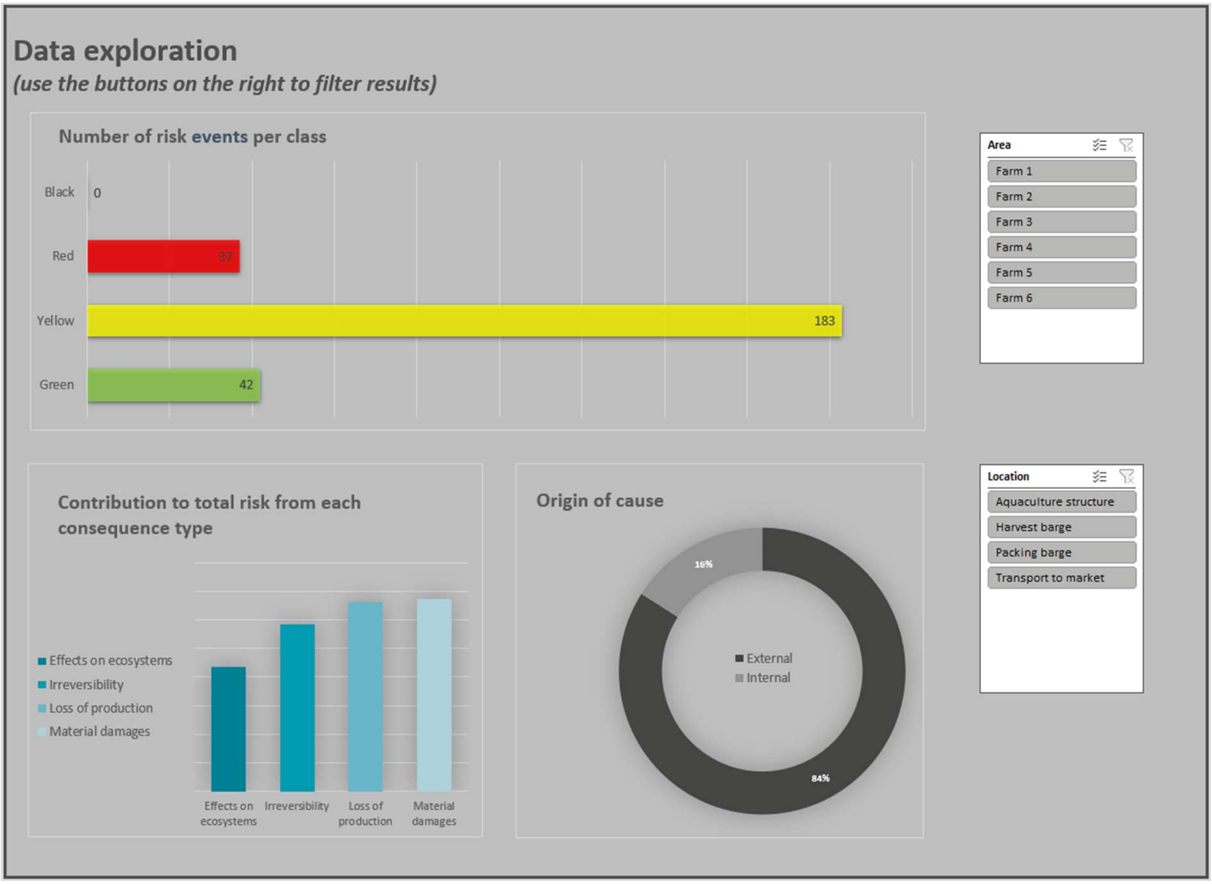


Figure 7. Screenshot from the data exploration section in the risk assessment tool that allows the company to explore differences and hotspots for different locations and geographical areas.

The stakeholders' exposure to risk will decline by repeating the assessment process regularly and developing action plans based on the outcomes. The successive lowering of total risk level is the basic idea of structured risk management. The visualisation of risk simplified the massive datasets generated into something tangible and hopefully actionable.

The participants were predominantly positive about having participated in the workshops. Several of them pointed out that it had been an interesting and educational process, giving them new insights into their production system and its interactions with the surrounding environment. The following quotes give two more examples of lessons learned by the participants:

"The risk assessment was a learning curve. At first, it was hard to find risks, but as you go along, it gets easier and easier. I think this work is important, and will require many years to perfect."

"I learned that there are many risks that you don't consider as risks at first. Like one person said during one of the workshops, it's the small risks that are the most costly. It's easy to get stuck on the big risks and forget the small risks."

4.2 Collated stakeholder risk assessments

During the workshops and follow up work, each stakeholder assessed the risks from their specific perspective and operations. The most striking observation was that the composition of risk events and sources of risk events differed significantly between stakeholders. The assessments have clearly been made from the stakeholder perspective, which was the objective, however this also causes challenges in terms of generalisations. Nevertheless, some general analyses and conclusions can be drawn based on the data.

The total number of unique risk events per stakeholder, irrespective of the number of occurrences in different process steps, varied between 4 and 30 (Figure 8), but were in average 19. For stakeholders with larger operations, the same risk event might be repeated, being present at several locations or in different process steps.

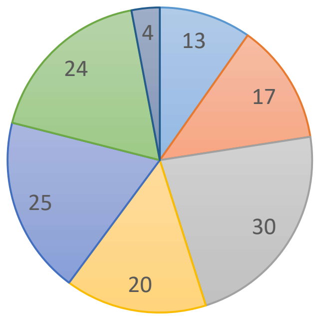


Figure 8. The number of identified unique risk events per stakeholder.

Table 3 shows the distribution of the risk events between consequence class, type and assessed likelihood jointly for all operators. Each risk event has one likelihood, determined by its likelihood (Table 2), while the consequence can differ between environment and material damages (Table 2). E.g., one stakeholder determined that "predation of eider ducks" had a likelihood 5 (occurs daily), while the consequence was 2 in terms of effects on ecosystems, irreversibility, and material damages but 4 in terms of loss of production. Most risk events were observed to happen yearly (likelihood class 3), but the consequences were expected to be minor (class 1-2, Table 3). The higher consequence class contained more risk events in the "loss of production"-type, while "effects on ecosystem" was more commonly found in the lowest consequence class. No records of events in the most severe likelihood or consequences were recorded.

Table 3. The total number of risk events per consequence class, type, and likelihood for all stakeholders. Each risk is assessed for four consequence classes (Effects on ecosystems, Irreversibility, Loss of production and Material damages). Number of risks are indicated by colour from few (blue) to many (orange).

Consequence		Likelihood				
		1	**2**	**3**	**4**	**5**
5	Effects on ecosystems	0	0	0	0	0
	Irreversibility	4	6	6	0	0
	Loss of production	7	18	18	0	0
	Material damages	0	6	6	0	1
4	Effects on ecosystems	2	9	4	6	0
	Irreversibility	7	5	3	1	0
	Loss of production	17	32	14	8	3
	Material damages	15	21	17	0	0
3	Effects on ecosystems	12	34	3	3	0
	Irreversibility	14	81	6	5	0
	Loss of production	0	36	32	4	1
	Material damages	0	40	70	8	0
2	Effects on ecosystems	3	37	119	5	4
	Irreversibility	7	55	134	21	4
	Loss of production	5	31	139	6	0
	Material damages	3	10	60	4	3
1	Effects on ecosystems	25	82	118	17	1
	Irreversibility	10	15	95	4	0
	Loss of production	13	45	41	13	1
	Material damages	24	85	91	19	1

The assessments of risk events were found to be specific for each operation and operator (Table 4). Notably, none of the 20 highest risk events identified was shared between the operators. This is partly a consequence of terminology and inconsistent assessment of cause, risk events and effect. One example of this is that several operators described the occurrence of fouling as a major risk, yet in different terms. Nevertheless, the data shows that many, if not most, of the assessed risks, are unique and context dependent.

A summary of the most frequent causes of risk events (Table 5) indicates that weather-related phenomena and pandemics were the causes which operators most frequently noted. Except for these two causes, the other causes were essentially unique for the risk events identified by stakeholders, enhancing the image of risk analysis being specific for each stakeholder. Also, the results illustrate the potential bias that may occur due to anchoring (see section 2.3), i.e., that by experiencing an event such as the pandemic, you are more likely to assess it. Risk assessments are per default, limited to the imagination of the assessor.

The results from the stakeholder risk assessments were left unedited to a large extent to avoid bias in the analysis as the underlying risk event was sometimes not clear. The only exception to this was a categorisation of unique combinations of risk events and causes based on their character (economic, environmental, governmental, social, and technical) and whether the operation was exposed to (to) or if the operation exposes the surroundings (from) to, a risk. Most risk events/causes identified by the stakeholders were classified as environmental or technical, i.e., extreme weather or fouling. Also, the surroundings affected the operation for most identified combinations of risk events and causes, not the opposite (Figure 9). The perception aligns well with the stakeholders' operational perspective on risks.

Table 4. The average risk factor (average consequence rounded to the nearest whole number multiplied by likelihood) per risk event assessed by stakeholders. The table shows the 20 risk events with the highest average rating. Note that stakeholder #6 did not identify any of the top 20 risks..

Risk event	#1	#2	#3	#4	#5	#6	#7
Eider ducks	13.0						
Unforeseen health risks in gonad of sea urchins					11.5		
Fouling	9.4						
Pest out-break of fouling by high stocking density							9.0
Absence of knowledge							9.0
Seawater quality							9.0
Pesticides							9.0
Oceanographic				9.0			
Authority conflict	8.7						
Poor husbandry				8.0			
Release of wild stock by captive bread stock				8.0			
Release of farmed Abalone in wild				8.0			
Use of antifouling in mussel rafts			8.0				
Increased stress in sea urchins during transport					8.0		
Insufficient knowledge regarding holding and transport					8.0		
Insufficient planning or maintenance					8.0		
Mussel rafts			8.0				
Epiphyte outbreak competing for resources		8.0					
Pathogens	8.0						
Inorganic loading - Effluent water				8.0			

Table 5. The most frequent causes of risk events per stakeholder.

Source	#1	#2	#3	#4	#5	#6	#7	Grand Total
Pandemic	Yes	Yes	Yes	Yes	Yes			5
Extreme weather	Yes			Yes		Yes	Yes	4
Storm activity				Yes		Yes		2
Storm activity (including flooding)		Yes				Yes		2
Storm		Yes						1
Natural storm events					Yes			1
Temperature peaks		Yes				Yes		2
Currents	Yes			Yes				2
Misinformation on natural stock size		Yes	Yes					2
Energy breakdown		Yes				Yes		2
Increase in organic load	Yes			Yes				2
Pest out-break of fouling by season							Yes	1

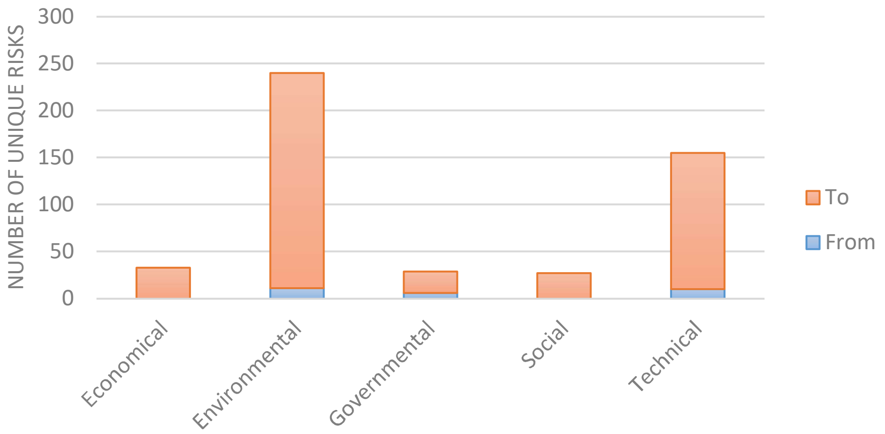


Figure 9. The total count of unique sets of risks per stakeholder and whether it exposes the operations (to) or if the operation is exposing the surroundings to risk (from).

