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# European mussel farming

## A practical manual






***Cover photos captions:***

Harvested blue mussel (*Mytilus edulis*) seed ready for on-bottom cultivation (top left – © PO Mosselcultuur, Kingdom of the Netherlands); Commercial size blue mussel dredging (top centre – © PO Mosselcultuur, Kingdom of the Netherlands); Star-wheel oriented overboard for mussel headline lifting (top right – © L. Gennari); Mussels seed ropes spiralled on wooden poles (*bouchots*) in Maine Père et Fils, France (bottom left – © L. Gennari); Mussel harvesting – lifting mussels ropes from a workboat (bottom centre – © Consello Regulador Mexillón de Galicia, Spain); Declumped Mediterranean mussel (*Mytilus galloprovincialis*) grading on-board using a horizontal vibrating grader (bottom right – © Coop. La Fenice, Cervia, Italy).

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# Preparation of this document

This manual focuses on the practical techniques and cultivation strategies needed to successfully farm the blue mussel (*Mytilus edulis*) and the Mediterranean mussel (*Mytilus galloprovincialis*). Mussels are a highly nutritious food source and, requiring no manmade feed or fertilizer to grow, are an example of sustainable, low carbon aquaculture production that can make an important contribution towards the goal of feeding an expanding global population in a responsible and environmentally friendly fashion.

The manual provides a detailed and exhaustive list of the components necessary to construct each of the cultivation systems that are described within its pages. The manual guides the user as to how to create and execute a management and monitoring plan, ensuring that all the necessary cultivation procedures are implemented in accordance with the production schedule.

This guide is not intended to be a scientific paper and if the reader requires a more in depth understanding of the organism itself, there are many other publications available that can provide this, some of which are listed in the further reading section at the end of the manual.

This publication includes many technical illustrations, instructional drawings, tables and photographs to ensure that all the subjects examined within its pages are elucidated. Where necessary, a clear visual representation of each topic, technique or piece of equipment is included to assist the reader in understanding what is being explained in the text. Supplementary details of the subject matter can be found in the appendixes at the end of the manual that elaborate further on some of the more technical matters described in selected chapters.

Hatchery seed production is not included in this manual but a list of reference publications that describe this process are listed in the further reading and the in the FAO publications section at the end of the manual if the reader wishes to research this phase of the production cycle further.

Clear definitions of all the technical terms used in the text are included in the glossary and should be consulted when clarification is required.

This document is one of three technical guides on shellfish culture produced as part of a project funded and implemented by the Food and Agriculture Organization of the United Nations (TCP/DRK/3803) in enhancing coastal livelihoods and food security in the Democratic People’s Republic of Korea.

# Abstract

The purpose of this manual is to give the reader a foundation of practical knowledge regarding all aspects of blue mussel and Mediterranean mussel cultivation. It is targeted at new entrants to the market wishing to establish a farm, and existing operators who wish to develop their farms and explore new cultivation techniques. The methodologies described can be applied to both low-tech, low budget, small-scale farming operations and to high-tech, big budget, industrial-scale aquaculture production enterprises. This guide focuses on the functional expertise and technical equipment required to construct and manage an operational farm in the diverse environmental and physical locations in which they can be situated, from the initial stages of finding and selecting a suitable site, to the conclusion of the first production cycle and harvesting the crop.

The manual contains a brief introduction which describes the relevance of the species with regards to global aquaculture production figures and how it can form an important part of future food production strategies. Chapter 2 describes the anatomy and biology of blue mussel and Mediterranean mussel and gives an indication as to the environmental conditions in which the species thrives as well as the pathologies and predators that can result in poor health leading to potential mortalities. Quality assessment parameters are also discussed with regards to desirable attributes when selling final product into the market and what is necessary to be aware of when considering consumer safety.

Chapter 3 deals with all aspects of undertaking a survey of potential mussel farming sites and what data should be collected and examined in order to both assess a site's suitability, but also which areas are best suited to different cultivation techniques. After this, Chapter 4 introduces the main farming techniques, some of which will be described in detail in the following chapters, and gives details of some of the most common cultivation equipment necessary to undertake these operations.

Chapters 5 and 6, constitute the main body of the manual and provide an in-depth look into the two major cultivation techniques that this guide concentrates on: "On-bottom cultivation in the intertidal or subtidal zone" and "Offshore long-line cultivation". These represent two of the most common farming techniques adopted in a multitude of locations and, although other farming techniques are utilised, the two described are responsible for the majority of blue mussel and Mediterranean mussel production around the globe. In each chapter, all aspects of the farming process are explored including site selection, farm design, farming practices and main constraints.

Finally, the manual ends with some suggestions for further reading, a glossary and appendices which includes information on food safety in regard to bivalve molluscs.

**Keywords:** Blue mussel, Mediterranean mussel, seed recruitment, on-bottom cultivation, suspended cultivation, offshore cultivation, long-line, *bouchots*, *bateas*.

# Contents

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# Tables

# Acknowledgements

Practical manuals, such as this one, benefit greatly from hands-on experience. As authors, we have been fortunate to work with some of the leading experts in the mussel cultivation industry, whose knowledge and experience have informed both our own farming activities and the development of this guide. We are grateful to all of them, as well as to the many dedicated and innovative mussel farmers worldwide who continue to advance the industry.

We would also like to thank the following individuals and organisations for providing descriptive and informative photographs, which are invaluable in illustrating the technical aspects discussed in this manual: Ben Wright, Wright Brothers Ltd (United Kingdom of Great Britain and Northern Ireland); James Wilson, Deepdock Mussels (United Kingdom of Great Britain and Northern Ireland); Juan Martin Baigorria, Emilia-Romagna Mussel Growers' Consortium (Italy); Paul Lethaby (Bermuda Institute of Ocean Sciences); Mulot SAS (France); Dutch Mussel Producers' Organisation (Kingdom of the Netherlands); Galician Mussel Regulatory Council (Spain); MARE Società Cooperativa arl (Italy); and Cooperativa "La Fenice" (Italy).

The authors also wish to express their thanks to Esther Garrido Gammaro (FAO) and Rachel Hartnell (CEFAS) for their valuable contribution in preparing Appendix I on food safety considerations for the production and processing of bivalve molluscs. Additional thanks are due to Pierre Maudoux (FAO) for providing the mussel production statistics presented in Appendix II, extracted from the FAO Fisheries and Aquaculture Statistics database.

We are grateful to Massimiliano Lipperi for his artistic talent in producing the illustrations of various aspects of mussel cultivation, based on the authors' work. José Luis Castilla Civit carried out the graphic design and layout of the manual. Finally, we extend our appreciation to the staff of the FAO Country Office in the Democratic People's Republic of Korea for their support and assistance with project coordination.

# Abbreviations

| | |
|---|---|
| **AAC** | Aquaculture Advisory Council (European Union) |
| **ASFIS** | Aquatic Sciences and Fisheries Information System (FAO) |
| **CAC** | Codex Alimentarius Commission |
| **CE** | Common Era |
| **COP** | Code of Practice |
| **EU** | European Union |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **GAA** | Growing Area Assessment |
| **GAM** | Growing Area Monitoring |
| **GARP** | Growing Area Risk Profile |
| **GPS** | Global Positioning System |
| **HAB** | harmful algal bloom |
| **HDPE** | high density polyethylene |
| **hp** | horsepower |
| **ISO** | International Organization for Standardization |
| **NEI** | not elsewhere included |
| **PVC** | polyvinyl chloride |
| **USD** | United States Dollars |
| **UV** | ultraviolet |
| **VHF** | very high frequency |
| **WHO** | World Health Organization of the United Nations |

| | |
|---|---|
| **≥** | equal or greater than |
| **≤** | equal or less than |
| **>** | greater than |
| **<** | less than |
| **µm** | micron |
| **mm** | millimetre |
| **cm** | centimetre |
| **m** | metre |
| **km** | kilometre |
| **nm** | nautical mile |
| **$m^2$** | square metre |
| **ha** | hectare |
| **µg** | microgram |
| **mg** | milligram |
| **g** | gram |
| **kg** | kilogram |
| **t** | tonne |
| **L** | litre |
| **$m^3$** | cubic metre |
| **s** | second |
| **h** | hour |
| **y** | year |
| **atm** | atmosphere |
| **Kw** | kilowatt |
| **%** | percent |
| **‰** | parts per thousand |
| **°** | degree (angle) |
| **°C** | degree Celsius |
| **°F** | degree Fahrenheit |

# 1. Introduction

Archaeological evidence indicates that humans have harvested and consumed mussels since prehistoric times. Along parts of the South American coastline, researchers have identified extensive shell middens, large accumulations of discarded shells, that suggest mussels were an important and regularly exploited food source for early coastal communities. Mussel shells recovered from various prehistoric excavation sites also appear to have been repurposed as simple utensils, such as early forms of spoons or scoops.

The deliberate cultivation of mussels in Europe has a long history, with the earliest documented practices appearing in France during the 13th century CE. These early systems were relatively simple, relying on wooden stakes and natural spat settlement. Although traditional methods persisted for centuries, modern mussel aquaculture, characterised by structured farming systems, controlled seed collection, and large-scale production, began to develop more substantially in the 1950s. Since then, aquaculture has expanded globally and now encompasses numerous mussel species farmed in diverse marine environments.

In the Northern Hemisphere, the blue mussel (*Mytilus edulis*) and the Mediterranean mussel (*Mytilus galloprovincialis*) remain the most widely cultured species. Farming techniques vary considerably depending on regional traditions, oceanographic conditions and available technology. Common methods include on-bottom culture, raft and long-line systems, pole (bouchot) culture, and suspended rope techniques, each optimized for local ecological and economic conditions.

In 2023, global mussel production, expressed in live-weight equivalent, accounted for approximately 1.7 percent of total world aquaculture output, 4.5 percent of global marine aquaculture production, and 8.5 percent of worldwide mollusc aquaculture production (Table 1.1). The estimated farm-gate value of mussel production in 2023 was USD 2.215 billion. Appendix II lists the recent production volumes and economic values for blue and Mediterranean mussels, along with the leading producing countries.

TABLE 1.1
**Global FAO aquaculture statistics (2023)**

| | Production | |
|---|---|---|
| Fisheries & aquaculture | 188.9 m tonnes | Seaweeds excluded |
| Aquaculture | 98.5 m tonnes | Seaweeds excluded |
| Marine aquaculture | 36.7 m tonnes | Seaweeds excluded |
| Shellfish aquaculture | 19.3 m tonnes | Inland & marine aquaculture |
| Mussel aquaculture | 1 641 997 tonnes | All mussel's species included |

***Notes***:
In FAO Fisheries and Aquaculture data, mussel species are registered under the following names:
- ASFIS species name "Sea mussel NEI", ASFIS species scientific name "Mytilidae".
- ASFIS species name "Blue mussel", ASFIS species scientific name "*Mytilus edulis*".
- ASFIS species name "Mediterranean mussel", ASFIS species scientific name "*Mytilus galloprovincialis*".
- ASFIS species name "Chilean mussel", ASFIS species scientific name "*Mytilus chilensis*".
- ASFIS species name "Korean mussel", ASFIS species scientific name "*Mytilus unguiculatus*".
- ASFIS species name "Australian mussel", ASFIS species scientific name "*Mytilus planulatus*".

NEI: Not Elsewhere Included.
ASFIS: Aquatic Sciences and Fisheries Information System.

Mussels are bivalve molluscs and, as filter feeders that obtain their nutrition from naturally occurring phytoplankton and zooplankton in seawater, they require no artificial feed inputs. This characteristic, combined with their low carbon footprint and minimal space requirements, makes mussels particularly well suited to sustainable aquaculture and long-term food security. Alongside macroalgae and other shellfish species, mussels can play a key functional role in integrated multi-trophic aquaculture (IMTA) systems, where their natural filtration capacity contributes to nutrient recycling, water-quality improvement, and the creation of more ecologically balanced farming environments.

Increasingly, other marine industries, such as finfish aquaculture and offshore renewable energy projects, are exploring the integration of mussel farming into their operations. In these combined-use systems, mussels can help mitigate environmental impacts by removing excess organic matter and dissolved nutrients, thereby contributing to ecosystem services while adding an additional revenue stream.

Mussel aquaculture also holds significant social and economic value for coastal regions, particularly those experiencing declining employment opportunities or reductions in wild fisheries. Because mussel farming requires relatively low capital investment and can be operated at multiple scales, it provides an accessible option for coastal communities seeking to stabilise household income, strengthen local food systems, and reduce vulnerability to fluctuations in wild fish stocks.

When planning a mussel farming operation, it is important to assess how introducing cultured stock may interact with the existing wild populations of the same species. Although this manual does not specifically address stock enhancement or restoration activities, such measures can sometimes support sustainable seed collection near the farm site. In many regions, naturally occurring mussel beds provide an abundant, self-renewing supply of seed. In other locations where natural recruitment is limited, farmers may need to source seed from areas with more reliable settlement. The use of hatchery-produced seed is currently restricted to a small number of specific cases because the cost of production under controlled conditions is typically higher than the value of seed collected from the wild. As most mussel farms operate with low input costs and rely directly on local natural recruitment, hatchery seed is seldom economically viable. Nevertheless, mussel farming can benefit from adaptive management of wild stocks and, reciprocally, can contribute positively to local restoration efforts.