4.3 Stakeholder perception of LTA's exposure to climate risks

Since climate change is one of AV's main concerns, the participants were asked if they think that LTA is more or less exposed to climate risks than other aquaculture or food production, and why. The question was included in the evaluation form, distributed after the workshops. This was done to ensure that the question would not affect or guide the assessments. Unfortunately, it also resulted in only three answers, quoted below:

> *"No, I don't think LTS aquaculture is particularly more exposed although some species would be more at risk."*

> *"Low trophic aquaculture, in particular any unfed aquaculture conducted in the natural environment is highly dependent on the environmental conditions of the culture area and, consequently it may be affected by climate change. However, strong storms, heat waves and other risks linked with climate conditions that are expected to be more frequent and intense in the next decades due to climate change, shall also affect high-trophic fed aquaculture if this production facilities are also located in fjords, estuaries or in the open sea."*

> *"I think we first need to separate aquaculture and food production. Terrestrial food production I think have fewer risks, since most risks are local, while food production in*

the sea has more risks, since most systems are open. The spreading of climate related pathogens can go much faster in open system aquaculture than closed systems. To conclude, I think that the climate risk is more about if the system is opened or closed than if it's LTS or e.g., salmon aquaculture."

5 Identification of future foreseeable risks

5.1 Trends

In 2015 the European Environment Agency (EEA) updated its first assessment of emerging global trends. The exploratory analysis summarised 11 global megatrends (GMTs) grouped into five clusters (Table 6). The five clusters correspond well with AV's four dimensions of sustainability (Figure 3), with the addition of technological GMTs.

These GMTs cannot give a comprehensive description at a headline level but rather outline the complexity of foreseeing one future development. Figure 10 presents an attempt to structure the GMTs according to the DAPSI(W)R(M) approach, thus suggesting relationships between different GMTs. It should be emphasized that the GMT and the DAPSI(W)R(M) are two separate and not directly compatible frameworks. Thus, this the linking is only done on a conceptual level.

In addition to the GMTs, two additional frameworks provide important knowledge for the trend analysis. As mentioned in section 3, one is the SDGs, and the trend analysis in the coming chapters consequently include aspects related to the top five SDGs most closely linked to LTA (Figure 3). The other framework of significance is the planetary boundaries (Steffen et al. 2015). The planetary boundaries describe vital biogeochemical systems and limits of these systems which we cannot exceed without putting our society at risk. These are climate change, biodiversity loss, ocean acidification, ozone depletion, atmospheric aerosol pollution, freshwater use, biogeochemical flows of nitrogen and phosphorus, land-system change, and release of novel chemicals. The drivers, primarily rapid population growth and consumption, is destabilizing these systems, endangering the stability of the "safe operating space for humanity", with strong implications for the entire planet and for the future of LTA. Some of the implications of relevance to LTA is therefore integrated into the trend description below.

Table 6. The 11 global megatrends described by EEA (2015).

Social	**Technological**	**Economic**	**Environmental**	**Political**
1. Diverging global population trends	4. Accelerating technological change	5. Continued economic growth?	8. Growing pressures on ecosystems	11. Diversifying approaches to governance
2. Towards a more urban world		6. An increasingly multipolar world	9. Increasingly severe consequences of climate change	
3. Changing disease burdens and risks of pandemics		7. Intensified global competition for resources	10. Increasing environmental pollution	

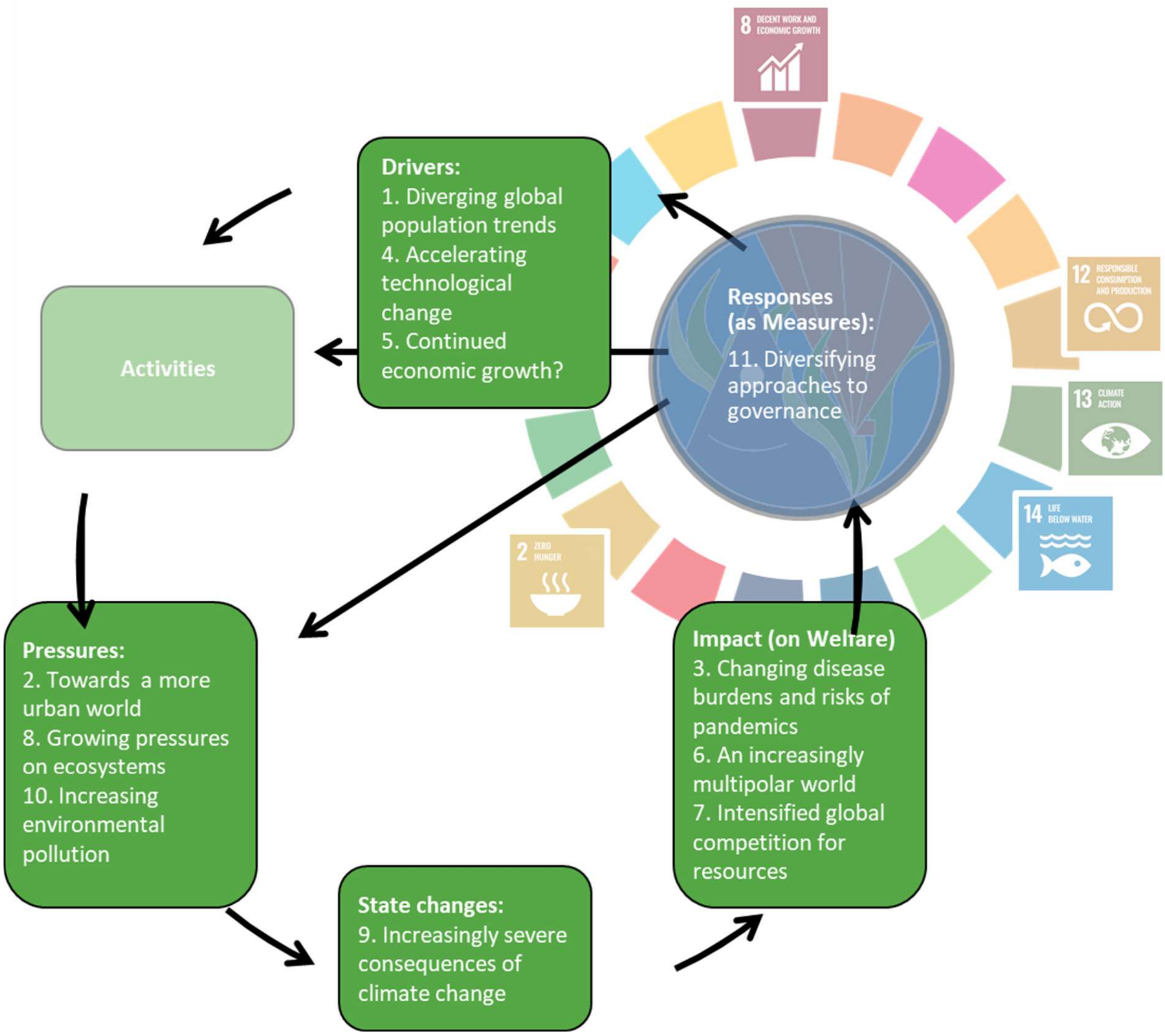


Figure 10. Suggested relationships between EEA's 15 GMT (2015) seen through a DAPSI(W)R(M) lens. AV is promoting sustainable LTA in the Atlantic Region, directly contributing to five prioritized SDGs, and is thus part of responses (as measures).

5.1.1 Drivers

Arguably the most important underlying driver for aquaculture development is food security or Zero Hunger, as stated by SDG 2. This is directly related to the increasing global population (UN 2019) and to the diverging population trends of ageing and in some cases reducing populations in advanced economies and rapidly expanding populations in the least developed countries (GMT 1, EEA 2015). Moreover, with a rising demand for food, cropland expansion and intensification represent the main strategies to boost agricultural production yet may result in lower crop prices globally (Zabel et al. 2019) and may consequently affect profitability of farm operations. Combined with the decreasing proportion of the population engaged in primary food production (GMT 2, EEA 2015), this may result in mobilisation of workers towards alternative sources of employment and incomes. The population growth and investments in human capital will continue to provide a boost to global economic output, thereby increasing the burdens on natural resources (EEA 2015). Urbanisation is an integral aspect of this development, with jobs and earnings in urban settings creating strong incentives for national migration as countries transition from primarily agricultural economies. The combination of a growing global population and widespread increasing living standards is a strong driver for more people to require more resources, such as crops, seafood, forest products, energy, and minerals, and increasingly larger economies to support the economic development (Camill 2010), thereby further exacerbating the strain on the planetary boundaries (Steffen et al. 2015).

Intertwined with this demand for resources, a few positive drivers are emerging. One of these is a growing focus on sustainability among the public (EU barometer 2016). Increasing consumer awareness of sustainability, legality, safety, and quality issues is driving demand for traceability systems and certification schemes of a growing range of products, including seafood (FAO 2021). Other aspects receiving increasing attention are animal welfare and ethical production (EU Barometer 2016; Eurogroup for animals 2018; Segner et al. 2019; Franks et al. 2021). To no small degree, these trends are spearheaded by youth movements such as Fridays for future, demanding change (FAO 2021; SOFI 2021; Food Systems summit 2021).

Increasing living standards also create a positive feedback loop with accelerating technological change (GMT 4). Economic and social megatrends are driving the ever-faster pace of technological development and market adoption (EEA 2015). Another reason for technological change is the intensified competition for resources (GMT 7), forcing societies to look for alternatives to present day products. As new technologies are adopted, new opportunities (or, possibly, threats) will arise. E.g., genetically modified crops (GMO) have been intensely debated, despite being cultivated on approximately 10 % of global cropland in 2012 (EEA 2015).

5.1.2 Activities

The aforementioned drivers result in a range of activities, many of which are based in the marine environment. Examples are shipping, energy production, oil, and gas extraction, as well as fisheries and aquaculture. All of these has played and continue to play an important role in global and regional economies. In fact, the global aquaculture production (not LTA specifically) has been increasing faster than all other food production sectors and has been doing so since the 1970s (Hall et al. 2011, Naylor et al. 2021) and today more than half of the world's production of seafood comes from aquaculture (FAO 2020). Over 80 % of aquaculture production takes place in developing countries including China (Ababouch et al. 2021) and contribute to increase exports that support economic and social development (Nyandat and Yang et al. 2022). In addition to more traditional maritime activities, new activities such as deep seamining is being established, and is likely to expand into the Arctic and Antarctic regions as the ice melts (IPBES 2019).

With an increasing use of the sea, the potential for conflicts between actors increase, in particular for emerging activities as LTA that aims to establish in areas already intensively used by other actors. This issue is also emerging in recent offshore technological developments and establishments (Stojanovic and Farmer 2013). LTA has experienced significant technical innovations in the recent years (Sims et al. 2022), which may allow for the production to expand to remote areas (Krause et al. 2022). This reflects the increasing exploitation of the Blue Economy which can be defined as "smart, sustainable, and inclusive economic and employment growth from oceans, seas, and coasts" (e.g., marine energy production, aquaculture, maritime-, coastal- and cruise tourism, marine mineral resources, blue biotechnology, EC 2012).

Moreover, advanced technology in monitoring of disease and/or harmful algal blooms may increase product safety and farm resilience, and live updates on product demand might allow more control of release of product to market and more profit to the farmer. Technological advances in feed aquaculture production may also increase demand of LTS for inclusion into the feed as wild fish populations are dwindling (FAO 2020). Rapid advances in technology will likely create an imbalance in some production areas compared to others due to uneven technological transfer and implementation rates. Overall, the continued increase in demand for seafood and sustainably produced products, and a trend to move activities further offshore, will likely lead to a shift in production levels for existing LTA operations as well as establishment of new companies and utilisation of new and emerging species (which obviously is at the core of AV's rationale)

5.1.3 Pressures

Humanity has already pushed beyond at least six of the planetary boundaries; climate change, biodiversity, land-system change, biogeochemical flows (Steffen et al. 2015), novel entities[5] (Persson et al. 2022) and freshwater (Wang-Erlandsson et al. 2022). Each one of these transgressions threaten to generate large-scale abrupt or irreversible environmental changes.