Before establishing a cultivation site, a thorough preliminary assessment is required. Mussel farming must not be viewed as an isolated activity; rather, it interacts dynamically with the surrounding ecosystem, fisheries, and coastal uses. Environmental parameters such as water quality, current velocity, food availability, substrate type, and potential conflicts with other marine activities must be evaluated in advance.

Mussel production systems can generally be divided into three main categories: on-bottom, off-bottom, and suspended culture. Each category includes numerous variations that have evolved to suit local ecological conditions, traditional practices, and available infrastructure. The aim of this manual is not to describe every possible method, but to present the most widely adopted intensive production techniques and to offer guidance on selecting the most appropriate approach for the environmental and logistical characteristics of a given site. Many of these techniques can be adapted to cultivate other mussel species, and likewise, methods used for alternative species may be transferable to *M. edulis* (blue mussel) and *M. galloprovincialis* (Mediterranean mussel).

Other commercially relevant mussel species in the global market include the Chilean mussel (*Mytilus chilensis*), River Plata mussel (*Mytilus platensis*), Australian or Tasmanian blue mussel (*Mytilus planulatus*), Far Eastern or Korean mussel (*Mytilus unguiculatus*), New Zealand green-lipped mussel (*Perna canaliculus*), Asian green mussel (*Perna viridis*), Korean thick-shell mussel (*Mytilus coruscus*), and the brown mussel (*Perna perna*). Farmers should always consider the specific biological and ecological requirements of their native or cultivated species.

Prospective mussel farmers must consult local regulatory authorities responsible for aquaculture management to ensure full compliance with permitting processes, environmental regulations, biosecurity measures, and any national or regional guidelines governing the establishment and operation of aquaculture facilities.

Finally, the economic context varies significantly between regions. Because factors such as labour costs, construction materials, fuel prices, site accessibility, and seed availability differ widely from country to country, it is not feasible for this manual to provide universal profitability estimates. For this reason, farmers should conduct a detailed, location-specific economic assessment to determine the feasibility and long-term sustainability of their proposed mussel farming operation.

# 2. Mussel biology



This chapter will provide an overview of the major aspects relating to the biology of blue mussel and the Mediterranean mussel. It will also provide guidance on how to assess the quality of the end product and which important aspects of consumer safety should be considered when producing this seafood product for public consumption.

## 2.1 DESCRIPTION OF THE SPECIES

The genus *Mytilus* includes seven species of mussels and some of them can be difficult to recognize without conducting a molecular analysis. For instance, *Mytilus edulis* and *Mytilus galloprovincialis* can easily be confused and are also able to crossbreed with each other.

### 2.1.1 Anatomy

*Mytilus edulis* and *Mytilus galloprovincialis* are marine bivalve molluscs. Bivalve refers to the two-hinged shells that enclose the main body of the organism and provide it with protection from predation and environmental factors. The ability to seal its shells together allows the mussel to settle and populate intertidal as well as subtidal areas. It can maintain a habitable environment within the confine of its own shells whilst out of the water and survive until the tide returns to cover it once more.

*Mytilus edulis* and *M. galloprovincialis* are equivalve (both valves have the same size and shape) and inequilateral (beak is not situated medially). They have a roughly triangular outline with the anterior end being more pointed and the posterior end gently rounded. They are proportionally longer from anterior to posterior than they measure from the ventral to dorsal edges (Figure 2.1 and Figure 2.2). In the blue mussel, the hinge has three small teeth on each valve. In the Mediterranean mussel, the hinge has two small teeth on the right valve and a single tooth on the left valve. The ligament is external, generally smaller in the Mediterranean mussel than in the blue mussel.

For both species, the shell shape and colour can be slightly affected by the environmental condition in which they grow. The shell colour can range from blue to purple with some animals being brown and demonstrating radial stripes emanating from the umbo. Concentric growth lines are visible on the exterior of the shell with greater spacing between the lines indicating periods of faster growth. The internal margin of the shell is perfectly smooth.

The texture of the interior of the shell is smooth. Internal coloration varies from a whitish colour at umbo level to a dark colour of the posterior part. The nacreous aragonite layer provides the organism with a comfortable environment in which to live.

The rest of the shell is made almost entirely of calcium carbonate ($CaCO_3$) apart from a very thin outer layer that is un-calcified and known as the periostracum.

The mussel has two adductor muscles, one posterior and one anterior, that are used to close the valves when the organism is out of the water. The scar of the anterior muscle is small and near the umbo, while the scar of the posterior muscles is bigger and in the shape of a comma. The scar of the anterior muscle is normally smaller in the Mediterranean mussel.

The variability in shape and coloration can make it difficult to differentiate between *M. edulis* and *M. galloprovincialis*. Compared to Mediterranean mussels, blue mussels are usually more tapered (see photos). Even if it is not fully assessed, they are considered

FIGURE 2.1
**European mussel inner and outer shell features**

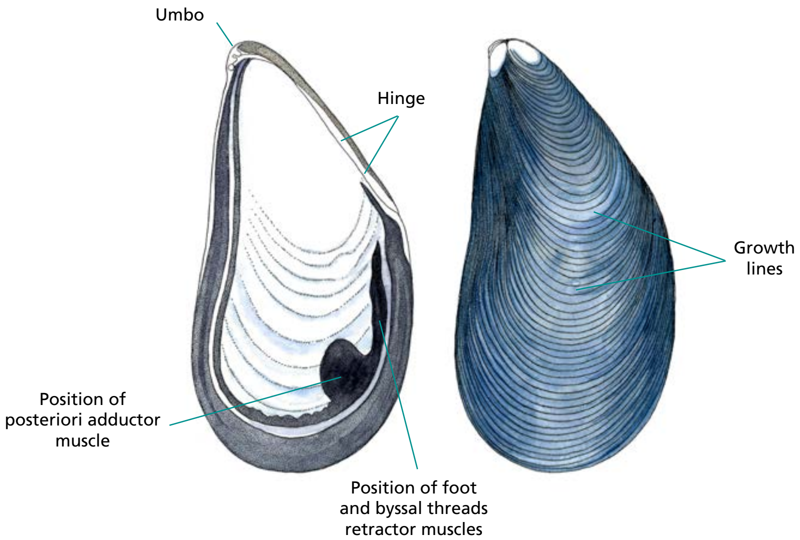



FIGURE 2.2
**Outer shell appearance of the two European mussel species**
(a) *Mytilus galloprovincialis* from the Adriatic Sea; and (b) *Mytilus edulis* from the North Sea Channel

two distinct species. From an evolutionary point of view, the Mediterranean mussel probably genetically evolved from the blue mussel having adapted to the environment of the Mediterranean Sea. Hybrids of the two species have been reported.

Aquaculture activities can have an impact on the distribution of the species and their genetic diversity. For *M. edulis* and *M. galloprovincialis*, this aspect was addressed in the European Union (EU) "Genimpact" project which recommended that a survey be conducted on the distribution of the two mussel species and their hybrids in European waters. In the meantime, studies carried out on a local scale have shown considerable mixing of the two species with a significant presence of hybrids in some areas. Given the ongoing climate change, the hypothesis that adaptive traits, such as resistance to high temperatures, may be reduced or lost as a result of hybridisation processes should be investigated.

Mussels are sessile bivalves. They attach themselves to suitable substrate by producing proteinaceous (collagen) threads from their byssal gland. The collection of these filaments is generically referred to as "byssus". Each thread is composed of three sections: a corrugated proximal section close to the mussel body, a longer, smooth distal section connecting the proximal region to the ending plaque, and the adhesive plaque itself, which anchors the mussel to the substrates. Recent studies were conducted to assess the impact of increased sea temperatures on the mussels' ability to attach themselves to the substrate by exposing Mediterranean mussels to 28 °C for more than 10 days: they showed a decrease in the number and strength of the byssal threads, unchanged lengths and an increase in distal plate malformations.

The internal organs and their arrangement within the shell are illustrated in Figure 2.3 and Figure 2.4. It is possible to reveal the sex of the mussel by the colour of the flesh. Males have flesh that is a pale cream colour, whereas females exhibit a vibrant orange pigmentation.

FIGURE 2.3
**Illustration of the internal anatomy of European mussels**

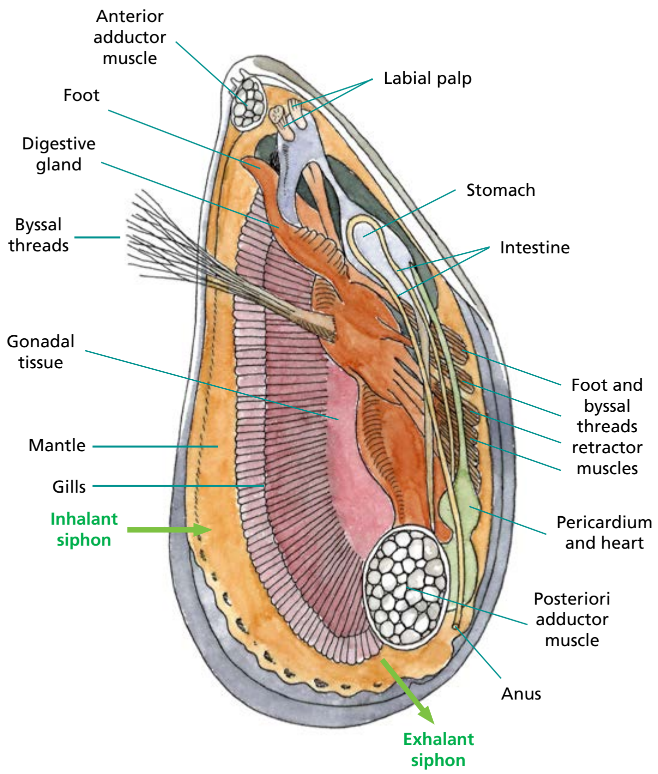


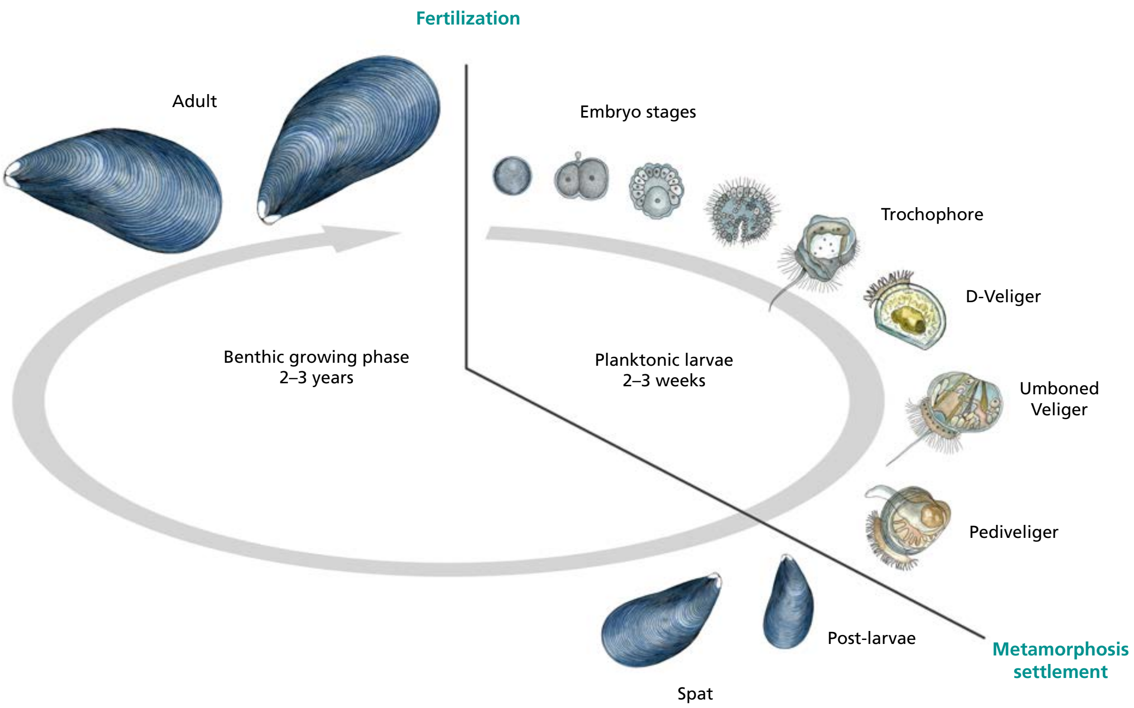
FIGURE 2.4
**Internal appearance of a fresh European mussel showing the soft body tissues**

© L. Gennari

### 2.1.2 Life cycle

Mussels go through several stages of development during their life cycle and these can be categorised as follows: fertilisation, free swimming larval stages, settlement and metamorphosis into spat, maturation into juveniles and then growth into fully developed adults (Figure 2.5).