Growing pressures on ecosystems (GMT 8, EEA 2015) and increasing environmental pollution (GMT 10, EEA 2015) are unwanted results of human activities (Camill 2010; EEA 2015). Landscapes are changing worldwide, as natural land covers like forests, grasslands, and deserts are being converted to human-dominated ecosystems, including cities, agriculture, and forestry (Camill 2010) with devastating effects on global biodiversity (IPBES 2019). Agriculture has been, and still is, a major cause of land use change (IPBES 2019, WWF 2020), but according to EEA (2015) the global crop area is likely to peak before 2030. Future projections claim that bioenergy crop cultivation could be an expanding activity maintaining land use change (EEA 2015). In addition, ecosystems are today exposed to critical levels of pollution (EEA 2015). All in all, terrestrial ecosystems are under severe pressure with global competition for scarce land resources (GMT 7, EEA 2015) justifying the rapidly increasing expectations on, and need for, a Blue Economy. Therefore, global marine ecosystems have become increasingly exploited in recent decades (EEA 2015), with only 3 % of the oceans being described as free from human pressure in 2014 (IPBES 2019). Overfishing is a global concern (EEA 2015, FAO 2020) and 90 % of wild fish stocks are now overfished or fully fished (FAO 2020). Aquatic ecosystems such as rivers, lakes, and coastal oceans have traditionally been used for pollution disposal from industry and sewage treatment plants, but they have also been subject to unintentional runoff from upland watersheds, such as nitrogen and phosphorus loss from agricultural soils and home septic systems as well as plastics washed into rivers and oceans from storm sewer systems (Camill 2010). Microplastics and organic pollutants are becoming ubiquitous (if they are not already) and are present in higher concentrations around urban areas. Release of pathogens and parasites as well as non-native and invasive species through, for example, ballast water, or of human pathogens through sewage outflows, can be a real risk to LTS in some areas.

Climate change, a state change due to emissions of greenhouse gases from the use of fossil fuels in countless applications, adds even more pressure to global ecosystems including the oceans. Ocean, coastlines, and coastal communities are being disproportionately impacted by climate change effects (IUCN 2017). The ocean plays a central role in regulating the Earth's climate and has so far absorbed around 90 % of the excess energy that accumulates (IPCC 2021, WMO 2022), causing rising sea temperatures measured at various ocean depths, up to 2,000 m deep (WMO 2022) as well as increased ocean stratification (prevention of water mixing due to different properties of water masses), changes in ocean current regimes, and expansion of depleted oxygen zones (IUCN 2017). With additional global warming, the frequency of marine heatwaves will continue to increase, particularly in the tropical ocean and the Arctic (IPCC 2021). Rising sea and atmosphere temperatures, in turn effect weather

[5] Originally called Chemical pollution, but renamed Novel entities by Rockström, Steffen, Noone et al. (2009). Novel entities are described as new substances, new forms of existing substances and modified life forms, including chemicals and other new types of engineered materials or organisms not previously known to the Earth system as well as naturally occurring elements (for example, heavy metals) mobilized by anthropogenic activities.

patterns, with extreme events increasing in frequency (WMO 2022). The oceans are not only absorbing excess energy, but carbon dioxide (CO_2) which reacts with seawater and increases its acidity (Camill 2010, Cavicchioli et al. 2019, IPCC 2021), Increasing acidity makes many marine species and ecosystems increasingly vulnerable (IUCN 2017), threatening organisms and ecosystem services, including food security (WMO 2022). One particular threat to unfed LTA is the depletion of food for native species (McKindsey 2013, Ferreira et al. 2018). Changes in precipitation has caused changes in near-surface ocean salinity (IPCC 2021).

All production inevitably affects the planetary boundaries in one way or the other. Aquaculture products have become one of the most globalized food commodities. This significant development and globalization of aquaculture have exacerbated concerns over its impacts, in particular on the environment, in different parts of the world where production development has exceeded the capacity of planning, controls and oversight (Ababouch et al. 2021). Aquaculture is contributing to some of these pressures by e.g., littering, including microplastics (Skirtun et al. 2022, Tian et al. 2022), release and/or concentration of organic material and of pollutants through both deposition in sediments, bioaccumulation and fouling treatment (Serpa and Duarte 2008) and negative effects on local wildlife (Gorenzel et al. 1994) are known risk that are likely to increase with a growing LTA sector. Aquaculture is also a contributor to the dispersal of invasive species (Cook et al 2008, James 2009), and can also act as stepping-stones for invasive species by providing substrates (as can other coastal and marine infrastructure, Adams et al. 2014, van den Burg et al. 2020). However, the impact from LTA is significant less compared to other food production sectors (Hilborn et al. 2018, Marino et al. 2022), and can even infer some benefits (e.g., contributing to closure of biogeochemical element cycles (Sinha et al. 2022), increased biodiversity (The Nature Conservancy 2021, Theuerkauf et al. 2021) and reduced eutrophication effects (Kotta et al 2018, Thomas et al. 2021) to the point where the activity even becomes restorative (The Nature Conservancy 2021).

5.1.4 State changes

Human activities have had a large and widespread impact on the world's oceans. These include direct exploitation, in particular overexploitation of fish, shellfish and other organisms, land- and sea-based pollution, including from river networks, and land-/sea-use change, including coastal development for infrastructure and aquaculture (IPBES 2019). In 2009, at least 30 % of marine fish stocks were over-exploited or depleted, producing yields below their biological and ecological potential (EEA 2015, IPBES 2019). Many seafood species, including marlins, tunas, swordfish, codfish, sailfish, and sharks have declined 80–90% (Camill 2010). This situation is predicted to worsen, resulting in lower marine catches and stocks in the world's main fishing regions unless fishing efforts are reduced and as well as rising demands for fish (EEA 2015). The depletion of top predators inevitably infers trophic cascade effects which (among other things) exacerbate the negative effects of eutrophication. Moreover, pollution is causing diverse impacts on species populations, ranging from plastics to inorganic and organic compounds that may cause reproductive failure in many bird, fish, and reptile species, to nutrients causing phytoplankton blooms leading to oxygen deficiency due to bacterial degradation of organic material (Camill 2010). As early as 2008, run-off from fields due to excessive or inappropriate application of fertilizer, has produced more than 400 hypoxic zones that affected a total area of more than 245,000 km^2 (IPBES 2019).

Increasingly severe consequences of climate change (GMT 9, EEA 2015) and loss of biodiversity are the two most severe aspects of the ongoing global ecological crisis. These state changes have recently been thoroughly reported by the intergovernmental panels of climate change (IPCC) and biodiversity and ecosystem services (IPBES) respectively. In their sixth assessment report, IPCC (2022) states that "*Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial,* *freshwater and coastal and open ocean marine ecosystems. (…) Approximately half of the species assessed globally have shifted polewards or, on land, also to higher elevations."* This strong link to loss of biodiversity reflects IPBES' (2019) conclusion: *"Human actions threaten more species with global extinction now than ever before. (…) Climate change is a direct driver that is increasingly exacerbating the impact of other drivers on nature and human well-being. (…) Climate change alone is projected to decrease ocean net primary production by between 3 and 10 per cent, and fish biomass by between 3 and 25 per cent (in low and high warming scenarios, respectively) by the end of the century.*" Climate change and biodiversity loss threaten global food production and further underlines the importance of sustainable aquaculture, including LTA. Even though the value of agricultural crop production has tripled since 1970, regulating ecosystem services, such as soil organic carbon and pollinator diversity, have declined (IPBES 2019). Agriculture is also a significant contributor to biodiversity loss (WWF 2020). This indicates that gains in crop production are often not sustainable.

Increases in ocean temperature or changes in currents, due to climate change, can cause widespread and cascading effects on the ecological system. In subpolar and polar regions, marine biodiversity is projected to decline mostly because of warming, sea ice retreat and enhanced ocean acidification (IPBES 2019). Accordingly, changes in species richness and distribution are widely reported (Lafferty et al. 2004, Talmage and Gobler 2011, Poloczanska et al. 2016, IUCN 2017, Steeves et al. 2018, Cavicchioli et al. 2019). Such changes in the vicinity of an LTA farm might influence which larvae are present and may consequently impact wild seed capture on sea-based collectors in LTA. Also, wild fishery of predator species and/or wild populations of the farmed species may cause trophic cascade effects and may result in a limited supply of larvae. However, changes in water temperature and/or currents may also bring new species into the farming areas (Doney et al. 2012), including invasive species that may cause damage to native ecosystems and/or also be of commercial value (Mortensen et al. 2021) or that may act as fouling on LTA structures, as well as pathogens, competitors and predators present in the vicinity of LTA farms (Lafferty et al. 2004, Burge et al. 2014). Ocean acidification also exacerbates existing physiological stresses (such as impeded respiration and reproduction) and reduces growth and survival rates during the early life stages of some species (IUCN 2017), cause so called coral bleaching (e.g., Camill 2010), increased susceptibility to pH induced stress in bivalves (Talmage and Gobler 2011, IUCN 2017) and increased production and range of harmful algae (Cavicchioli et al. 2019).

All-in-all, this could lead to lower reproduction, species fitness, and cause populations to decline faster than expected. In addition, many species will not be able to adapt fast enough to new environmental conditions, further accelerating the rate of species extinction (Camill 2010).

5.1.5 Impact (on Welfare)

On a global level, political, economic, and diplomatic influence is gradually shifting from today's wealthiest economies to other countries and regional power (GMT 7, EEA 2015). This will affect competition for not only food, arable land, and marine resources but also for many other resources, not least so called "critical raw materials" necessary for the transition of energy systems and climate change mitigation. Even if they are not scarce in absolute terms, resources may be unevenly distributed globally, making access uncertain and potentially fostering conflict (EEA 2015).

As apparent, the state changes threaten food security in general, the ocean health and consequently also marine ecosystems and the prerequisites for LTA. IPCC (2022) warns of reduced fisheries yields and aquaculture production in all regions with possible exceptions for North America and Europe. Warming temperatures and decreased precipitation may cause crop yields to decline, particularly in southern Asia and Africa, leading to rising food prices and increased difficulty in gaining access to food (Camill 2010). At the same time, the global population continue to increase, albeit likely at a slower rate than during the last century (GMT 1, EEA 2015). The State of Food Security and Nutrition in the World (SOFI) in 2021 concluded that affordability of healthy diets is a major factor in food security and nutrition and points to conflicts, climate variability, and economic slowdowns, resulting in poverty and inequality. The report suggests that the high cost of healthy diets and persistent inequality put healthy food out of the reach of over 3 billion people in every region of the world. Even though poor people in developing countries are expected to be those most strongly affected by the projected degradation of ecosystems and their life-supporting services (EEA 2015), malnutrition is unacceptably high in both developed and in underdeveloped countries (Development Initiatives 2018). Historically malnutrition has manifested primary as underweight. Today, however, more people are obese than underweight, both globally and in all regions except parts of sub-Saharan Africa and Asia (Ezzati et al. 2016).

Notably, global production of aquaculture (not LTA specifically) has been increasing faster than all other food production industries and has been doing so since the 1970s (Hall et al. 2011, Naylor et al. 2021), alleviating some of the negative impacts on food security. Indeed, more than half of the world's production of seafood now comes from aquaculture (FAO 2020). While the volumes of wild caught fisheries including LTS have been relatively constant since the 90s, showing no growth, aquaculture production continues to increase (Figure 11). Specifically, aquaculture production has tripled, reaching a production of 85 million metric tonnes (Mt) of aquatic animals and 35 Mt of aquatic plants in 2019, yet with equal live weight of fed species and extractive species (Verdegem et al. 2021). Krause et al. (2022) argues that the greatest gains in decarbonizing global food production will come from a transition from animal to plant-based and LTA foods, since global animal protein production (meat, dairy, and fish) occupies over 80 % of farmland, but produces only 37 % of human food protein and 18 % of calories.