FIGURE 2.5
**Illustration of the life cycle of the European mussel species**



### *Reproduction*

Mussels are a dioecious species, meaning that they have two distinct sexes, male and female. However, occasionally hermaphrodite specimens have been reported. For both species and in most regions, mussels generally reach sexual maturity after one year. In the Adriatic Sea, the Mediterranean mussel reaches maturity 6–8 months after settlement. In some studies, made on adult populations, sex ratios of 54 percent females and 46 percent males have been found.

Gametogenesis, the development and maturation of the reproductive organs (gonads), occurs in different periods for the blue and the Mediterranean mussels. The maturation period also varies when moving from north to south along the Atlantic coast and from west to east in the Mediterranean Sea. Consequently, the commercial harvesting season coincides with the maturation period, which varies among European countries depending on the origin of the mussels.

In blue mussels along the North Atlantic coast, gametogenesis begins when water temperatures drop to between 10–12 °C and continues throughout the winter months. Gametogenesis occurs within a wide range of salinities, even in environments where permanent low salinity (<10 ‰) or high salinity (>35 ‰) persists. The primary spawning event of the year usually occurs in late spring, the exact timing of which is highly dependent on an increase in water temperature. A secondary spawning can occur during the late summer but is contingent on suitable environmental conditions and food availability.

In the central Adriatic Sea, Mediterranean mussels undergo gametogenesis later and spawning occurs during autumn and winter for a longer period. The main spawning event occurs in October and smaller spawning events can be observed until March. Spat collection is usually done from February to April. Timing is different when moving to the north of the Adriatic Sea and the Tyrrhenian Sea. Probably due to ongoing climate change, as a result of rising mean sea temperatures with increasingly frequent variations, episodes of gamete emission have recently been observed all year round, although the two main peaks in the autumn-winter period remain.

In all cases and for both species, males release sperm and females release eggs into the water column where fertilization takes place when a single sperm combines with a single egg. This produces what is known as a zygote, which is initially a single celled fertilized egg, and contains the necessary genetic building blocks to enable the development of the mussel. The process by which mussels release sperm and eggs into the water for external fertilization is called broadcast spawning. The emission of sperm and eggs is usually triggered by sudden changes in temperature and/or salinity and also influenced by food availability.

Fecundity is high and a single female may produce between 5–10 million eggs during each spawning. In blue mussels, fecundity varies depending on the size with bigger females (50–100 mm in length) releasing between 6–9 million 70–75 µm eggs in a single spawning. Female may release the entire load of eggs in just 15 minutes. In Mediterranean mussels, a female can release up to 10 million eggs of 50–55 µm in size.

The next stages in mussel development are the trochophore, the D-shaped veliger (first veliger stage), and ultimately the pediveliger, which represents the final larval stage before settlement (Figure 2.5). In these phases, the larvae swim freely in the water column using microscopic hairlike structures on their exterior called "cilia" and are widely dispersed by currents and tidal movements. Mussel larvae remain planktonic for a period that varies from 2 to 12 weeks, depending on the species, environmental conditions and the availability of suitable settlement substrates. Specifically, some studies report a planktonic period of 2–6 weeks for *M. edulis* and 3–12 weeks for *M. galloprovincialis*. During this period, the larvae grow from 70 µm to around 250–280 µm.

### *Settlement*

After the planktonic period, they are ready to move on to the next phase, which entails finding a suitable surface on which to initially settle or attach themselves. While Mediterranean mussels prefer hard substrates to settle on, blue mussels colonise both hard and smooth sandy substrates and are therefore more adapted for on-bottom cultivation.

By this point of their development, they have gained the ability to produce byssal threads that are strong secreted filaments they use to attach themselves to their chosen location. Due to the high variability of the maturation period, spawning and larval phase duration, it is difficult to predict when settlement will occur. Following settlement, metamorphosis occurs and the larvae transform themselves into spat. Spat are essentially miniature mussels and this is the first time that they will take on the physical form of their much larger adult counterparts. During their larval stage, they can absorb oxygen from the water through their cell membranes. As spat, they develop gills for the first time and they can now use these, in combination with the exchange of gases through blood vessels in their mantle, to breath and trap phytoplankton. They are still highly mobile during this period and will quite often move from their original settlement surface (often seaweed and other marine plants) to a more solid substrate to continue their development from spat to a young adult mussel. They achieve this movement by the use of a foot and deploying their byssal threads. Suitable surfaces on which they will settle long-term are rocks, other shellfish including dead shells (cultch), solid structures in the marine environment and ropes such as those deployed by mussel farmers to collect spat.

### *Feeding*

Mussels are filter feeders that obtain nutrients primarily by extracting phytoplankton and, to a lesser extent, small zooplankton and suspended organic matter from seawater. Due to the microscopic nature of their food source, mussels must filter vast quantities of water to obtain sufficient nutrition to sustain their survival, growth and reproduction. An adult mussel is capable of filtering up to 100 L/day, depending on prevailing environmental conditions. Through this filtration process, they also extract oxygen from the water, which is essential for their survival.

Picoplankton smaller than 10–20 µm cannot be trapped and are therefore below the suitable size range for feeding. During filtration, mussels also accumulate some inorganic suspended solids present in the water. These are immediately eliminated as "pseudo-faeces," as they cannot be assimilated. When large volumes of suspended solids are present in the water, mussels may exhibit a reduced growth rate. This occurs because the molluscs expend energy filtering these particles without gaining any nutritional benefit from the process.

### *Growth*

Once juvenile mussels have found a suitable substrate on which to attach themselves, they become relatively sedentary. Although they remain capable of limited movement using their foot and byssal threads, the distances covered are minimal. Like many other shellfish species, mussels are characterized by nonhomogeneous growth rates among individuals within the same population or batch.

Under farming conditions, periodic grading is necessary to ensure that slower-growing mussels are not outcompeted for food by faster-growing individuals. If grading is not performed, the competitive advantage of larger mussels will lead to reduced growth and lower survival rates among smaller specimens.

Growth rates are primarily influenced by temperature and nutrient availability in the water, and they vary depending on site location and seasonal fluctuations in key environmental parameters. From year to year, even during the same period, significant variation in product size may occur.

In the wild, mussels can live up to 20 years. Mediterranean mussels can reach lengths exceeding 15 cm, while blue mussels, which are generally smaller, rarely exceed 10 cm. Under farming conditions, mussels are typically harvested at a market size ranging from approximately 5–10 cm, depending on the country and local consumption habits. Along European coasts, the time from fertilisation to reaching market size varies between 12 and 36 months.

### *Life cycle depending on geographic location*

As mentioned above, the production cycle of European mussels varies depending on the species and is influenced by the prevailing environmental conditions of their habitat. For the purposes of this manual, Chapter 5 (On-bottom cultivation) refers specifically to the cultivation of the blue mussel under the typical climatic conditions of the North Atlantic coast, where this technique is commonly practiced.

The life cycle and growth data are summarized below (Figure 2.6). Mussel spat measuring 0.5–1.5 cm in length can grow to about 5 cm within 12 months under favourable conditions. Within 36 months of spat introduction, all mussels under 8 cm in length are expected to reach market size and be ready for sale.

Mussels have a spawning period that extends over approximately six months, characterized by progressive and asynchronous spawning among individuals. The peak spawning activity occurs over a 2-month period, typically between April and May. Larval settlement takes place roughly one month after spawning begins, meaning that settlement starts before spawning has completely ended. As a result, the different stages of the reproductive cycle partially overlap.

After spawning, mussels enter a physiological "gonadal resting period". Maturation resumes about two months after the end of the peak spawning phase. The marketable period begins roughly one month after gametogenesis (the formation of reproductive cells) starts and ends when spawning recommences. Sales are generally suspended during the spawning period, when mussels become "milky", and for the following two to three months, during which meat content remains low due to the resting phase.

FIGURE 2.6
**Blue mussel life cycle timing in the North Atlantic region**

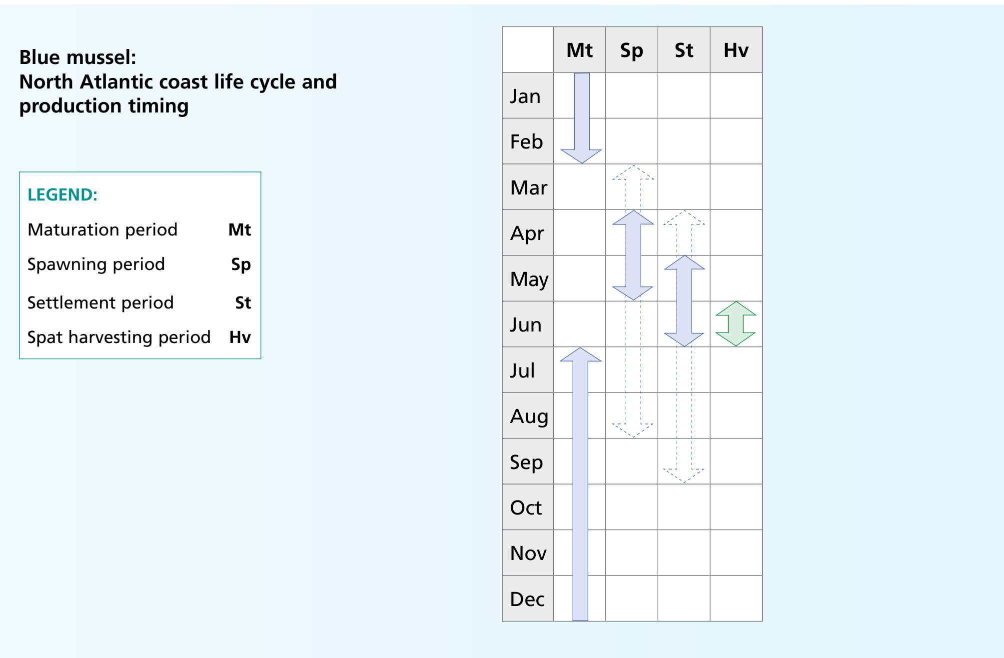


FIGURE 2.6 (CONTINUED)

| Culture phases | Period |
|---|---|
| Maturation/gametogenesis | July to February |
| Spawning | March to August<br>peak in April-May |
| Settlement | April to September<br>peak from May to June |
| Wild spat harvesting | June |
| Best sales period | August to February |
| Market size: 4.5–8 cm in shell length | |

For the purposes of this manual, Chapter 6 (Suspended long-line cultivation) focuses on the cultivation of Mediterranean mussels under the prevailing climatic conditions of the central Adriatic Sea, where this method is commonly practiced.

The life cycle and growth data are summarized below (Figure 2.7). Starting from spat measuring 0.5–1.5 cm in length, faster-growing mussels can reach approximately 5 cm within about eight months. All mussels under 10 cm in length are expected to reach market size and be sold within 24 months of spat collection and socking.

The general sequence and overlap of the maturation, spawning, settlement, and marketable periods are broadly similar to those described previously, although the timing differs considerably. Mussels spawn over a 6-month period (progressive and asynchronous spawning), with a 2-month peak from November to December. The market period begins approximately one and a half months after the onset of gametogenesis and ends when spawning begins. Sales are suspended during the spawning period (when mussels are "milky") and for the following two to three months, when meat content remains low due to the gonadal resting phase.

FIGURE 2.7
**Mediterranean mussel life cycle timing in the central Adriatic Sea**

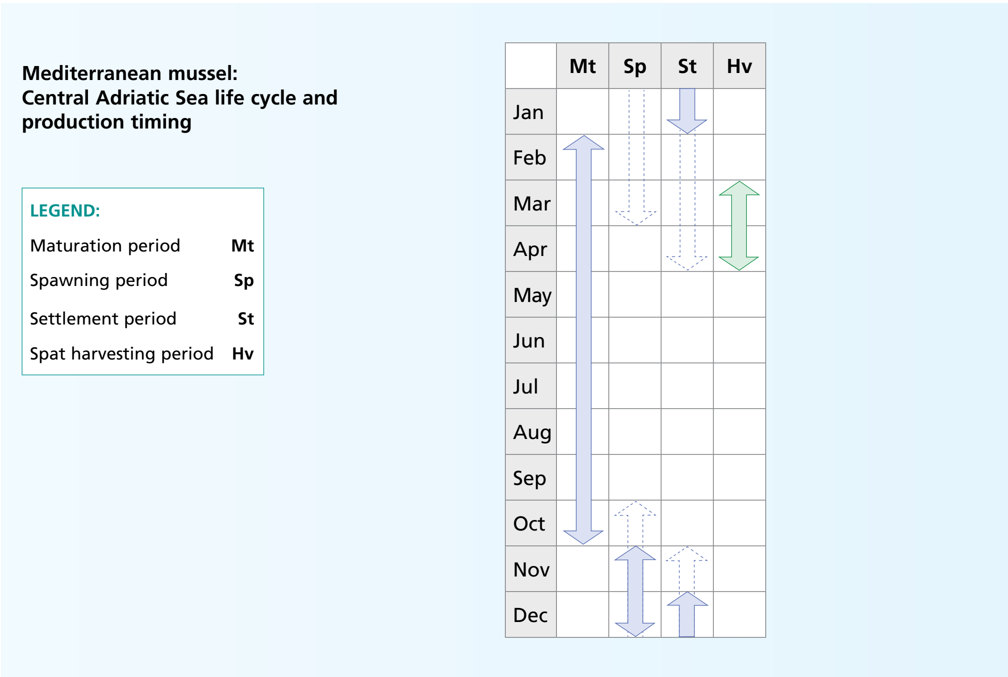


FIGURE 2.7 (CONTINUED)

| Culture phases | Period |
|---|---|
| Maturation/gametogenesis | February to October |
| Spawning | October to March<br>peak in November-December |
| Settlement | November to April<br>peak from December to January |
| Wild spat harvesting | (0.5–1.5 cm in length) from March to April |
| Best sales period | mid-March to September |
| Market size: 5–7 cm in length for mussels that settled the previous year (representing 80–90% of the harvest), and 8–10 cm in length for mussels that settled two years earlier (accounting for 10–20% of the harvest). | |

### 2.1.3 Optimal environmental conditions

The blue and the Mediterranean mussels are highly adaptable organisms being both eurythermal (able to tolerate a wide range of temperatures) and euryhaline (able to tolerate a wide range of salinity). The parameters listed in Table 2.1 are discussed in greater detail in Section 3.1, along with all other factors to be considered when selecting a site for mussel farming.

The blue mussel is widely distributed across temperate and equatorial regions of the Northern Hemisphere and along the Australian coast in the Southern Hemisphere. It has also been reported in the Mediterranean Sea.

The Mediterranean mussel is broadly distributed throughout the Mediterranean Sea, the Black Sea, and along the western Atlantic coast from the English Channel to Morocco. The species has also been introduced for aquaculture in several other countries, including Mexico, United States of America, Japan and Republic of Korea.

TABLE 2.1
**Optimal water parameters for the two commercial European mussel species**

| Predators | Range |
|---|---|
| Water temperature | *M. edulis*: Range 2–26 °C [(1)] & optimum 5–20 °C<br>*M. galloprovincialis*: Range 4–28 °C [(1)] & optimum 8–24 °C |
| Air temperature (intertidal areas) | -5–35 °C |
| Salinity | 4–38 ‰ [(2)]<br>Optimum between 18–36 ‰<br>*M. edulis*: Minimum 4 ‰<br>*M. galloprovincialis*: Minimum 10 ‰ |
| pH | 7–9 |
| Dissolved oxygen | >2 mg $O_2$/L |
| Chlorophyll-α concentration | Optimum 2 µg/L<br>Minimum 0.5 µg/L |

***Notes***:
[(1)] Lower (0 °C) or higher temperature (28–30 °C) values can be tolerated for short periods.
[(2)] Lower (2 ‰) or higher salinity (40 ‰) values can be tolerated for short periods.

TABLE 2.2
**Main production countries – Global FAO aquaculture statistics (2023)**

| Country | ASFIS [(1)] species name | Production (t/%) | | Value/year (USD 1 000/%) | |
|---|---|---|---|---|---|
| China | Sea mussels NEI [(2)] | 777 065 | 47.32 | 432 825 | 19.54 |
| Chile | Chilean mussel | 388 992 | 23.69 | 1 128 077 | 50.94 |
| Spain | Sea mussels NEI | 155 752 | 9.49 | 135 777 | 6.13 |
| France | Blue & Mediterranean mussels | 54 556 | 3.32 | 146 963 | 6.64 |
| Republic of Korea | Korean mussel | 54 322 | 3.31 | 22 507 | 1.02 |
| Italy | Mediterranean mussel | 53 596 | 3.26 | 101 775 | 4.60 |
| Netherland (Kingdom of the) | Blue mussel | 32 501 | 1.98 | 60 093 | 2.71 |
| Canada | Sea mussels NEI | 21 989 | 1.34 | 33 409 | 1.51 |
| Germany | Blue mussel | 18 029 | 1.10 | 32 165 | 1.45 |
| Greece | Mediterranean mussel | 18 008 | 1.10 | 12 864 | 0.58 |
| Ireland | Blue mussel | 14 684 | 0.89 | 13 972 | 0.63 |
| United Kingdom of Great Britain and Northern Ireland | Sea mussels NEI | 14 091 | 0.86 | 17 822 | 0.80 |
| Türkiye | Mediterranean mussel | 8 738 | 0.53 | 13 134 | 0.59 |
| Denmark | Blue mussel | 6 211 | 0.38 | 4 778 | 0.22 |
| United States of America | Blue mussel | 4 387 | 0.27 | 22 593 | 1.02 |
| Russian Federation | Sea mussels NEI | 4 116 | 0.25 | 6 174 | 0.28 |
| Portugal | Sea mussels NEI | 3 274 | 0.20 | 3 096 | 0.14 |
| South Africa | Mediterranean mussel | 2 547 | 0.16 | 1 332 | 0.06 |
| Australia | Australian mussel | 2 341 | 0.14 | 13 378 | 0.60 |
| Norway | Blue mussel | 2 199 | 0.13 | 3 471 | 0.16 |
| Sweden | Blue mussel | 1 684 | 0.10 | 2 698 | 0.12 |
| Bulgaria | Mediterranean mussel | 1 096 | 0.07 | 1 788 | 0.08 |
| Croatia | Mediterranean mussel | 925 | 0.06 | 2 086 | 0.09 |
| Montenegro | Mediterranean mussel | 244 | 0.01 | 765 | 0.03 |
| Slovenia | Mediterranean mussel | 188 | 0.01 | 272 | 0.01 |
| Albania | Mediterranean mussel | 186 | 0.01 | 209 | 0.01 |
| Senegal | Blue mussel | 78 | 0.00 | 259 | 0.01 |
| Jersey | Blue mussel | 52 | 0.00 | 97 | 0.00 |
| Algeria | Mediterranean mussel | 50 | 0.00 | 166 | 0.01 |
| Morocco | Blue mussel | 48 | 0.00 | 71 | 0.00 |
| Bosnia and Herzegovina | Mediterranean mussel | 40 | 0.00 | 80 | 0.00 |
| Argentina | Blue mussel | 5 | 0.00 | 16 | 0.00 |
| Mexico | Sea mussels NEI | 1 | 0.00 | 3 | 0.00 |
| | | **1 641 997** | **100** | **2 214 715** | **100** |

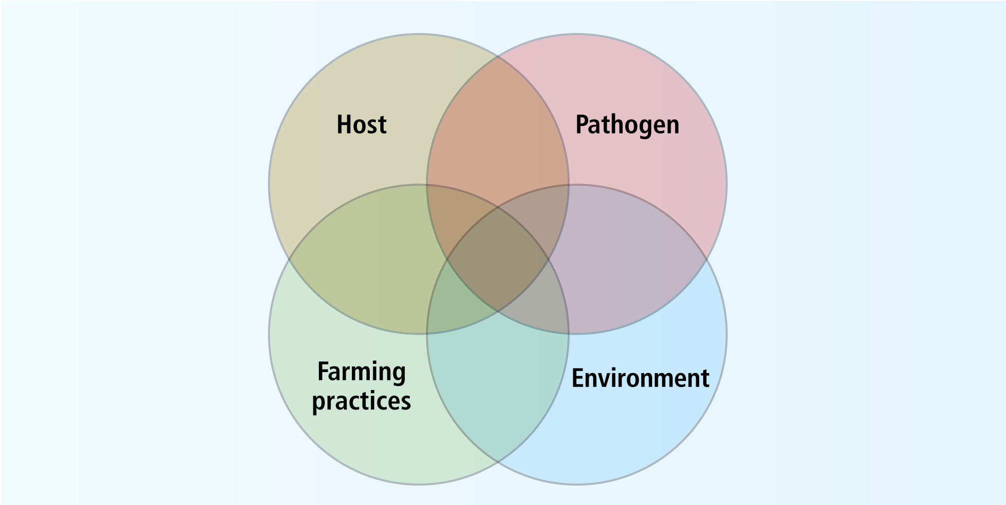
***Notes:***
1) ASFIS: Aquatic Sciences and Fisheries Information System.
2) NEI: Not Elsewhere Included.

In FAO Fisheries and Aquaculture data, mussel species are registered under the following names:
- ASFIS species name "Sea mussel NEI", ASFIS species family name "*Mytilidae*".
- ASFIS species name "Blue mussel", ASFIS species scientific name "*Mytilus edulis*".
- ASFIS species name "Mediterranean mussel", ASFIS species scientific name "*Mytilus galloprovincialis*".
- ASFIS species name "Chilean mussel", ASFIS species scientific name "*Mytilus chilensis*".
- ASFIS species name "Korean mussel", ASFIS species scientific name "*Mytilus unguiculatus*".
- ASFIS species name "Australian mussel", ASFIS species scientific name "*Mytilus planulatus*".

### 2.1.4 Pathogens, parasites, predators and competitors

A variety of factors can lead to mortality and ill health in mussels. Figure 2.8 below summarises the factors to take into account when mortalities occur: a multifactorial approach should always be adopted, with particular attention to environmental conditions and farming practices which represent the majority of outbreak causes.

FIGURE 2.8
**Host, pathogens, practices and environment relationship with regards to ill health in mussels**




In the above-mentioned multifactorial approach, the farming practices represent the main factor on which the farmer can really act to prevent disease outbreaks or to mitigate their impact. In most cases, when mortality events occur, it must be noted that changes in farming practices can significantly reduce losses. The other factors are out of the control of the farmer, who can only accumulate as much information as possible on all potential risks while doing the site selection process, and to collaborate with the sanitary authorities to set and apply the outlined strategies to control the effects of pathogens and minimise the risks.

Ongoing climate change is expected to increasingly affect the frequency and severity of episodes of reduced growth or elevated mortality in mussel populations. These impacts may result from environmental changes such as a decline in available phytoplankton, or alterations in the quality and size composition of phytoplankton communities, leading to periodic food shortages. They may also stem from environmental conditions that are suboptimal for mussels, such as periods of elevated summer temperatures approaching the species' maximum tolerance threshold. Additionally, climate change may create more favourable conditions for the proliferation of pathogens or parasites.

In many cases, these effects may occur simultaneously, with cumulative impacts arising from two or more of the aforementioned factors. Under such circumstances, the systematic collection and analysis of available data - including environmental parameters, the presence of pathogens and pests, and mortality rates - becomes critically important. Equally essential are the increasingly sophisticated methods used to analyse risk factors, which play a key role in identifying and developing effective mitigation strategies.

### *Pathogens and parasites*

Pathogens can cause harm or impede the mussel's normal bodily functions. In severe cases this can cause mortality events, not just in the individual, but also on a mass scale and can lead to significant losses in the overall population.

Measures to mitigate mortalities are limited:

- Farming is conducted in an open environment so treatments that are based upon adding therapeutics into the water are not feasible;
- Bivalves feed on naturally occurring phytoplankton and therefore treatments based upon the addition of therapeutics to manmade feed, such as is the practice in other areas of marine livestock production, is not feasible.

Treatments can only be made in hatchery or nursery facilities where water flow is controlled and the volumes are relatively small.

When possible, the harvesting of deceased animals and their disposal should be done according to the local sanitary protocols. In many cases, limiting transfers of stocks to avoid the spread of the pathogens is advisable or can also be enforced.

Table 2.3 reports the most common pathogens farmers are likely to encounter. For more information, experts and scientific publications can be consulted.

For the reader's convenience, pathogens and parasites are classified into four categories based on their size: viruses (0.05–1 µm), which are visible only under an electron microscope; bacteria (1–10 µm) and protozoans (10–100 µm), both of which can be observed with an optical microscope; and metazoans (>100 µm), which are visible to the naked eye.

TABLE 2.3
**Main pathogens and parasites of European mussels**

| Pathogens & parasites | Susceptible species and aetiology |
|---|---|
| **Viral diseases** | |
| Picornavirus-like virus | *M. edulis, M galloprovincialis* and *Perna canaliculus*<br>Uncertain aetiology |
| **Microsporidian parasites** | |
| *Steinhausia mytilovum* | Mussels and other bivalve species<br>Uncertain aetiology |
| **Bacterial diseases** | |
| *Vibrio* spp. | Mussels and other bivalve<br>(high variability depending on *Vibrio* species/strains and hosts)<br>Observed in cases of mussel mortalities - Uncertain aetiology |
| *Francisella halioticida* | In some abalone and pectinid species: established aetiology<br>Observed in *M. edulis* and *M. galloprovincialis* in cases of mortalities |
| *Nocardia crassostreae* | Observed in cupped oyster in cases of mortalities<br>Observed in *M. galloprovincialis* without mortalities |
| Rickettsia-like | Observed in some mussel species without mortalities |
| **Diseases caused by protozoans** | |
| *Minchinia mytili* | *M. edulis* and *M. galloprovincialis*<br>Unknown aetiology |
| *Marteilia pararefringens*<br>*M. refringens* type M) | Some oyster species, *M. edulis* and *M. galloprovincialis*<br>Observed in mussel without mortalities |
| *Bonamia ostreae* | Some oyster species, *M. edulis* and *M. galloprovincialis*<br>Observed in mussel without mortalities |
| *Perkinsus olseni* | In some abalone and clam species: established aetiology<br>Observed in *M. galloprovincialis* without mortalities |
| **Diseases caused by metazoans organisms** | |
| *Mytilicola intestinalis*<br>*Mytilicola* sp. | Mussel and other bivalve species<br>Infestation with continuous and low mortalities |
| Trematodes | Mussel and other bivalve species<br>Possible low mortalities |

### Picornavirus-like viruses

Often observed, sometimes in association with mortality episodes, but it cannot be conclusively identified as the aetiological agent.