LTA is a high-quality food production system with a relatively low cradle-to-gate carbon footprint (Marinho et al. 2022). The carbon dioxide (CO_2) and other greenhouse gasses released during operations (fuel, consumables, etc.) associated to the culture method, and the biological production of CO2 during shell formation and respiration processes, contribute to this carbon footprint. Conversely, long-term burial of a portion of the faeces in the sediment contributes to carbon sequestration. Moreover, the overall carbon footprint is also affected by the faith of the rest products of shelled organisms (e.g., the shells of mussels, oysters, and abalone) and whether the carbon in the shells is immobilised or not. The major benefit in terms of LTA is consequently not carbon sequestration but the replacement of food items with a high carbon footprint with food items with a lower carbon footprint, consequently lowering the overall carbon footprint of our food production systems (Marinho et al. 2022).

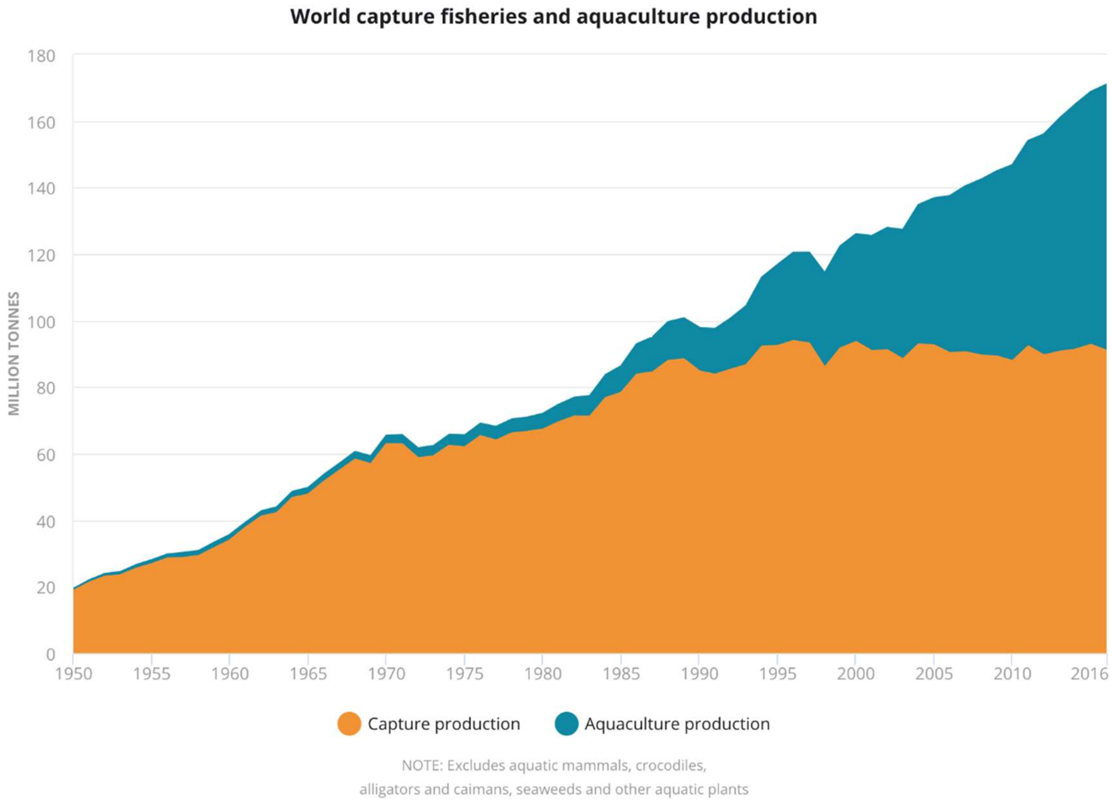


Figure 11. World production of aquaculture and capture production. The data excludes algae production which would undoubtedly make the aquaculture production figures even more impressive given that is the world's most farmed group in terms of volume globally (FAO 2020).

Aquaculture is also being promoted as a significant growth sector, providing livelihood and as an activity that can empower women and young people, notably by facilitating women's decision-making on the consumption and provision of nutritious food (FAO 2017). However, Brugère and Williams (2017) recall that attention must be given to the species grown, preconceptions about gender roles and control over production in order for women to be indeed empowered and benefit from these potential advantages. In the developing world there is a high reliance on manual skilled labour, whereas more advanced aquaculture systems are becoming increasingly reliant on automated computer-controlled feeding systems (Glencross et al. 2022). The evolution of aquaculture systems and equipment results in shifts in production and labour markets. Some types of LTS production are labour intensive yet produce low value, e.g., kelp production, and a shift in the willingness and availability of workers might affect the ability to recruit workers.

5.1.6 Responses (as Measures)

Understanding the development of LTA starts with understanding its current and potential role in food security, as food security is the primary driver of change. SOFI (2021) suggested that a deeper reflection is required on how to address global food security and nutrition. LTA might be a mitigating factor in these trends, allowing for easier access and providing food security and a healthy, nutritious diet at a lower cost to every region of the world. According to Troell et al. (2022), sustainably produced LTS can provide a relatively cheap, local, nutritious food option (thus contributing to SDGs 2 and 3), increase environmental sustainability of oceans, water, climate, and land (SDGs 6, 12, 13, 14, and 15), reduce poverty, achieve gender equality, improve livelihoods, and reduce inequalities (SDGs 1, 5, 8, and 10). This presupposes responsible production/consumption, lowering many of the hidden costs associated with current consumption patterns, while at the same time reducing environmental nutrient pollution, increasing biodiversity, and lowering the carbon footprint of food production. E.g., the on-going urbanisation may require mitigating measures to reduce nutrient leakage from land to sea. Extractive LTS such as filter-feeding bivalves and macroalgae may be used as a tool to mediate the problem (D6.1) while also providing circularity in terms of biogeochemical cycles (Thomas et al. 2021, Sinha et al. 2022) and in the production of feed for fed species of higher trophic levels (D6.1). For more information about the environmental effects of LTA, please refer to section 5.1.3. More and more attention is given to the concept of circular economy for efficient recovery, use and reuse of aquaculture waste, and by-products (Ababouch et al. 2021) as well as biocircularity in the feed ingredient supply chains (Glenncross et al. 2022). Integration of land and ocean-based aquaculture with emerging renewable energy systems, existing agricultural systems, and other sectors of the economy (e.g., tourism) to accelerate aquaculture's contributions to the SDGs should be further explored to build cohesive strategies with common goals (Troell et al. 2022).

A large enough upscaling and outscaling of LTA to deliver on these potential benefits requires a transformative change based on transdisciplinary approaches and a whole new perspective and proactive development of policymaking (Krause et al. 2022). However, according to Verdegem et al. (2021) increasing the global production volume should not be a major goal by itself. Instead, integration of aquaculture into local nutrition-sensitive, circular, and sustainable food systems should become the major driver for future aquaculture system development. There is thus a need for a paradigm shift that encourages small-scale producers to engage in sustainable intensive aquaculture, moving towards production intensification and expansion (Nyandat and Yang et al. 2022). Broadly speaking, impactful innovations in present day aquaculture are improved techniques for selective breeding, refinements in feed formulations, expanded use of vaccines and better extension, outreach and training for farmers (Sims et al. 2021). These are however often overlooked in favour of high-profile aquaculture innovations such as large-scale intensive land-based recirculating aquaculture systems (RAS), highly automated offshore net pen systems, increasing use of robotics and remote command-and-control and novel financing tools for larger companies and small start-ups (Sims et al. 2022). Digital platforms and blockchain technologies will drastically change the structure, logistics and performance of value chains and how producers and consumers interact through virtual platforms (Ababouch et al. 2021) on local, regional, and global scales. New techniques in modelling and monitoring might aid in the prediction of harmful algal blooms (Cavicchioli et al. 2019).

The global aquaculture sector has good conditions for resilient and locally adapted production system, currently including over 300 species farmed commercially (Naylor et al. 2021). However, this emphasizes the importance of having information and monitoring systems to assess the status of both farmed and wild populations, in the latter case to be able to identify needs for conservation programmes for threatened populations (Sonesson et al. 2021). There are studies showing that restorative aquaculture can significantly help restore ocean health, as well as support economic development and food production in coastal communities worldwide, if right practices are deployed in the right places (The Nature Conservancy 2022). Sonesson et al. (2021) states the urgency to accelerate development of well managed breeding programmes and ensure fair and equitable LTA. Some genetic technologies, despite having been resisted or more slowly adopted, could provide benefits to industry, genetic diversity, and ecosystem health (Sims et al. 2021, Alday-Sanz and Jie et al. 2022). In parallel, there is a growing need to deliver a "precision nutrition" approach to farmed aquaculture species, as gains in the efficiency of feeds is slowing for developed species (Glencross et al. 2022). Marine resources are increasingly seen as a low-volume, high-value resource, with e.g., microalgal and genetically modified crop options emerging as alternatives (Glencross et al. 2022). Alday-Sanz and Jie et al. (2022) outlines the threat of emergence of antimicrobial agent resistance associated with aquaculture and the aquatic environments. At the same time, antibiotic use in aquaculture is likely to continue to decrease (Aquafeed 2018), which could lead to a positive change in attitudes towards LTA. While antibiotic use mainly affects fed species and not LTS, it may influence the overall acceptance level of aquaculture products.

An expanded and intensified production of fed LTS might lead to an increase in the effective trophic niche due to the inclusion of fish meal and oil in the formulated feed fed to fish in intensive culture (Cottrell et al. 2021). In contrast, yet based on the same principle, the use of fish meal and fish oil is decreasing worldwide, often by inclusion of vegetable components in the diets of fed species, and in some cases even by LTS such as marine algae or mussels (Naylor et al. 2021). This trend infers a reduction of the effective trophic nice of high-trophic species. If this trend continues, it could be argued that even LTS-fed salmon and other higher trophic species could be considered as LTS in comparison to their wild counterparts (Cottrell et al. 2021). This will likely increase demand for some LTS, such as algae but also mussels, etc.

With expanding aquaculture, both fed and extractive aquaculture need to pay more attention to scale, site selection and the health of the wider production environment (Verdegem et al. 2021). This is increasingly important given ClimeFish's (2020) conclusion that there are huge knowledge gaps associated with how the environment is changing, especially at the farm-scale, which is most relevant for aquaculture producers. Water temperature was the only climate stressor common to all their case studies. Other stressors, such as climate (e.g., heat waves, wind speed, evaporation), climate-related (e.g., ocean currents, chlorophyll a (Chl-a), prey availability), managerial (e.g., seeding/stocking time, food supply, fishing mortality) or other human-related (e.g., eutrophication) have been modelled or considered depending on the case study (ClimeFish 2020). Based on this, ClimeFish (2020) concludes that planning for adaption to high temperature periods require data and models of both fish physiology and farm responses, and good aquaculture management also requires climate projections that capture stressors at a scale relevant to production.

Going forward, aquaculture, including LTA, needs to gain a social license to operate under these new conditions. Troell et al. (2022) recommends accelerated education on wider benefits for local decision makers and the public to make informed choices, improve consumers' understanding of aquaculture's role for achieving the SDGs, and evidence-based narratives to help combat the negative image of the sector which impacts political will. This is important, since limitations to the comprehensive legislative framework persist and is aggravated by lack of clarity in rules and regulations which is currently complicated or prevents the expansion of LTA (Chapela et al. 2020). As mentioned above, there are several trends in favour of aquaculture, and arguably particularly so for LTA, as it can be linked to many positive aspects of sustainability. A key driver will be the increasing demand from the youth of the world for food produced in a sustainable manner with a minimal effect on climate and resources which will drive the demand for LTS. The UN Food Systems Summit (2021) suggested that the world must listen to, and empower, local farmers, indigenous peoples, and the youth of the world. These general suggestions were made with reference to traditional agriculture but the same may also hold true for aquaculture, which is supported by Brugere et al. (2021). One aspect of gaining social licensing is establishing systems for standards and certifications. This has increasingly been the case for global aquaculture value chains, where mainly non-governmental organizations (NGOs) or importing government institutions have been promoting or even imposing regulations. Despite having obvious benefits, Ababouch et al. (2021) explains that because these international standards and regulations are intended to reflect the expectations of consumers that are remote in both geographical and cultural senses, they can be disconnected from the realities that prevail at the local level, neglecting or marginalizing local schemes, practices and knowledge dedicated to governing the use and management of natural aquatic resources. Related to social license for LTA and marine aquaculture in general is the concept of ocean literacy, becoming more widespread. The concept aims to raise the awareness on the conservation, restoration and sustainable use of our ocean and its resources (Ocean Literacy Portal 2022). Promoted by UNESCO, the Ocean Literacy Portal (2022) provides a platform and toolkit to develop public knowledge and build global partnerships to transform ocean knowledge into action.