### *Steinhausia mytilovum*

Known as "mussel egg disease", this microsporidian infects both the cytoplasm and nucleus of mussel ova and can trigger a moderate to severe diffuse haemocyte infiltration response.

*Vibrio* species/strains

*Vibrio aestuarianus*, *Vibrio splendidus*, and other *Vibrio* species are frequently detected in mussels and other bivalves, both during mortality events and in the absence of mortality or clinical symptoms. In many cases, it is difficult to determine whether they act as primary pathogens. These species are often considered ubiquitous in marine environments. In some instances, they may play a partial role in multifactorial mortality outbreaks. Notably, virulent strains of *V. splendidus* have been associated with mussel mortality outbreaks on the Atlantic coast of France (2014–2015), although a definitive aetiology has not been established. Additionally, because shellfish are filter feeders capable of accumulating bacteria from surrounding water, interpreting high bacterial concentrations can be challenging.

Even if they are not pathogenic to their bivalve hosts, three *Vibrio* species - *Vibrio parahaemolyticus*, *Vibrio vulnificus* and *Vibrio cholerae* - are noteworthy due to their presence in seafood and their responsibility for the majority of human illnesses caused by *Vibrio* strains (see Section 2.3).

*Rickettsia-like organisms* (RLOs)

Rickettsia-like organisms, are found in mussels and other bivalves, forming inclusions within the host's cells. These organisms seem well-tolerated by the host and do not cause mortalities.

*Marteilia refringens, Bonamia ostreae* **and** *Perkinsus olseni*

- *Marteilia pararefringens* (or *Marteilia refringens* type M) is a parasite belonging to the Cercozoa phylum and the Paramyxida order. It causes heavy mortalities in flat oyster populations. When detected in mussels or cupped oysters, it does not cause mortality. It is an endemic species in Europe.
- Bonamia ostreae is a parasite belonging to the Cercozoa phylum and the Haplosporidia order. It causes heavy mortalities in *Ostrea edulis*, *Ostrea chilensis* and other oyster species. Even when present in mussels and cupped oysters, it does not cause mortality.
- *Perkinsus olseni* is a parasite belonging to the Mizozoa phylum and the Perkinsida order.

*Bonamia ostreae*, *Marteilia refringens* and *Perkinsus olseni* are reported by OIE (World Organisation for Animal Health, formerly the Office International des Epizooties) in the list of species to be notified. These parasites are not known to cause mortality in mussels, but their mandatory reporting can lead to restrictions on available farming sites and the transfer of products.

*Mytilicola intestinalis* (copepod)

This common disease, known as "red worm disease" due to the red coloration of the adult worms, involves 0.2 mm free eggs in the plankton that are filtered and retained in the mussels' intestines. There, the parasite multiplies to the point of hindering intestinal transit, potentially leading to mortality. The parasite is generally considered commensal and may slow growth when its abundance does not reach lethal levels.

### Trematodes

Several species of trematodes are reported as parasites of bivalve molluscs, particularly mussels. These parasites typically require two or more hosts to complete their life cycle. Symptoms vary depending on both the parasite and host species and can range from weakness affecting valve closure and attachment to the substrate, to reduced growth and reproductive performance.

The main trematode species reported in mussels include *Proctoeces* sp. and *Prosorhynchus* sp. These are usually observed in mussels either as sporocysts (the parasite's multiplication phase) or as metacercariae (the parasite's stalling phase). Mortalities in mussels have been reported in association with these parasites.

- *Proctoeces maculatus* (also known as *Cercaria tenuans*) is a parasite of mussels and cockles. Sporocysts have been reported in both *M. edulis* and *M. galloprovincialis*. Residing in the vascular system, *P. maculatus* can cause parasitic castration by reducing the nutrients available for gonadal growth and maturation.
- *Prosorhynchus* sp. is a parasite of the blue mussel. Living in the gonadal tubules, it can induce parasitic castration and impaired growth.
- *Cercaria margaritae* (also known as *Gymnophallus margaritae*) causes "orange disease" in *Perna perna*, where sporocysts and subsequently cercariae invade the mantle, resulting in epithelial proliferation.
- *Labratrema minimum* is primarily reported as a parasite of the cockle *Cerastoderma edule*.

### *Predators*

Mussels have many natural predators, with humans being only one of them (Table 2.4). Their nutrient-rich flesh makes them an attractive food source for a variety of animals and depending on the density of predatory species in the same environment, these predators can consume a significant portion of native or farmed mussels.

The impact of predation varies according to the cultivation system used:

- Bottom-cultivated mussels are directly exposed to benthic predators.
- Off-bottom cultivation exposes mussels to both benthic and pelagic predators.
- Intertidal mussels are vulnerable to predation by birds, particularly around low tide.
- Mussels grown on long-lines or other suspended systems may experience predation from fish and turtles.

In all of these cases, protective nets can be installed. However, the associated costs of materials and additional handling often make such measures economically unviable compared to farming in areas with lower predation pressure.

TABLE 2.4
**Main predators of European mussels**

| Predators | Examples |
|---|---|
| Birds | Atlantic coast during low tide: sea gulls, crows, eider ducks, etc. |
| Cetacean | Mediterranean Sea in long-line farms: dolphins. |
| Fish | Mediterranean Sea in long-line farms: sea breams (Sparidae).<br>Atlantic coast on bottom: flounders (Pleuronectiformes) and sandpipers (Scolopacidae). |
| Reptile | Mediterranean Sea in long-line farms: turtles (*Caretta caretta*). |
| Starfish | Atlantic coast: common starfish (*Asterias rubens*). |
| Urchins | Atlantic coast: *Strongylocentrotus droebachiensis*. |
| Gastropods | Atlantic coast: Atlantic dog welk (*Nucella lapillus*) (Figure 2.9). |
| Flatworms | Mediterranean Sea: *Stylochus mediterraneus* (Figure 2.10). |
| Crabs | Atlantic coast: European spider crab or spiny spider crab (*Maia squinado*), shore crab or green crab (*Carcinus maenas*) and brown crab (*Cancer pagurus*).<br>Mediterranean Sea: *Pinnotheres pisum* and *Carcinus aestuarii*.<br>Mediterranean Sea (Alien species): blue carbs (*Calinectes sapidus* and *Portunus segnis*). |
| Sponges | Atlantic coast: red boring sponge (*Cliona celata*). |

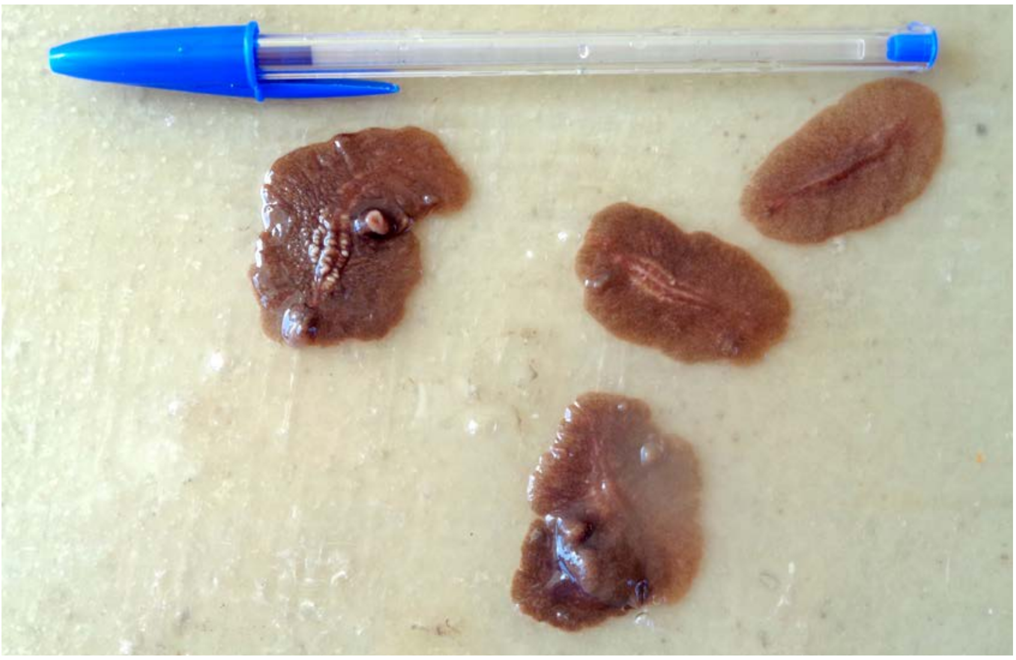
*Stylochus mediterraneus*
This polyclad flatworm is a common predator of both oysters and mussels in the Adriatic Sea, active from late summer to autumn, regardless of the cultivation method. It is an opportunistic species that primarily targets weaker mussels but can also feed on healthy individuals. The worm enters mussels while they are open for filtering and consumes the adductor muscle along with other internal organs. Its impact can be partially mitigated through grading operations or by reducing mussel density.

FIGURE 2.9
**Eggs of Atlantic dog welk (*Nucella lapillus*) on bouchots**

© L. Gennari

Boring sponge *(Cliona calata)*
*Cliona calata*, often called "boring sponge", is known to burrow into the shells of molluscs, including mussels, causing damage and potentially impacting their survival. This sponge bores round holes up to 5 mm in diameter in limestone or the shells of molluscs, especially oysters. They primarily damage the shell rather than consuming the soft tissues, leading to potential shell weakening and increased vulnerability to predation. It is found worldwide.

FIGURE 2.10
**The flatworm *Stylochus* spp.**



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## *Competitors*

Mussels compete directly for food with numerous other filter feeders that can settle in and around cultivation devices. Like mussels, most of these organisms have planktonic larvae that are carried into the cultivation structures by water currents, where they grow and compete with the cultivated mussels.

The mussels' main competitors are:

- Other filter-feeding organisms that settle directly on mussel shells, forming the so-called "fouling" layer (see Section 2.2.4).

- Gastropods such as slipper limpets (*Crepidula fornicata*), medium-sized sea snails of the Calyptraeidae family, which colonize extensive areas where mussel farming occurs. They consume phytoplankton from the seawater and must be removed when preparing the seabed for on-bottom cultivation.
- The invasive gastropod, Asian rapa whelk or veined rapa whelk (*Rapana venosa*), introduced in many regions worldwide from the Pacific.
- The invasive bivalve *Arcuatula senhousia*, also introduced in many parts of the world from the Pacific region.

*Other constraints*

In many regions, shellfish farming is also affected by organisms or phenomena that temporarily alter environmental conditions, such as algal blooms, the formation of large mucilage patches, or the proliferation of certain species. These events primarily reduce dissolved oxygen in the water or impede water circulation around mussels, often resulting in mass mortality of cultured species. The frequency and intensity of such occurrences are increasing due to ongoing climate change.

Algal blooms are primarily caused by microalgae and can become severe enough to be classified as harmful algal blooms (HABs).

Pelagic mucilage, which forms within the water column, appears as amorphous aggregates of organic material produced by plankton and inorganic particles. These aggregates can embed bacteria, phytoplankton cells, zooplankton, detrital material and other components.

Finally, environmental imbalances and the introduction of alien species can lead to abnormal proliferation of a single species, disrupting the entire ecosystem. A notable example is the proliferation of the tunicate *Clavelina oblonga* in the Adriatic Sea.

## 2.2 QUALITY ASSESSMENT PARAMETERS

This section provides guidance on the factors that must be considered when evaluating the quality of mussels at the end of the cultivation process. Meat content, shelf-life, and shell characteristics are interdependent and cannot be considered separately. Consequently, final product quality depends on farming practices applied from the seed stage onward, with particular attention to stocking densities and handling frequency. Quality also depends on how the final sorting is conducted after harvesting and before packaging. During the final inspection prior to sale, it is essential to remove open or dead mussels, broken or empty shells, undersized individuals, and any other unwanted material. Failure to do so will result in a batch appearing of poor quality and can lead to unpleasant odours as damaged shellfish die and decay.

The criteria outlined below are considered by buyers and influence the market price of the product. The relative importance of each factor may vary depending on the intended end use of the mussels. For example, if the product is sold as shucked meat, the shell's aesthetic appearance is irrelevant to the consumer. However, if the product is sold whole, shell quality and appearance become more significant, as they are visible to the end user and contribute to the presentation of the final dish.