A growing trend, at least in parts of the Atlantic Region such as Sweden and Denmark, is the public engagement in marine allotments (Göteborgs universitet 2022, Havhøst 2022). Marine allotments enable city people to engage in small scale food production as recreational activities (similar to the allotment gardens concept). Albeit insignificant in scale, it could potentially contribute to (or perhaps be seen as part of) the shift in perception of LTA and its social licensing to operate.

5.2 Future scenarios for LTA 2050

The following defining dimensions, or strategic uncertainties, were selected, based on AV's overall objective to sustainably introduce new LTS products and processes, the components of the DAPSI(W)R(M) and the trend analysis:

- **Change in demand:** Even though a continued increase in demand currently appears the more likely development, a slowdown in demand would have a profound effect on LTA.
- **Operational prioritisation:** Ideally, LTA manages to optimize produced amount of food and other ecosystem services (output) and utilized energy and other resources (input). In reality, there shifting priorities must constantly be made. This justifies the analysis of situations when either operational priority – i.e, maximising output or minimising input – takes precedence over the other.

Note that neither of these strategic uncertainties are mutually exclusive. In reality both increase and slowdown of demand can occur simultaneously (e.g., for different products and/or in different regions), while AV strive to optimise input/output ratios. We therefore explore the extremes to identify similarities and differences between them.

Note that the following four scenarios are forecasts of different future development paths. Even though they are based on identified trends, they are not meant to predict or assume actual future events.

Inspired by the aforementioned trends and the selected strategic uncertainties, four different scenarios describing possible future situations for LTA around 2050 were developed. Figure 12 illustrates the resulting scenarios from combining the two strategic uncertainties; Evergreen[6] (Increase in demand, maximising output), Oceanbird[7] (increase in demand, minimising input), Jetski (decrease in demand, maximising output) and Rowingboat (decrease in demand, minimising input).

[6] The Evergreen A class is a series of 14 container and are currently the largest container ships in the world. (Wikipedia 2022. Evergreen A-class container ship. https://en.wikipedia.org/wiki/Evergreen_A-class_container_ship)

[7] Oceanbird is a large, wind-powered vessel under development by Wallenius Marine. The ship design aims to lower emissions by up to 90 percent. (Wikipedia 2022. Oceanbird. https://en.wikipedia.org/wiki/Oceanbird)

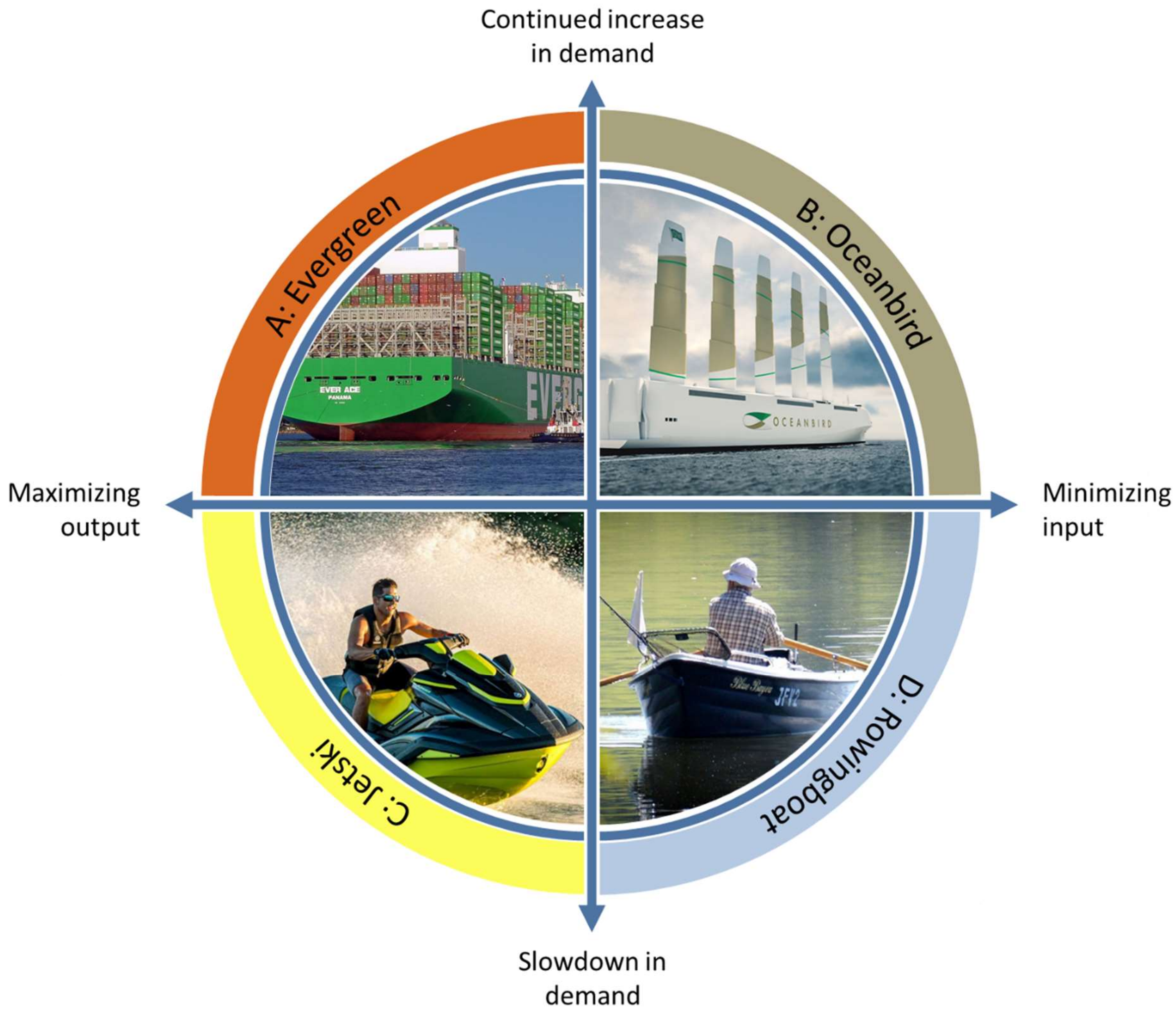


Figure 12. Visualisation of the four forecasting scenarios defined by the strategic uncertainties "change in demand" (continued increase or slowdown) and "operational prioritisation" (maximising output of food and other ecosystem services or minimising input of input and other resources).

5.2.1 A: Evergreen – Continued increase in demand and maximising output

Scenario: Effectivization of farming methods makes big scale farming more profitable, food trends which include LTS aquaculture are popular, partly due to obesity leading to search for alternative sources of healthy food.

Recently, it was stated that the biggest health issue on the planet nowadays is obesity rather than malnutrition. Finding its way even to remote areas of the world the fast-food industry, delivering increasingly cheaper and unhealthy food with larger portions, has created health problems which will not be solved during this generation. Since health problems connected to obesity such as heart diseases, diabetes etc. often require high standard health care, this causes already vulnerable parts of the world's population even more distress. High profile health and food systems experts claim that the food industry has an important role in promoting healthy and cheap diets, and as a result, in the beginning of the 2030s the world confirmed that the need for competitive alternatives to the steadily growing fast food industry was urgent. This development caused the search for alternative food sources to

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become top priority to world leaders. Along with other solutions LTA, being nutritious, lean, and popular, was highlighted as a potential solution.

This led to a major shift in the LTA production. The need for change was immediate and the pressure to deliver large quantities of LTA food was heavy. This triggered significant investments in the sector, and cheap, yet efficient, systems which could meet the production demands was developed with little consideration of impact on the environment or other maritime activities. The expansion occurred primarily in the sea as space on land was limited, and in both near-shore as well as in exposed areas. Consequently, the LTA sector mainly consists of giant farms of oysters, mussels, seaweeds and other LTS. The increase in LTA products has caused a transformation of the perceptions of LTS, which is now considered cheap everyday food and food chains serving mussels and macro algae are now as common as McDonalds previously was.

The established farms have great production capacity, and the focus is on being economically profitable. This has inferred higher automatization and reduced need for labour, yet increased the required education level of staff, thereby increasing unemployment levels in local communities. The effects on the ecosystem, both locally and globally are troubling. The big farms affect the local environment resulting in increased plastic pollution, negative effects on sensitive wildlife and local eutrophication effects (although primarily in nearshore areas). Some farms with extractive species have exceeded the local carrying capacity causing food depletion for native species around the farms. The expansion of off-shore activities has also increased the dispersal of invasive species that now used the farms as a steppingstone, rendering mitigation measures such as open ocean ballast water exchange useless. The negative impact of the activities causes a low social licence, yet the opposition to LTA is overruled by licensing authorities which has a clear directive to enable an expansion of the sector.

Despite these drawbacks, the increased occurrences of LTA have also led to an increase in biodiversity. This is, however, considered as fouling by the sector and intensive research is performed to combat this problem, often with the use of pesticides and other chemicals. The intensive production also of fed species, albeit low trophic, has led to an increased use of formulated feeds, and consequently also in the use of fish meal and fish oil, causing an increase in the effective trophic niche for some farmed species and is causing a complete collapse of the few remaining wild fish populations. The high stocking densities has increased the risks of pathogen and disease outbreaks, and the use of GMOs is spiralling to maintain the high production in less favourable conditions.

5.2.2 B: Oceanbird – Continued increase in demand and minimising input

Scenario: LTS (not only in aquaculture) is considered an environmentally friendly alternative which can decrease the environmental footprint of food production as awareness of its impact on the environment is rising. There is also a societal movement towards a circular economy and an increased demand of ethically and sustainable produced food.

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Since the 2020s, environmental issues have had a high priority globally. The world population has recently hit the 10 billion mark (2050) and having a sustainable and reliable food supply is crucial to minimise the environmental footprint of human activities. The world is now painfully aware of the importance of healthy marine ecosystems as overfishing and pollution caused a complete collapse of marine ecosystems in several areas in the beginning of the 2030s. A source of food and livelihood that had been taken for granted was depleted. Loss of jobs and source of food for local communities set aside it was the tourists who no longer could have their sea food, earlier considered mandatory on a holiday, which made the headlines of the world news. The distress call caused an unforeseen economic stress, and some parts of the world has not fully recovered since. Moreover, the climate change has had a major influence on decision making in the world. This awareness has over the recent decades forced the food production to dramatically lower its green-house gas emissions and its overall impact on the environment. Therefore, the food industry, encouraged by global environmental and governance bodies, decided to shift its orientation towards food production of LTS, primarily marine species, as this represented an already well accepted alternative to meat production. The Atlantic Committee of Sustainable Aquaculture, funded in the mid-2020s, played an important role in this process. Being an international organisation aiming for an innovative and eco-friendly LTA, it pushed for innovative solutions, creating possibilities for even more species to be farmed and a Zero Waste approach towards a circular economy.