In Europe, many products are placed on the market following certification processes that take multiple quality criteria into account, enhancing their value and consumer appeal. Two French examples illustrate the importance of quality factors in the value chain:

Certification of "*Moules de bouchot*" requires compliance with three quality criteria, in addition to geographical origin and the farming method used:

- Individual mussels must display an average depth of 12 mm, with less than 5 percent undersized individuals;
- A minimum flesh-to-shell ratio based on the Lawrence & Scott index of ≥100 (see Section 2.2.2);
- Less than 5 percent of mussels exhibiting abnormal colour after boiling.

Certification of "*Moules de bouchot de la Baie du Mont-Saint-Michel*" also requires compliance with three quality criteria, in addition to geographical origin and farming method:

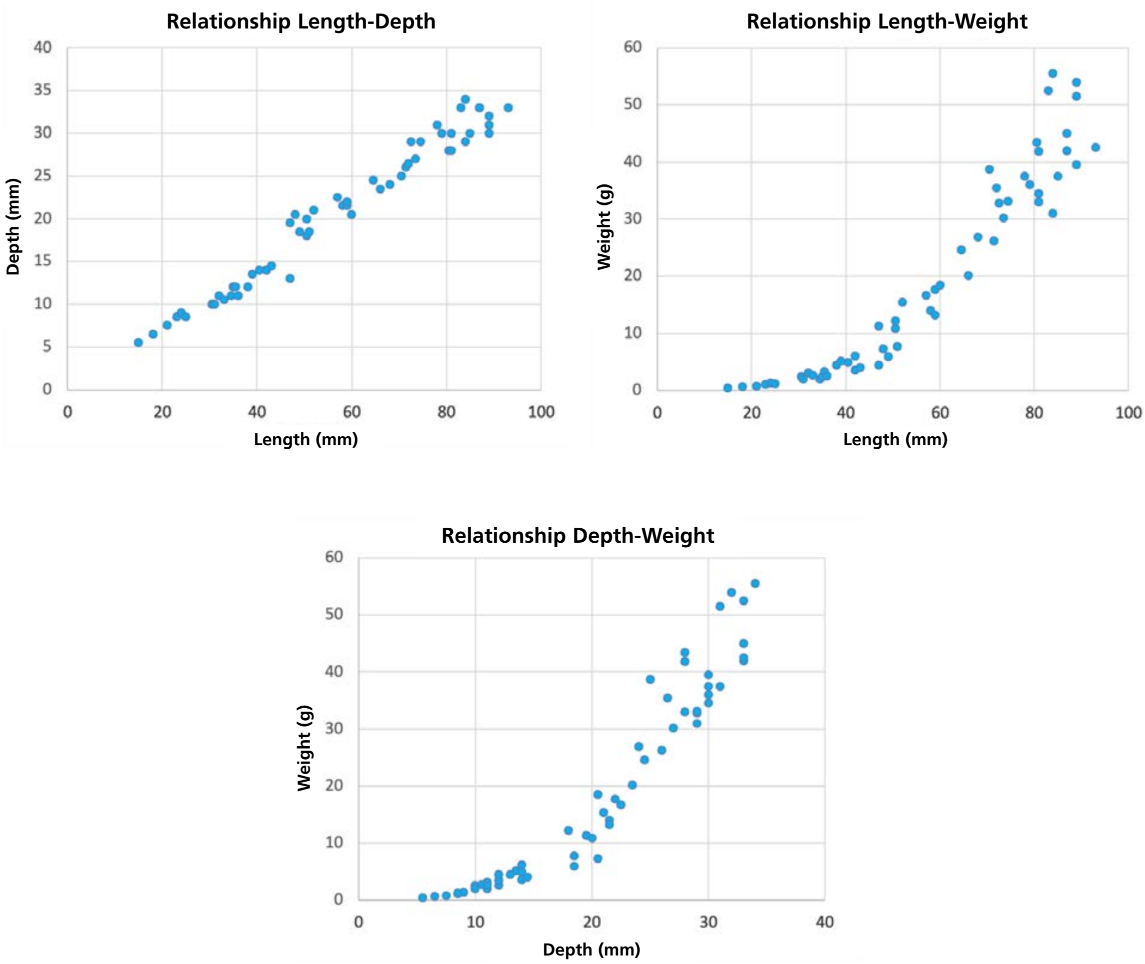
- A shell length >4 cm;
- A Lawrence & Scott index of at least 120 (see Section 2.2.2);
- A carbohydrate content in the meat after boiling of at least 4 percent.

### 2.2.1 Size standards

Marketable size of mussels is usually in the range 45–75 mm in total shell length. Depending on production protocols and local traditions, market size may significantly change.

Size can be expressed in several ways, including average live weight, average shell depth, average length, and the number of specimens per kilogramme. These parameters are correlated, although the relationships vary depending on the species, production site and cultivation method. Since size grading is primarily based on shell depth – with average depth directly determining the size of the grading mesh – this parameter is the most commonly used. For Mediterranean mussels reared offshore, an example of the correlations among these different parameters, from seed to fully grown individuals, is shown in Figure 2.11.

FIGURE 2.11
**Example of biometrics of Mediterranean mussels**



It is essential to grade mussels before commercialization and to discard undersized individuals. Product size homogeneity is important, as it significantly affects the final market price. As noted above, for products sold under strict specifications - such as geographical origin or traditional specialty certifications - size uniformity is one of the key criteria.

The chosen harvesting and grading strategies for market-ready mussels influence various quality parameters, particularly shelf-life. These aspects are discussed in greater detail in Section 2.2.3.

### 2.2.2 Meat content and quality

The mussel meat is ultimately where the value of the product lies and, therefore, the higher the meat to shell ratio is, the higher the potential price of the product that can be demanded from the market. However, there are other factors, such as supply versus consumer demand and the taste of the product, that will affect the market price. Figure 2.12 gives an example of the meat content in Mediterranean mussels.

#### *Meat content assessment*

Meat content is arguably the most important quality criterion for mussels. It is influenced primarily by farming practices and by environmental factors such as phytoplankton concentration and composition, tidal and coastal currents in the farming area, position in the intertidal zone, and rearing densities.

Meat content is typically expressed as a percentage, representing the weight of the drained meat relative to the total weight of the mussel before opening (including shells, meat, and inter-valvar water). Values can vary considerably, but under normal conditions, meat typically constitutes between 20–50 percent of the total mussel weight. A meat content exceeding 30 percent is generally considered excellent quality.

The procedure for conducting a meat-to-shell-ratio analysis and calculating the resulting value is as follows:

- Take 20 whole mussels and clean the shells to ensure that there is no bio-fouling or other detritus attached to their exterior.
- Dry and weigh the 20 whole mussels and record the overall figure.
- Shuck the mussel' meat from the shells and place the meat onto an absorbent cloth to remove any excess liquid.
- Weigh the collected meat and record the total figure.
- Divide the weight of the meat by the weight of the whole mussels and multiply this figure by 100.
- The resulting figure is the percentage of meat contained within the whole organism.

FIGURE 2.12
**Examples of European mussel meat content**



This method has the advantage of being quick and simple. However, as noted above, the result is influenced by the mussel's actual water content prior to opening for meat extraction. To account for variations in water content, another method commonly used in product certification and scientific studies is the Lawrence & Scott index, calculated as: Dry weight × 1 000/(total weight – shell weight).

### *Impact of shell thickness on meat content assessment*

The shell thickness and density will also affect the meat-to-shell ratios. For a constant weight of meat, the meat-to-shell ratios will appear lower in mussels with thicker shells and vice versa. Consequently, where the mussels are grown will have a bearing on their meat-to-shell ratios. Mussels cultivated in the intertidal zone that are slower growing and therefore produce thicker shells will have a relatively lower meat to-shell ratio. In contrast, mussels cultivated in the subtidal zone or on long-lines that grow faster and present thinner shells will yield better meat-to-shell ratios than their intertidal equivalents. The shell's internal volume will also affect the meat-to-shell ratios.

### *Chemical composition and organoleptic traits*

The chemical composition and the organoleptic traits of the mussels are affected by the site characteristics (phytoplankton and salinity), the season and the farming practices (Table 2.5). Consequently, their taste (sweet, sour, salty, bitter, umami) and their texture (tender, tough, fatty, etc.) are influenced by these factors. Finally, the conditions and duration of storage post-harvest will also have to be considered, as oxidation processes will quickly take place, modifying both the taste and organoleptic traits.

## 2.2.3 Shelf-life

Shelf-life is the period during which mussels can remain alive and suitable for human consumption after being removed from the water. It is expressed in days post-harvest and depends on factors such as prior growing conditions, gonad maturation, harvesting and grading protocols, and storage conditions. When mussels are sold as whole, live animals, their ability to withstand handling and exposure directly affects the quality of the product received by the customer.

If mussel meat is processed at the same site as the harvest, or shortly thereafter at a nearby processing facility, shelf-life is of limited concern. Conversely, if mussels must be transported alive to distant markets or processing locations and are not consumed shortly after harvest or dispatch, it is essential that they have a sufficient shelf-life to ensure their suitability for human consumption. In this context, the end-product size-grading strategies described in Section 2.2.1 are particularly important.

TABLE 2.5
**Composition and nutritional status of Mediterranean mussels depending on seasons**

| | August | November | February | May | August |
|---|---|---|---|---|---|
| Meat (% total live weight) | 28.8 | 28.7 | 38.3 | 29.5 | 31.2 |
| Shell (% total live weight) | 38.6 | 33.6 | 40.7 | 36.6 | 40.2 |
| Water (% total live weight) | 32.6 | 37.6 | 21.0 | 33.9 | 28.6 |
| Proteins (% total dry weight) | 60.3 | 60.9 | 54.3 | 52.7 | 55.4 |
| Lipids (% total dry weight) | 7.9 | 9.5 | 10.0 | 7.3 | 9.3 |
| Carbohydrates (% total dry weight) | 18.8 | 12.5 | 22.2 | 23.9 | 19.6 |
| Ash (% total dry weight) | 13.1 | 17.1 | 13.5 | 16.2 | 15.6 |
| Saturated fatty acids (%) | 33.0 | 31.3 | 29.5 | 30.0 | 34.0 |
| Monounsaturated fatty acids (%) | 13.5 | 15.8 | 11.0 | 15.0 | 13.8 |
| Polyunsaturated fatty acids (%) | 53.5 | 53.0 | 59.5 | 55.0 | 52.3 |
| n6 polyunsaturated fatty acids (%) | 13.0 | 11.0 | 8.5 | 9.0 | 12.5 |
| n3 polyunsaturated fatty acids (%) | 39.0 | 42.0 | 52.0 | 46.0 | 38.0 |
| Cholesterol (mg/100 g) | 63.0 | 58.0 | 44.0 | 52.0 | 64.0 |
| Phytosterols (mg/100 g) | 72.0 | 59.0 | 79.0 | 55.0 | 79.0 |

*Source*: Data from University of Camerino.

### *Impact of cultivation environment on shelf-life*

The cultivation site of mussels has a significant effect on their shelf-life. Mussels grown in subtidal zones or on long-lines spend most of their lives with shells open while filtering nutrients from the water. Because they do not regularly open and close their shells, their adductor muscles are relatively weak. As a result, when removed from the safety of their underwater environment, they are less able to keep their shells closed for extended periods, reducing their tolerance to air exposure and, consequently, their shelf-life.

In contrast, mussels grown on intertidal sites must close their shells each time the tide recedes, exposing them to air. This repeated exposure strengthens their adductor muscles, allowing them to remain tightly closed for longer periods when removed from the water. By retaining moisture within their shells, these mussels have an increased ability to survive, resulting in a longer shelf-life.

At the end of the maturation cycle, immediately before and during gamete release, shelf-life is also reduced. Harvesting and selling mussels during this period should be avoided.

### *Impact of harvesting and grading practices on shelf-life*

More than any other factor, harvesting and grading strategies have a major impact on shelf-life. Immediately after harvesting, mussels remain clumped together by their byssal threads. Mussels grown in net socks are also intertwined with the net in which they were placed at the beginning of the fattening phase. During declumping and grading, separating the mussels can tear the byssal threads of some individuals, reducing their ability to keep their shells closed and consequently shortening their shelf-life.

Final grading can be performed at different stages, depending on farming practices and commercial agreements:

- Pre-harvest grading: Mussels can be graded a few days before final harvesting and kept in water on the farm, allowing them to recover from handling stress. In this case, the product is ready for sale without further grading before conditioning and transportation.
- Post-harvest grading: Mussels can be graded immediately after harvesting and prior to conditioning for transportation.
- Grading at processing plant: Mussel socks or segments can be sent to a processing and conditioning plant, where grading is performed after transportation.

In the first scenario, shelf-life is optimized. In the second scenario, shelf-life is expected to be very short, requiring the product to be sold within about one week. In the third scenario, delaying declumping and grading allows shelf-life to be extended by the few days spent during transportation to the processing and conditioning facility.

These strategies also affect final production yield. In the first two cases, grading is performed by the producer, allowing undersized mussels to be retained and used to create new socks for further on-farm growth. In the third scenario, undersized mussels are typically lost.