The Zero Waste approach has been especially successfully implemented in LTA based on extractive marine species since these can support biogeochemical cycles. Agriculture has long suffered from shortage of phosphorous, often referred to as the phosphorous crisis, which has threatened its production efficiency and has caused a decline in agricultural production over time as well as increasing prices for crops. Phosphorous obtained from processing side streams of extractive marine species has become one of few reliable sources and has helped to sustain the agriculture sector. Moreover, the concept of restorative aquaculture, where the ecosystem services provided by aquaculture are regarded as resources and turned into advantages, is widely acknowledged, and is integrated into socioeconomic systems. For example, the large variation in farmed species has worked as a bank for threatened species and has helped areas where some species has been lost, and biodiversity is increasing steadily, both as a consequence of colonisation of organisms on the culture structures but also through the provisioning of seed and seedlings contributing to recolonisation of native species. Many aquaculture sites are now complementing food production with species preservation, biodiversity enhancement and nutrient recapture, which has increased both the importance and the demand for LTA as well as the social licence of the activities, with reduced conflicts with local communities and authorities as LTA becomes more widely recognised. Consequently, the LTA sector is present all around the world and has reached areas where it was previously underutilised. There is a great diversity both in the number of species that are farmed and in farming methods. Innovation has been promoted over the years which has led to a diverse and resilient LTA sector. Both large- and small-scale farms are common, hence supporting both local and national economies. The sector itself aims *at being as sustainable as possible, with little or no negative impact on the climate or biodiversity. The actors take pride in being a part of the solution to end world hunger and support the societal transition back into sustainable levels of the planetary boundaries. As LTA has emerged as an essential industry for society by being a food supplier of significance, the authorities are more familiar with the sector, hence significant effort is spent on achieving efficient and constructive communication and facilitated permit applications.*

Consequently, the LTA sector is present all around the world and has reached areas where it was previously underutilised. There is a great diversity both in the number of species that are farmed and in farming methods. Innovation has been promoted over the years which has led to a diverse and resilient LTA sector. Both large- and small-scale farms are common, hence supporting both local and national economies. The sector itself aims at being as sustainable as possible, with little or no negative impact on the climate or biodiversity. The actors take pride in being a part of the solution to end world hunger and support the societal transition back into sustainable levels of the planetary boundaries. As LTA has emerged as an essential industry for society by being a food supplier of significance, the authorities are more familiar with the sector, hence significant effort is spent on achieving efficient and constructive communication and facilitated permit applications.

5.2.3 C: Jetski – Slowdown in demand and maximising output

Scenario: "Old habits die hard/Business as usual" – traditional food sources are still most popular, food trends do not include LTA, effectivization of a few farming methods makes big scale farming profitable (with only a few LTS being produced).

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Despite significant political efforts, consumer preferences remain focused on traditional food products. With an increasing proportion of the world population experiencing higher economic status, the consumption of red meat grows even more, causing an increased strain on natural resources and exacerbating climate change. More food is also sourced from agriculture, and the markets are yet to accept LTA as a significant contributor to the food systems. Consequently, the sector is small and with low economic sustainability. In its place, conventional fishing has increased causing the marine ecosystems great stress, and in some areas complete collapse. Trying to spare the marine ecosystems, the agricultural sector has been intensified and now occupy more land. However, a major concern with this strategy is the lack of phosphorous for fertilisers. The yield from crops is steadily decreasing, increasing the price of crop products, and famines are more common than earlier which threatens the political stability in some regions. Inclusion of fish meal and fish oil in the feed of fed LTS is increasing due to the challenges experienced by the agriculture sector, consequently increasing the trophic niche of the produced organisms, and putting an even higher pressure on the dwindling wild fish populations.

To achieve cost efficiency the LTA production has developed into gradually larger facilities in fewer locations around the world and is mainly focused on a few species. Due to the need to reduce costs, shortcuts are taken, resulting in several cases of large-scale farm collapses, and associated *environmental disturbance, including plastic pollution. The limited profitability limits innovation and few alternatives to the prevalent technical solutions exists. This makes adjustment to climate change and declining demand difficult for the LTA sector. The techniques used has not changed much since the 2020s, but an increased automation has made it less labour intensive, hence reducing employment options in rural areas.*

Jointly this reduces the social licence of LTA, leading to a negative spiral with complicated and extended licenses procedures, public opposition, sabotage, and threats against producers, resulting in even lower production. Moreover, the shortages of both forage fish and plant-based materials threatens not only the consistency of the production but also increases production prices, making fed LTA luxury products out of reach for most people. The consumption of extractive species is not recommended as seawater quality is a continuous problem near the farms.

5.2.4 D: Rowingboat – Slowdown in demand and minimising input

Scenario: Earlier complete stop of fishing led to recovered populations of wild species causing a decreased need for LTS aquaculture, and other types of LTS food (insects, larvae, yeast etc.) is now the main source for cheap and nutritious diets.

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The current situation of LTA was greatly affected by the fact that large parts of the fishing areas in the world made a complete stop of fishing in the end of the 2020s. The main reason behind the stop was the risk of ecosystem collapse leading to irreversible consequences to the marine environment and to food supply. Campaigns to achieve this change were driven by the public, based on the drive in recent years to increase ocean literacy. The decision to stop fishing was taken rapidly and the demand in food production food was quickly changed towards other sectors, in particular to other LTS alternatives such as insects, yeast, and fungi, which now serve as the main source for cheap and nutritious food. The production of in-vitro meat and 3D printed meat has exploded and is a sustainable alternative to the classical "Sunday steak" desired by the growing middle class. The complete stop of fishing led to recovered populations of wild species, and a successive increase in fishing has just started.

Because of alternative sustainable food sources, the interest in today's LTA sector is mainly academic but thriving within this field. The production sites are generally relatively small-scale but innovative aiming towards a small impact on the surrounding environment. The fact that LTA can contribute to an enhanced environment by for example lowering the carbon footprint of food production, nutrient uptake and biodiversity enhancement has put it top of mind in public and scientific domains. Small-scale farms of extractive species are used as a method to mitigate eutrophication in specific areas and there is an intense collaboration between restoration practitioners and the aquaculture sector. Innovations at pilot scale are continuously developed to further enhance the ecosystem services provided by, and strengthened by, LTA and to support zero waste objectives and circular economies. In the LTA sector, the intense research focus has caused a growing number of species in cultivation and new methods to decrease the environmental impact by circulating resources within the farms. Small-

scale farms and better management practices, e.g., IMTA, have led to fewer pest outbreaks and less fouling.

Moreover, the LTA sector has followed the overall trend of urbanisation, yet with the added will of people to stay close to nature and to produce their own food in a sustainable way. The increase in ocean literacy has surged a significant increase in urban culture with a LTS focus, and rooftop and basement small scale LTA production is increasing, often combined with salt tolerant plants in aquaponics facilities. This has also resulted in a movement to move the allotment garden concept into coastal areas through the establishment of marine allotments. The allotments enable the city people to engage in small scale food production nearby the cities as recreational activities. The proximity to the cities, however, makes the seafood produced in the marine allotments more vulnerable to pollution, and many participants therefore use the activity as a way of enhancing biodiversity and other ecosystem services provided. LTA is considered the hanging gardens of the sea and are often combined with nature experiences such as snorkelling and kayaking.

5.2.5 Identified risk events

Table 7 and Table 8 summarises threats and opportunities, i.e., risk events, that may arise from 2022 to 2050 based on the different scenarios. Note that the general societal development is assumed to be identical for all scenarios, outside the LTA sector. This includes drivers and pressures from all other sectors, as well as the development of the ongoing ecological crisis of climate change and biodiversity loss. Thus, the scenario 0: General, should be read as the base scenario, to which the four study specific scenarios add or subtract risks.

Table 7. Threats to, and caused by, LTA identified for the four forecasting scenarios

Scenario	Threats to LTA	Threats caused by LTA
0: General	• Increased frequencies and severities of production losses/stops and loss of equipment due to e.g.: ○ Extreme weather events. ○ Climate change induced alterations in habitat suitability of species changes the prerequisites for existing activities. ○ Heatwaves killing off both wild and farmed organisms, and adverse changes in natural species distribution and densities, obstructing production based on wild seed capture. ○ Increased dispersal of invasive species causing pathogen and pest (fouling) outbreaks.	• Increased likelihood of undesirable spread of farmed species, associated pathogens and fouling organisms lead to changed natural species distribution • High probability for negative (synergistic) cumulative effects. LTA pressures are exacerbated by climate change and biodiversity loss effects.
A: Evergreen	• Increased vulnerability of large-scale LTA to e.g.: ○ Diseases (especially monoculture)	• Increased negative impact on local, possibly sensitive, and remote, ecosystems, due to: ○ Local eutrophication (anoxic seabeds)

Scenario	Threats to LTA	Threats caused by LTA
	◦ Increased effects of pollutants on food safety ◦ Disturbances in supply chains for feed, feed quality etc. • Remote and exposed culture sites mean more technical malfunctions, difficult maintenance and longer repair times • Lack of trained personnel • Low social acceptance	◦ Disturbance of natural species distribution, density, and behaviour (exceeding ecological carrying capacity) ◦ Increased dispersal of non-native and invasive species. • Driver for overfishing, due to demand for fish meal and fish oil as feed • More visually noticeable • Increased conflicts with other maritime activities • Decoupling from local communities
B: Oceanbird	• Increased vulnerability of large-scale LTA to e.g.: ◦ Increased effects of pollutants on food safety ◦ Disturbances in supply chains for feed, feed quality etc. ◦ Technical malfunctions • Remote and exposed culture sites mean more technical malfunctions, difficult maintenance and longer repair times • Lack of trained personnel	• More visually noticeable • Decoupling from local communities • Increased competition with other sectors and local communities for space, due to diversified and numerous LTA locations • Increased conflicts with other maritime activities
C: Jetski	• Increased vulnerability of large-scale LTA to e.g.: ◦ Diseases (especially monoculture) ◦ Increased effects of pollutants on food safety ◦ Disturbances in supply chains for feed, feed quality etc. • Low social acceptance • Complicated permitting • Inadequate maintenance and strategic planning due to low profitability	• Poor or insufficient ESG (environmental, social, and corporate governance) performance, due to low profitability: ◦ Increased negative impact on local ecosystems ◦ Increased conflicts with local societies ◦ Decoupling from local communities • Increased conflicts with other maritime activities
D: Rowingboat	• Difficulties in funding both for research and innovation and industry due to low priority activity • Inadequate strategic planning due to low interest	• No major impacts from LTA production due to the small scale

Table 8. Opportunities provided for, and by, LTA identified for the four forecasting scenarios

Scenario	Opportunities for LTA	Opportunities by LTA
0: General	• Rising sea temperatures will increase growth rates (albeit not necessarily survival) and thus possibly production • Favourable conditions for cultivation of new species • New marine regions are exploitable due to climate change effects	• Positive contribution to nutrient uptake and indirectly to increased biodiversity
A: Evergreen	• Technical development fuels expansion into off-shore areas • Licencing procedures are quick and uncomplicated • Good funding opportunities • Well developed markets and attractive products	• Providing sufficient LTS as feed to significantly lower ecological footprint for higher trophic aquaculture (and possibly agriculture) • Reduction of the carbon footprint of food production by replacement of food items with a high carbon footprint
B: Oceanbird	• Technical development fuels expansion into off-shore areas • Licencing procedures are quick and uncomplicated • High social license • Good funding opportunities • Well developed markets and attractive products	• Increasing ecological resilience due to active enhancement of biodiversity • Ecological carrying capacity is respected, resulting in significant ecological and societal benefits • Providing additional ecosystem services, e.g., aqua-/agriculture feed, biological resources for energy, chemicals etc. • Reduction of the carbon footprint of food production by replacement of food items with a high carbon footprint • Increase in recreational values and ocean literacy
C: Jetski	• No specific effects in addition to the general development identified	• No specific effects in addition to the general development identified
D: Rowingboat	• No specific effects in addition to the general development identified	• Local value chains • Tailormade products and ecosystem services, thanks to cultivation of new species and technological innovations. • Increase in recreational values and ocean literacy

As can be seen in the tables above, there are a few cross-scenario threats and opportunities, reflecting the overarching climate change effects and loss of biodiversity together with the outcome of the strategic uncertainties. Climate change induced alterations in habitat suitability of species provide some opportunities in terms of cultivation of new species and access to new regions, but threats are most likely dominating and exacerbated by biodiversity loss. With increased demand, scenarios Evergreen and Oceanbird showcase both largest threats and opportunities, with scenarios Jetski and Rowingboat complementing and nuancing them. The scenarios' main similarities and differences are summarized below, laying the basis for the risk analysis in chapter 6:

- **Evergreen, Oceanbird and Jetski** are dominated by large-scale production and are thus vulnerable to different disturbances (see bullets below). They are all subject to conflicts with other marine activities.
- **Evergreen and Oceanbird** are utilizing remote and more challenging regions, making them vulnerable to technical malfunctions and longer repair times. They are also dependent of trained personnel, perhaps most so for Oceanbird, relying on technical advancements.
- **Evergreen and Oceanbird** benefits from quick and uncomplicated licensing procedures, good funding opportunities and well-developed markets driven by the continued increase in demand. Due to scale of production, LTA in these scenarios contribute to the reduction of carbon footprint of food production.
- **Evergreen and Jetski** are more vulnerable to diseases due to reliance on monoculture and have the lowest social license.
- **Oceanbird and Rowingboat** both contribute to the increase in recreational values and ocean literacy.
- **Oceanbird** is more diversified and has the highest social license.