Finally, the chosen strategy, together with the storage conditions and duration, affects the water content inside the shells, which influences all evaluation parameters based on live, whole mussels:

- Higher water content increases the batch weight at sale and can prolong shelf-life.
- Higher water content may also lead to an underestimation of meat content when expressed relative to live weight.

*Impact of conditioning and storage practices on shelf-life*

When packaging mussels, it is important to minimize the loss of the water retained within their shells. Mussels should always be packed in tightly closed net bags to prevent shell gaping. The recommended storage temperature is 4–6 °C.

### 2.2.4 Shell quality and appearance

Shell shape and quality, along with the presence of other organisms on the shell (biofouling), are important quality criteria to consider.

*Shell shape and strength*

Depending on the cultivation technique, the shape of the shell and its external appearance can change as the animals adapt themselves to their available space. Excessive densities or unsuitable socks mesh sizes can lead to malformed mussels and consequently to a reduced market price.

The density and strength of the mussel shell are additional important factors to consider when assessing product quality. Shell strength is influenced by the mussel's growth rate: mussels that grow rapidly in nutrient-rich, subtidal environments tend to develop thinner, weaker shells. A similar pattern is observed in the Mediterranean Sea, where higher water temperatures compared to the Atlantic Ocean contribute to faster growth and reduced shell robustness. In all locations, shell fragility is typically greatest at the end of summer.

During harvesting and declumping, mussels are subjected to mechanical stress, which can result in a portion of the stock having broken shells or damaged animals that must be removed before sale. The proportion of damaged shells directly affects the product's economic value, and higher shell fragility reduces overall yield.

Finally, shell weakness is also a problem for customers, as they are more likely to break during cooking.

*Biofouling*

Biofouling is the presence of organic growth on the outer surface of the mussel shell that will vary depending on the organisms present in the production area and handling practices. Most of these epibionts produce planktonic larvae that are carried into the cultivation area by water currents. These larvae then settle on the mussels' shells. Because the larvae are very small (<1 mm), their presence cannot be prevented.

Biofouling can include algal growth, sponges, tube worms, encrusting bryozoans, barnacles and other organisms. Some of these organisms compete directly with mussels for food, as described in Section 2.1.4, while others primarily affect the aesthetic appearance of the product. Additionally, as these organisms die and decompose, they can produce unpleasant odours that reduce product quality. Table 2.6 summarizes the main biofouling elements likely to be encountered, and Figure 2.13 provides illustrative examples.

FIGURE 2.13
**Examples of biofouling on European mussels**

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TABLE 2.6
**Main biofouling organisms on European mussels**

| Biofouling organism | Description |
|---|---|
| Algal biofilm | Aggregation of microalgae that forms mats on aquatic surfaces. |
| Macroalgae | Multicellular species of algae. |
| Bryozoa | Filter feeding, small aquatic organisms that live in colonies. They produce organic skeletons that can take many different forms. |
| Barnacles | Small crustaceans that are sessile suspension feeders. They encrust a marine surface and grow their shell directly onto the substrate. |
| *Serpula* worms | Calcareous tube worms that attach themselves to a substrate and live within their protective casing. |
| Tunicate | Commonly known as sea squirts. Oval shaped ascidians that attach themselves to marine surfaces using a sucker. |

## 2.3 CONSUMER SAFETY

Bivalve molluscs are filter-feeding organisms, and as a result can concentrate microorganisms, chemical contaminants and biotoxins present in their growing environment. Because of this, there is a requirement for stringent food safety protocols for their production and sale, thereby ensuring consumer protection and facilitating trade. Food safety considerations for production and processing of bivalve molluscs, and particularly for live and raw animals, are reported in Appendix I.

The main risks for consumer safety are related to:

- Microbiological contaminations.
- Illness caused by algal toxins.
- Illness caused by some *Vibrio* strains.
- Norovirus contaminations.

### Microbiological contaminations

Microbiological contaminations are usually related to anthropic activities on the seashore and fresh-water discharges into the sea. Each individual country where shellfish farming is performed adopts their own regulatory framework to prevent and/or monitor the risk for consumers.

In the European Union and in the United Kingdom of Great Britain and Northern Ireland, waters are classified depending on contamination levels through sampling made every 15–30 days. The criteria and thresholds are reported in Table 2.7.

Other systems are based more on prediction models, avoiding harvesting shellfish when conditions are expected to lead to higher contamination levels (for example, during certain seasons or after heavy rain).

#### *Algal toxins*

Algal toxins are produced by some phytoplankton species, which in turn are filtered and accumulated by bivalve molluscs. Depending on their chemical structure, algae toxins are classified in eight classes (FAO/WHO/IOC workshop, 2004):

TABLE 2.7
**Bivalve production areas classification in the United Kingdom of Great Britain and Northern Ireland**

| Class | Yearly limits |
|---|---|
| A | 80% of samples must be ≤230 *E. coli*/100 g of shellfish flesh;<br>All samples must be less than 700 *E. coli*/100 g |
| B | 90% of samples must be ≤4 600 *E. coli*/100 g of shellfish flesh;<br>All samples must be less than 46 000 *E. coli*/100 g |
| C | All samples must be ≤46 000 *E. coli*/100 g of shellfish flesh |
| Prohibited areas | Any samples containing >46 000 *E. coli*/100 g of shellfish flesh |

- Azaspiracids (AZAs)
- Brevetoxins (PbTXs)
- Cyclic imine toxins
- Domoic acids (DAs)
- Okadaic acid and derivative (OAs)
- Pectenotoxins (PTXs)
- Saxitoxins (STXs)
- Yessotoxins (YTXs)

These toxins are also classified, based on the effect they have on consumers' health:

- Paralytic Shellfish Poisoning (PSP) – Caused by saxitoxins (STXs), neosaxotoxins, gonyautoxins and cyclic imine toxins from algae like *Alexandrium catenella*, *Alexandrium minutum*, *Alexandrium tamarense*, *Pyrodinium bahamense*, *Gymnodinium catenatum*, etc.
- Amnesic Shellfish Poisoning (ASP) – Caused by domoic acid (DAs) from algae like *Pseudonitzschia seriata*, *Nitzschia pungens*, etc.
- Diarrhetic Shellfish Poisoning (DSP) – Caused by the lipophilic toxins (okadaic acid, azaspiracids, pectenotoxins, yessotoxins and dinophysistoxins) from algae like *Dinophysis* spp., *Gonyaulax grindleyi*, *Lingulodinium polyedrum*, etc.
- Neurotoxic Shellfish Poisoning (NSP) – Caused by brevitoxins from algae like *Gymnodinium breve*, *Karenia brevis*, etc.

### *Vibrio strains*

In response to a request from the Codex Committee for Scientific Advice in 2001, the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) of the United Nations established a risk assessment drafting group and convened an expert consultation to take the first steps in developing a risk assessment for *Vibrio* spp. in seafood products that would have the most impact on public health and/or international trade. The expert consultation concluded that three species, *Vibrio parahaemolyticus*, *Vibrio vulnificus*, and *Vibrio cholerae* were the species responsible for most cases of human illness caused by *Vibrio* strains, and several seafood vehicles associated with these illnesses were identified.

*Vibrio parahaemolyticus* is a marine microorganism native in estuarine waters throughout the world. The organism was first identified as a foodborne pathogen in Japan in the 1950s (Fujino *et al.*, 1953). By the late 1960s and early 1970s, *V. parahaemolyticus* was recognized as a cause of diarrhoeal disease worldwide, although most common in Asia and the United States of America. In 2011, FAO published the volume "Microbiological Risk Assessment series 16 – Risk assessment of *Vibrio parahaemolyticus* in seafood – FAO 2011" (see Further reading).

*Vibrio vulnificus* naturally inhabits warm estuarine environments and can infect humans via wound exposure or seafood consumption. These infections are rare and generally limited to individuals with pre-existing chronic illnesses or the immune-compromised. However, *V. vulnificus* can invade through the intestinal barrier into the bloodstream, causing primary septicaemia. As a result, it has the highest case/fatality rate (approx. 50%) among foodborne pathogens. In 2011, FAO published the volume "Microbiological Risk Assessment series 8 – Risk assessment of *Vibrio vulnificus* in raw oysters – FAO 2005 (see Further reading).

### *Norovirus*

Recently, attention has been paid to *Norovirus*-related foodborne infections. In November 2019 the European Food Safety Authority (EFSA) published its report on noroviral prevalence in areas of production and shipping of oysters in the European Union (see Further reading). In June 2020 the European Aquaculture Advisory Council (AAC) published its recommendation "*Norovirus* 2" (see Further reading) on the proposal for a delegated act to amend Annex III to Regulation 853/2004 (AAC 2020-04) where AAC agreed that the viral risk assessment should be based on a sound scientific basis and is relevant when:

- It is based on the detection of infectious particles and not on the detection of RNA genomes (the genetic material of *Norovirus*), using the current ISO 15216 standard;
- It demonstrates the link between the prevalence and amount of viral infectious particles in the foodstuff and the prevalence of gastroenteritis among consumers.

# 3. Site survey



Section 3.1 gives an overview of the possible typologies of sites that can be used for the cultivation of mussels. It also gives definitions and indications on the parameters to look for to assess if a site is suitable for farming or not. Once the reader has familiarised themselves with these factors, Section 3.2 lists the possible constraints to be taken into account before launching a farming activity.

The selection of a good site for bivalve aquaculture is a crucial process and is one of the most important elements that will contribute to the success of any intended farming activities. There are many contributing factors that need to be present in a successful site, some which are mandatory, such as good water quality and an abundance of suitable phytoplankton, and some that can be compromised upon, such as the proximity of the cultivation site to any land-based processing facilities. In an ideal world, all of the desired parameters that are discussed in the following chapter would be present in one site making it a perfect location for the cultivation of mussels. However, in reality, most sites will represent a compromise as there are very few locations that will fulfil every criterion. The site selection process should therefore highlight the strengths and weaknesses of the potential farming location, and the decision made about the suitability for cultivation should be based upon the most important factors that will lead to a successful outcome. An example of an acceptable compromise would be an offshore farm, where the water quality is good and there is an ample supply of the required planktonic nutrients, but the location is a long way from the land-based facilities (the port where the workboat is moored) and the site is exposed to wind and wave action. So long as the travel time to the site is not too long and the climatic conditions not too severe, then the inconvenience of the geographic location is outweighed by the ability to produce a quality product. An example of an unacceptable situation would be an estuarine site with easy access and protection from the elements, but with such poor water quality that the cultivated shellfish would be unsafe for human consumption. Undertaking a thorough site selection process should enable the farmer to pick a location based upon the required criteria and prevent them from attempting to undertake cultivation activities in an unsuitable environment.

## 3.1 SITE DESCRIPTION

### 3.1.1 Site typologies

The farm site can be defined as the limited area of operation, where the farm will be installed. More potential farm sites can be available in the extended area of the coastline. According to the seashore configuration, local rules for licensing and traditions, the farmer will have to choose both the farm site and the farming technique that is appropriate for the site.

The main aspects to be taken into account will be the presence of tides, the depth, the level of exposure, the supply of freshwater, the currents and the water parameters like temperature, salinity, dissolved oxygen, suspended solids and dissolved chemical elements.

The presence of tides and the mean tidal range will inform the operator whether it will be possible to farm shellfish in the area of the foreshore that is exposed over low tide, the so-called "intertidal zone". Many farming technologies have been developed in these areas, where access is clearly easier than in the open sea. As it will be pointed out later, farming in the intertidal zone will also impact on production costs and product quality. Farming can also take place in the "subtidal zone", that is in the shallow waters just after the "intertidal zone" before moving towards the open sea. In this last case, farming is carried out continuously under water. Where tides do not exist, or have a limited tidal range, all of the farming activities will be based around techniques that are suited to permanently submerged conditions such as exists on offshore sites. Figure 3.1 shows examples of different mussel farming zones and the most suitable cultivation technique based upon their position in relation to the water depth and tidal range.

The tidal range is the vertical distance through which the tide rises and falls, the difference in water height between low tide and high tide. The "mean tidal range" is calculated as the difference between mean high water (i.e. the average high tide level) and mean low water (the average low tide level).

The extension of the intertidal zone will also depend on the depth and the inclination of the foreshore in the area of coastline under consideration. If detailed cartography is not available, it will be necessary to do a preliminary survey to set up a bathymetric map of the possible areas.

"Exposure" is defined as the way the site can be affected by the potential effect of dominant winds and waves all-round the year. The severity of the effect will depend on the "fetch", which is the distance over the water that the wind has blown without hindrance in the direction of the farm site before impact with the cultivation equipment. The longer the fetch, the higher the risk will be that the farm will sustain some damage, particularly when maximum fetch corresponds to dominant winds or to tempest winds. For a given wind direction, fetch is calculated as the distance between the farm and the opposite coastline (miles or km). In "sheltered sites", for instance in lagoons, rivers, estuarine zones or bays protected by physical barriers, this distance will be reduced and the risks will be limited. In the "exposed sites", the fetch will be typically greater. Exposed sites can be near to the shoreline or completely offshore. Independently from the fetch, the waves' maximum and average height, depends also on the depth of the water: wave height is inversely proportional to depth. In shallow water the waves period will be shorter and waves breaking more frequent (Table 3.1).