6 Analysis of aggregated risks from workshops and scenarios

Based on the results from the workshop and the outcomes of the trend and scenario analysis, the major environmental risks to (i.e., effects on uncertainties on) AV's objective that "sustainable LTS aquaculture contributes to fulfilling the needs of the present without compromising the ability of future generations to meet their own needs" (i.e., the desired state, see section 3) were defined as:

a) Deteriorated ecosystems
b) Improved ecosystems
c) Increased production
d) Loss of production
e) Material damage

Risks a, d and e are obviously threats, while b and c are opportunities. These risks are reflected in the strategic uncertainties as being more or less present in the forecasting scenarios (Table 9).

Table 9. Primary links between major environmental risks and scenarios, with "general" referring to ongoing climate change and biodiversity loss, to which the four study specific scenarios for low trophic species aquculture development add or subtract risks.

Major environmental risks	General	Evergreen	Oceanbird	Jetski	Rowingboat
Deteriorated ecosystems		Yes		Yes	
Improved ecosystems			Yes		Yes
Increased production		Yes	Yes		
Loss of production	Yes				
Material damage	Yes				

An expert assessment of the most important environmental risk events was made of the combined results from both the stakeholder workshops and forecasting scenarios. Note that the scope of this study was limited to environmental risks, thus, economic, social, governance and technical risk were omitted from this step of the analysis, even though some examples of such risks were noted during the work (chapters 4 and 5). A few general observations of similarities and differences between the bottom-up and top-down approaches were made:

- Despite differences in geographical and temporal scope, there was good consistency of threats between workshops and scenarios. All current risks identified by the stakeholders are expected to be present in the foreseeable future (scenario analysis), albeit probably with changing likelihoods and/or consequences.
- The stakeholder workshops did not identify any opportunities, in practice equating risk with threat.
- The scenarios outline a number of exploitable opportunities, both to improve ecosystems and increased production.
- In general, threats exerted upon LTA will be exacerbated by ongoing climate change and biodiversity loss, and thus largely independent from likelihoods of the specific scenarios.
- The LTA sector arguably has a greater possibility to influence opportunities than threats, since many threats are largely independent of the LTA development. (This does not contradict the importance of systematic risk management also to mitigate threats.)

Table 10 presents the aggregated major environmental risks, based on the combined results from the stakeholder workshops and the forecasting scenarios.

Table 10. Aggregated major environmental risks to and from LTA, based on the combined results from the stakeholder workshops and the trend and scenario analysis. The risks are color coded to enhance readability. Note that the colors in this table do not correspond with the colors assigned to the forecasting scenarios (chapter 5.2)

Risk	Event	Source	Category[8]	Trend[9]
Deteriorated ecosystems	Pollution from e.g., faeces, antifouling	Operations	MaInThFr	
Deteriorated ecosystems	Release or escape of farmed stock	Operations	MaInThFr	
Deteriorated ecosystems	Intensified global fisheries due to LTA demanding fish meal and fish oil as feed	Operations	MaInThFr	
Deteriorated ecosystems	Entanglement of marine mammals in LTA infrastructure	Surrounding biota	UnInThFr	
Deteriorated ecosystems	Pollution from collapsing/damaged LTA infrastructure	Extreme weather conditions	UnExThFr	↗
Improved ecosystems	Reduced global fisheries due to LTA replacing fish meal and fish oil as feed	Operations	MaInOpFr	
Improved ecosystems	Positive contribution to biodiversity and other ecosystem services, e.g., nutrient uptake	Operations	MaInOpFr	
Improved ecosystems	Positive carbon footprint contribution by replacement of food items with a high carbon footprint	Operations	MaInOpFr	
Increased production	Rising sea temperature and eutrophication	Environmental conditions	UnExOpTo	↗
Increased production	Favourable conditions for cultivation of new species	Environmental conditions	UnExOpTo	↗
Loss of production	Predation or grazing	Surrounding biota	MaExThTo	
Loss of production	Fouling	Operations	MaExThTo	
Loss of production	Mortality due to diseases	Environmental conditions	MaExThTo	↗
Loss of production	Mortality due to seawater quality	Environmental conditions	MaExThTo	↗
Loss of production	Red tide/toxic algal bloom	Surrounding biota	UnExThTo	↗
Loss of production	Unpredictable access to offshore stock	Extreme weather conditions	UnExThTo	↗

[8] Category is any combination of Manageable (Ma)/Unmanageable (Un), Internal (In)/External (Ex), Opportunity (Op)/Threat (Th) and To/From (Fr). The last criterion refers to whether the LTA is exposed to the risk or whether the risk originates from the LTA.
[9] Arrows indicate that the risk magnitude is increasing. Absence of arrow indicates that the trend is inconclusive.

Risk	Event	Source	Category[8]	Trend[9]
Loss of production	Epiphyte outbreak competing for resources	Surrounding biota	UnExThTo	
Material damage	Collapsing/damaged LTA infrastructure	Extreme weather conditions	UnExThTo	➚

All sources are external except for *Operations*. Moreover, *Environmental conditions* and *Surrounding biota* are not strictly separable. In this context, however, *Environmental conditions* refers to the bio-chemo-physical conditions such as temperature, currents, nutrient levels, and pollution, but also to pathogens. *Surrounding biota* on the other hand focus on the wild organisms from phytoplankton to marine mammals. Both these sources are currently being changed by the ongoing ecological crisis of climate change and biodiversity loss, as is *Extreme weather conditions*. In many – but not all – cases, the changing conditions will lead to increasing risks. Thus, design and operations of LTA will be increasingly important to mitigate risk vulnerability as well as cumulative effects from LTA activities and other pressures combined.

7 Synthesis of major findings

The major conclusions from this study, elaborated below, are that:

1. LTA will be increasingly challenging to conduct despite rising demand and new opportunities.
2. Changing conditions present exploitable opportunities both for LTA and society at large.
3. Stakeholders' risk awareness focuses on operations-related threats exerted upon LTA.
4. Scale is an important aspect in risk identification and analysis.
5. There is an apparent need to strengthen the LTA sectors' risk management capacity

The conslusions are closely linked to the first part of the primary objective of WP6 and AV, i.e. to produce knowledge to enable prediction, adaptation and resilience to pressures exerted by, and upon, LTA. That said, further studies are required to pinpoint how these risks relates to the Atlantic Region compared to other parts of the world, as well as elaborating risks related specifically to emerging pollutants. In addition, many of the major risks on and from LTA identified in this study were similar to the risks identified as most significant in aquaculture by FAO (2008), with the exception of the inclusion of positive risks (opportunities) in this study (in agreement with the ISO 31000 standards). Moreover, the ambition of this study to explore environmental risks exerted by, and upon, LTA in the Atlantic Region using a holitic approach has involved the combination of bottom-up and top-down approaches, each covering different aspects of the scope. This methodology proved to be relevant to the scope of the report in view of the narrow focus on the risk concept identified in the stakeholder workshops.

7.1 LTA will be increasingly challenging to conduct despite rising demand and new opportunities

Ongoing climate change, loss of biodiversity and pollution, including eutrophication, will, if left unmitigated, fundamentally change the environmental conditions for world food production (and arguably all biologically dependent activities) on every level and in every environment, making LTA more challenging. These changes are non-linear and continuous, e.g., changing sea temperature, ocean acidification, eutrophication, natural species distribution and density, and instantaneous, e.g., extreme weather events. There are consistently more reports on gradual changes causing sudden and drastic shifts, so-called tipping points (IPCC 2022). How fast and how severely these challenges will manifest is affected by the global community's capacity to transition to a sustainable development, e.g., as expressed by the SDGs.

The LTA sector can respond to these challenges in different ways. Even though the threats seem dominating, they also present opportunities. One overarching trend, supported by statements from FAO, IFAD, UNICEF, WFP and WHO (SOFI 2021), is that it is very likely that the demand for LTS will continue to increase in the foreseeable future. This positive trend for LTA benefits from the youth of the world's demand for sustainability, good animal welfare, and general concern for the environment. Food will likely continue to be the main use of LTA. Still, there will be more exploitable opportunities for LTS as feed, possibly reducing demand for fish meal and fish oil, and biofuel, chemicals, cosmetics, and other ecosystem services, such as nutrient uptake. This will be facilitated by continued technical development, e.g., improved monitoring, control, and automation, and possibly by changing environmental conditions favouring the cultivation of new species.

These interactions between opportunities and threats in a dynamic environment justify a systematic risk management process, which includes continuous monitoring and capacity adaptation on both operational and societal levels. Moreover, the scenario description in this report may enable a discussion about alternative futures and the pros and cons of different pathways, hence supporting the inclusion of LTA in the vision for a low carbon future as suggested by Krause et al. (2022).

7.2 Changing conditions present exploitable opportunities both for LTA and society at large

There is currently a movement to promote the benefits of, in particular, marine LTA. In concurrence, positive risks, or opportunities, were identified in the trend and scenario analysis. Despite the political and academic interest for these opportunities, they are currently underexploited in today's society. As an example, the possibility to alleviate the pressure on dwindling phosphorous reserves by promoting methods and technology development to increase circularity from sea to land with the aim of loop closure should be a priority to sustain the ever-increasing agriculture production. Similarly, blue food should be promoted in parallel to plant-based diets to reduce the overall climate impact of the current food systems. Moreover, the restorative properties of marine LTA may enable biodiversity recovery in contrast to loss if the prospect of nature-based solutions is realised. Consequently, more focus should be directed towards supporting and expanding the positive environmental risks, i.e. the opportunities, of LTA.

7.3 Stakeholders' risk awareness focuses on operations-related threats exerted upon LTA

As could be expected, the stakeholders focused on operations-related threats exerted upon LTA during the data collection workshops, and the ratio between risks exerted upon LTA and by LTA was approximately 20:1. This is squewed in comparison to the exemplified risks to and from aquaculture presented by FAO (2008) where approximately equally many risks from aquaculture as to aquaculture were mentioned. Also, in the workshops, consequences on production were generally assessed to be higher than consequences for the ecosystem. The stakeholders represented the industry, and the risk assessment had a farm-specific context, hence these results were not unexpected. The results are likely reflecting the fact that these risks are the most important from a day-by-day and business perspective in order to operate a safe and profitable LTA business. Moreover, acknowledged, or experienced, risks are much easier to identify compared to more abstract risks, hence exacerbating the over-representation of operational risks in the analysis. This was clearly illustrated by pandemics (together with weather-related phenomena) being the most frequently identified risk source throughout the stakeholder group. This would probably not have been the case in 2019, which could raise the questions of which risks are currently overlooked by the LTA sector? The scenario analysis brought some balance to this perspective by integration of both positive risks (opportunities) as well as of a broader perspective less focused on the operational level.

Arguably more surprising was the large spread in identified risks between the stakeholders. In fact, none of the 20 risks with the highest risk levels were shared between the stakeholders. This could reflect the stakeholders representing LTA of different organism groups, with different production systems and in different geographical regions. It may also partly be a consequence of terminology and previous experience of risk assessment work. The workshop results illustrate the challenge of consistently defining sources, risks, and consequences in the assessment process. While conceptually easy to discern, these aspects are in practice often perceived as overlapping or even interchangeable. The iterative process, which is generally used when assessing risks, would gradually enable this consistency. As a rule of thumb, risks should be expressed in such a way that they can be acted upon. Nevertheless, the data shows that many, if not most, of the assessed risks were unique and context dependent. Consequently, more effort should be devloted to explore the identified risks more in detail with respect to specific geographical sectors, organism groups, production systems, modes and locations and VC steps as discriminated by the AD. This was, however, not within the scope of this study.

Unfamiliarity with risk terminology could also explain the fact that the stakeholders did not identify any opportunities, even though it is widely known in the LTA sector that e.g., demand of LTA-provided ecosystem services is rising and that changes in species distribution enables farming of new species.

Another possible explanation is the so-called "loss aversion" phenomenon, a universal tendency to prefer avoiding losses to acquiring equivalent gains prominent in economics. In this context, loss aversion could justify focusing on mitigating risks rather than exploiting opportunities. The reason for why stakeholder identified – or not – certain risks was outside the scope of the workshops but could be the subject of future studies.

Selection of target stakeholder groups is recognized as a key component of the risk assessment process by FAO (2008). In this case the industry in the LTA sector was the priority stakeholder group, and the results consequently reflect this selection with a farm-specific context. With the inclusion of e.g., competent authorities and a national geographical scope, the results may have been different because of a different context. Integrating additional stakeholder groups perspectives into the analysis would contribute significantly to the holistic perspective, as would the inclusion of risks in additional topics (e.g. socioeconomic perspectives), and these perspectives may consequently be worth exploring further. This would at the same time facilitate communication and explanations of risks and risk management between government and industry stakeholders involved with aquaculture, which, according to Holmen et al. (2018) is required to achieve effective risk analysis.

Similarly it is not possible to draw any conclusions on similarities and differences between organism groups and geographical sectors, since the collected data is either too specific (bottom-up approach) or too general (top-down approach) to support such conclusions. Based on the results presented in this study and the approach applied to establish the AD (Strand et al. 2022), it would be possible, and desirable, to design a quantitative risk identification and analysis exploring these perspectives further.

7.4 Scale is an important aspect in risk identification and analysis

This study also confirms the importance of establishing a proper context. Combining a bottom-up with a top-down perspective helps widen the scope but introduces challenges in comparability of individual risks as well as bridging operational and societal perspectives. A scenario analysis could arguably assist in expanding the scope – and possibly the participants' imagination – by underlining the temporal dimension and dynamic environment.

This illustrates the value of the mixed approach used here, despite the challenges of streamlining and synthesizing the results. Although the day-to-day challenges experienced at industry scale will most often have to be addressed on farm level, knowledge of these risks may support development of enabling governance structures at national level to mitigate likelihood and/or consequences. Similarly, communication of more large-scale risks which may be difficult to manage on local level may nevertheless enable development of long-term company specific strategies to prepare for changing conditions.

Although significant effort is directed at national and larger geographic scales to manage large scale threats in today's society, the identification of direct effects of these risks on every-day activities on farm level is largely lacking or is not fully recognized by the industry. Consequently, the results presented here are of limited practical use if there is no management framework suitable for addressing the most significant risks associated with LTA development. For some of the risks identified it is apparent that such frameworks are in place (e.g. FAO Guidelines for Sustainable Aquaculture, European Green Deal: Strategic guidelines for sustainable and competitive EU aquaculture, Global Principles of Restorative Aquaculture), yet others remain to be developed. This will be addressed in task 6.4 (monitoring) and 6.5 (recommendations) in the forthcoming work of WP6 in AV.

7.5 There is an apparent need to strengthen the LTA sectors' risk management capacity

As noted above, there is a discrepancy between the facts that on one hand there are LTA risks, primarily threats but also opportunities, increasing with potentially drastic effects in a near future, and on the other hand are stakeholders focusing on mitigating threats on a day-by-day or short-term basis. Thus, there is an apparent need to strengthen the LTA sector's risk management capacity to properly and sustainably mitigate threats and exploiting opportunities under changing conditions. This is not least true for small operations (Philips and Subasinghe 2008). It is outside the scope of D6.4 to leave recommendations on how to bridge this gap. This will be elaborated in D6.6, but a few remarks can be made already here:

- It was apparent that the overall knowledge level of risk assessments among the stakeholders varied but was in general low. Much can therefore be achieved by providing training to both the industry actors, and ideally also to governmental representatives, in how to perform risk assessments. Capacity-building in all aspects of environmental risk analysis for aquaculture is needed (Philips and Subasinghe 2008).
- Risk assessment can be facilitated by development of efficient tools. Providing sets with risks to choose from and intervals for common likelihoods and consequences could possibly both speed up the process and make it more comprehensive and at the same time support consistency of terminology. However, a universal tool would have to be very complex to cover the full range of LTA in the Atlantic Region, requiring a built-in adaptive user interface to avoid forcing the user to go through endless catalogues of possible risks. The tool should also preferably be continuously updated to reflect the ongoing changes in conditions. Finally, the value and importance of stretching one's imagination and exploring one's experiences to identify and analyse the risks relevant for the specific context at hand should not be underestimated.
- That said, it should not be ruled out that more specific tools with narrower scope, such as the tool used in the stakeholder workshops, can provide some of the benefits while avoiding most of the disadvantages. The participants found the Excel tool used in this study quite useful, not requiring too much training or guidance. Still, they would have preferred physical workshops over digital, partly because it would have been easier to ask questions about the tool's interface and functionality. Philips and Subasinghe (2008) also recommended that simple tools should be developed for the different hazards concerned with aquaculture.
- There seems to be a particular need for a tool or methodology to assess the dynamic risks of intermediate climate change states, not only for LTA. Traditional risk assessment focuses on one situation, be it current or future. If doing a risk assessment for an expected future situation and comparing it to the current one, the dynamics of the passage of events between those to moments are neglected. Knowing that the climate change (as well as biodiversity loss) is characterized by non-linear processes and tipping points, it could be that intermediate states may arise with conditions constituting risks being exerted by or upon LTA that are not as prominent at any of the end points.
- To summarize, there are obvious benefits of strengthening the LTA sector's/stakeholders' risk management capacity. It must, however, be balanced against the effort and costs.

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Appendix: Summary of the ISO 31000 risk management process

Risk assessment is the "overall process of risk identification, risk analysis and risk evaluation", and constitute the core of the risk management process, as illustrated in Figure 13. Identified risks will be analysed with regard to likelihood and consequence, and they will be categorised according to different criteria. The results will be ranked, and high-ranking risks of different relevant categories will be presented in terms of manageable/unmanageable, internal/external, positive/negative.

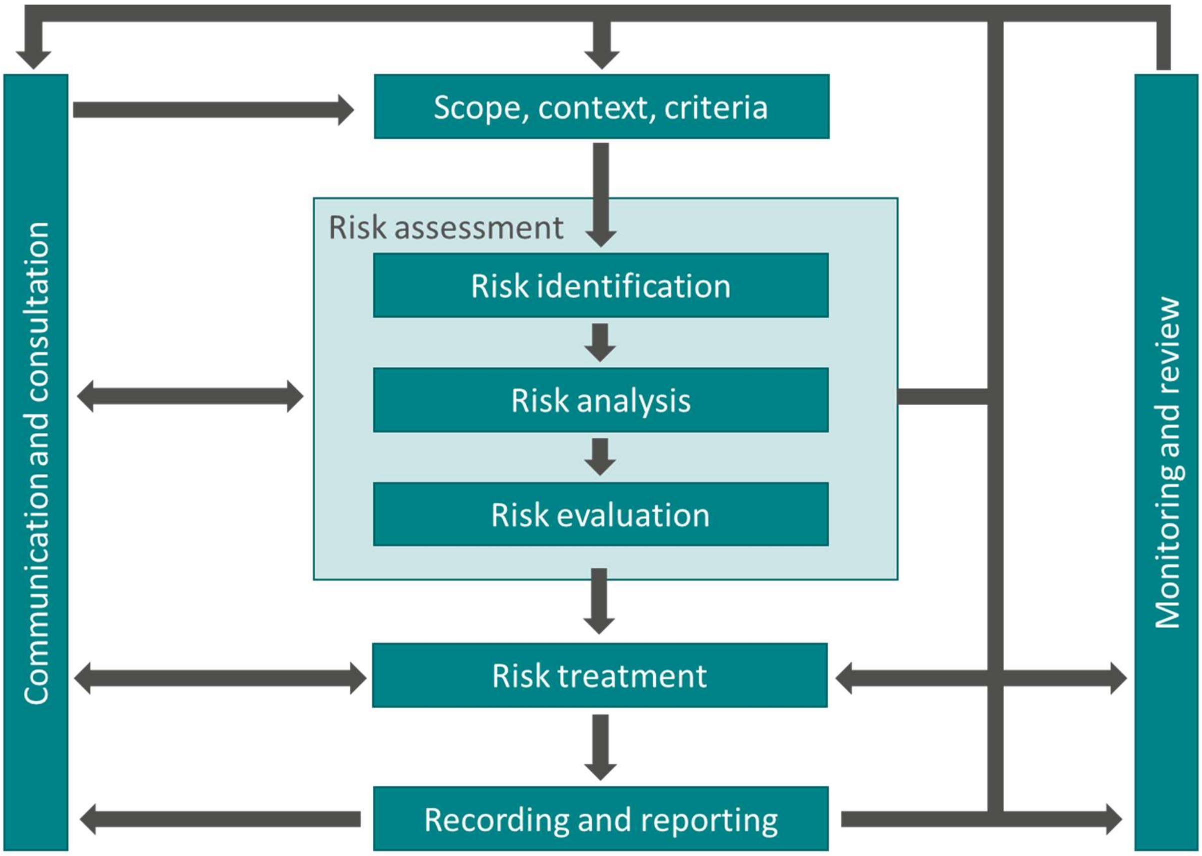

Figure 13. The risk management process. Figure modified from ISO 2021.

According to ISO 31073:2022 (ISO 2022), **risk** is defined as "effect of uncertainty on objectives" and can thus be both negative and positive. Negative risks are referred to as **threats**, meaning "a potential source of danger, harm, or other undesirable outcome. A threat is a negative situation in which loss is likely and over which one has relatively little control." In contrast, **opportunities** are "combination[s] of circumstances expected to be favourable to objectives. An opportunity is a positive situation in which gain is likely and over which one has a fair level of control. Taking or not taking an opportunity are both sources of risk".

In addition, the following terms are used throughout this report in accordance with the ISO 31073:2022 definitions:

- **Risk identification** is the process of finding, recognising, and describing risks. It involves the identification of risk sources, events, their causes, and their potential consequences. It can involve historical data, theoretical analysis, informed and expert opinions, and interested party's needs.
- **Sources** are elements which alone or in combination has the potential to give rise to risks.

- **Events** are occurrences or changes of a particular set of circumstances. An event can both be something that is expected which does not happen, or something that is not expected which does happen.
- **Risk analysis** is the process to comprehend the nature of risk and to determine the level of risk. This provides the basis for risk evaluation and decisions about risk treatment. Risk treatment falls outside the scope of D6.4 but will be included in D6.6.
- **Level, or magnitude, of a risk** or combination of risks is expressed in terms of the combination of consequences and their likelihood.
- **Consequence** is the outcome of an event affecting objectives. As stated above, a consequence can have positive (opportunity) or negative (threat), and direct or indirect, effects on objectives and can be expressed qualitatively or quantitatively. Any consequence can escalate through cascading and cumulative effects.
- **Likelihood** is the chance of something happening. Note that in risk management terminology, the word "likelihood" is used to refer to the chance of something happening, whether defined, measured or determined objectively or subjectively, qualitatively, or quantitatively, and is described using general terms or mathematically (such as a probability or a frequency).