When considering the exposure, two potential effects have to be considered: the risk of damages in case of exceptional events (storms, tempest or typhoon) and the deterioration of the farm components under the continuous effect of waves. In exposed sites, the "return time" of extreme events, that is the average time between two occurrences, will have to be evaluated (in some countries, historical data is available). In subtidal and offshore farms, the economic impact of the average number of days where the farm cannot be reached because of rough conditions will have to be estimated.

Many sites are affected by freshwater run-off that causes a high degree of variation in salinity and nutrients availability. Farming is currently carried out in these sites because of the resulting benefits in terms of feeding capacity and product quality.

Another physical parameter that needs to be accurately evaluated is the presence and strength of currents in the location of the farm. Currents can be the result of tidal flows, freshwater supply (rivers), dominant wind and marine water circulation. The assessment of currents will influence the choice of cultivation equipment and its positioning within the area as some systems will not be suitable for locations with particularly strong currents. However, the water exchange and the resulting refreshment of nutrients and dissolved oxygen caused by currents is vital for the successful cultivation of mussels.

FIGURE 3.1
**Overview of suitable site typologies**
(a) and (b) Cross-section view of different mussel farming zones and the most suitable cultivation technique based upon their position in relation to the water depth and tidal range; and (c) Aerial view of different cultivation zones

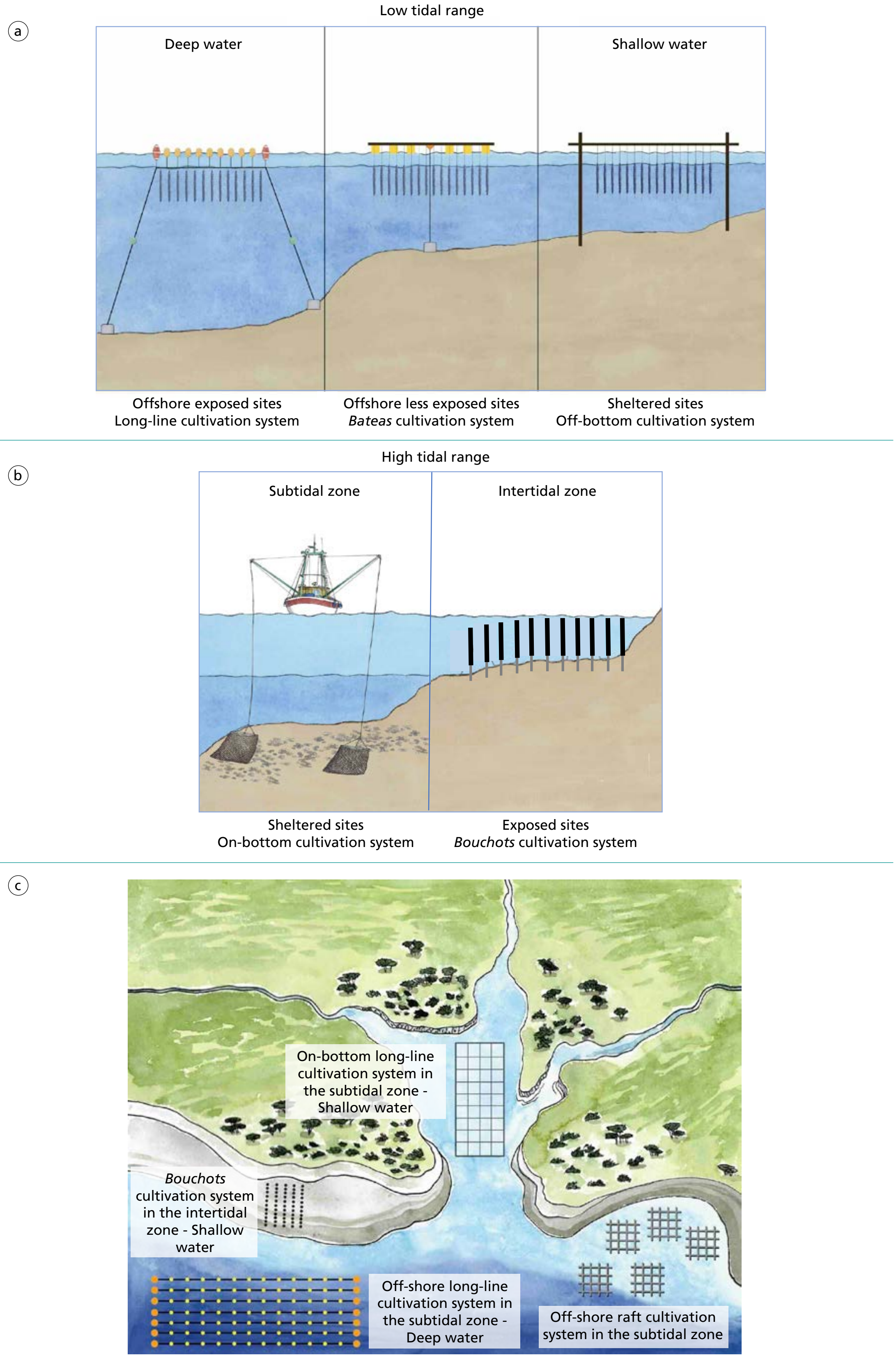


TABLE 3.1
**Sheltered and exposed site characteristics**

| | Sheltered site | Exposed site |
|---|---|---|
| Presence of physical barriers & fetch | Barriers protect the site from the effects of dominant wind and waves.<br>Fetch is typically low. | Barriers that can protect the site from the effects of dominant wind and waves do not exist. Fetch is high and has to be accurately assessed. |
| Example | Lagoon, bay, river, estuarine area, channel. | Open sea, unprotected shoreline. |

For example, in sheltered areas with limited wind and wave action, currents play a key role in refreshing the water around the stock and thereby reduce the risk of the conditions becoming anoxic which can cause mortalities in the mussels. For mussel farming, current velocities of 25–35 cm/s are deemed suitable.

### 3.1.2 Environmental parameters to be collected for site description

Environmental conditions can be highly variable from one year to the next and therefore these fluctuations, and their effect on the mussels will have to be taken into account. If available, then the assessment of historical data can help to give a picture of the average conditions that are likely to be experienced on the site. When studying this information, it is important to look at as many previous years as possible. If data is not available, data collecting and in situ surveys should be undertaken for a period of at least 1–2 y. If other farms are already operating in the local area, then it is recommended to consult them to gain insight into the general conditions. Local fishers will also have an in-depth knowledge of the environment and can be an invaluable source of information regarding this.

Tables 3.2 to 3.6 provide key physical, meteorological, chemical and biological parameters that would require to be assessed during a site survey.

TABLE 3.2
**Physical parameters to be assessed during site survey**

| | To be assessed |
|---|---|
| Coastline configuration<br>Depth | • Cartography<br>• Bathymetric cartography or preliminary survey<br>**Map scale:**<br>- Map scale of at least 1:5 000 for land-based or intertidal facilities<br>- Map scale of at least 1:100 000 for marine maps |
| Access to the potential farm sites | Access to the facilities is a key factor that has to be considered from the beginning as it can have a significant effect on profitability.<br>• Road access to land-based facilities<br>• Tractor and boat access to intertidal facilities<br>• Boat access to offshore facilities (nearest harbour)<br>**Expression:**<br>- Mile or kilometre, but also in time (hour/minute) to reach the farm |
| Tides | • Presence of tides and related tidal range<br>• Tide flows and related currents<br>• Extension of the intertidal zone (depending on bottom inclination)<br>**Expression:**<br>- Mean tidal range in meters/feet<br>- Mean tidal flow (knot or m or cm)/unit of time (second, minute) |
| Water flow<br>Currents | • Presence of currents independently from tide flows<br>**Expression:**<br>- Velocity (knot or m or cm)/unit of time (second, minute) |

TABLE 3.2 (CONTINUED)

| | To be assessed |
|---|---|
| Freshwater supply | • **Presence**, magnitude and seasonal variations<br>• Related currents and seasonal variations<br>**Expression:**<br>- For rivers in cubic m/time unit (second, minute, hour)<br>- Flow (m or cm)/time unit (second, minute) |
| Bottom | • Sandy, muddy, rocky<br>• Presence of seaweed or seagrass |
| Temperature | • For each potential site in a given area: temperature range and related seasonal variations with particular attention to minimum and maximum values that can be a limiting factor for the cultivated species.<br>• In subtidal and open sea conditions, possible water stratification (thermocline) and related seasonal variations.<br>**Expression:**<br>°C (Celsius) or °F (Fahrenheit) |

TABLE 3.3
**Meteorological parameters to be assessed during site survey**

| | To be assessed |
|---|---|
| Wind orientation & related fetch | • Dominant wind orientation and related fetch<br>• Tempest wind orientation and related fetch<br>• Winter tempest average duration (number of days)<br>• Risk of typhoon<br>**Expression of wind speed:**<br>knots, kilometres/h, miles/h<br>Wind can also be expressed in "strength" with reference to the Beaufort scale or other similar scales |
| Waves height | Wave height of a surface wave is the difference between the crest and a neighbouring trough and is twice the amplitude.<br>• Maximum wave height in the case of extreme events<br>• Significant Wave Height (SWH) defined as the average height of one-third of waves having the greatest heights<br>• Number of days where waves are expected to be too high to allow to work on the farm (this estimation will have to be referred to the workboat design and its dimensions)<br>**Expression of wave height:**<br>metres or feet<br>Table of the World Meteorological Organization (WMO) Sea state code (Table 3.4) |
| Return time of extreme events | • Winter tempests<br>• Typhoons<br>• Drought periods<br>• Harmful algal blooms (HABs) and anoxia events<br>Take into consideration the fact that, due to climate change, the frequency of extreme events may increase significantly. |

TABLE 3.4
**World Meteorological Organization sea state code (Douglas Sea Scale)**

| State | Wave height (m) | Description |
|---|---|---|
| 0 | 0 m – (0 feet) | Calm (glassy) |
| 1 | 0–0.1 m – (0.00 to 0.33 feet) | Calm (rippled) |
| 2 | 0.1–0.5 m – (3.90 inches to 1 foot 7.7 inch) | Smooth (wavelets) |
| 3 | 0.5–1.25 m – (1 foot 8 inches to 4 feet 1 inch) | Slight |
| 4 | 1.25–2.5 m – (4 feet 1 inch to 8 feet 2 inch) | Moderate |
| 5 | 2.5–4 m – (8 feet 2 inches to 13 feet 1 inch) | Rough |
| 6 | 4–6 m – (13 to 20 feet) | Very rough |
| 7 | 6–9 m – (20 to 30 feet) | High |
| 8 | 9–14 m – (30 to 46 feet) | Very high |
| 9 | >14 m – (46 feet) | Phenomenal |

TABLE 3.5
**Chemical environmental parameters of the seawater to be assessed during site survey**

| | To be assessed |
|---|---|
| Salinity | • Presence of fresh water supply and seasonal variations<br>• Salinity range and seasonal variations<br>**Expression:**<br>In g/L or g/kg or ‰ (equivalent per thousand – ‰) |
| Dissolved oxygen | • Verify if anoxic events have occurred in the past and where.<br>**Expression:**<br>mg/L |
| Turbidity or light penetration | Turbidity can be defined as an obstacle to the vertical penetration of the light into the water column. It depends mainly on suspended solids and phytoplankton concentrations.<br>• Light penetration in the water can be roughly measured with a Secchi disk (Appendix III).<br>**Expression:**<br>Depth in metres at which the disk disappears for an observer looking down from the water's surface |
| Suspended solids | It refers to small solid particles that remain in suspension in water. Some of the suspended solids will be filtered by the shellfish and immediately eliminated as "pseudofaeces" that cannot be assimilated. An excess of water turbidity will cause the shellfish to waste energy and result in slower growth rates.<br>• Suspended solids can be assessed through sampling and laboratory analysis or by electronic measurement devices.<br>**Expression:**<br>- In case of sampling and analysis, it is usually expressed as "Total suspended solids" (TSS in mg/L) that is the dry weight of suspended particles that can be trapped using a filtration apparatus. |
| Chemical pollutants | Potential pollutants are numerous and, in many cases, difficult and expensive to detect. It is not technically and economically sustainable to carry out periodical samplings and analysis to get a thorough overview of the situation. Alternatively, the best approach is to refer to reports from local authorities or to conduct a survey of pollution sources to focus on a few analyses.<br>Main pollution sources to be consider are:<br>• Presence of industry and related discharge<br>• Presence of polluted river effluents<br>• High population density<br>• Maritime traffic<br>Main pollutants to take in account are:<br>• Cadmium, mercury, lead, nickel and copper<br>• Heavy metals<br>• Aromatic hydrocarbons (benzene, toluene, xylene, etc.)<br>• Chemical compounds that can enter the nitrogen cycle and phosphorus cycle, causing eutrophication and algal blooms |

TABLE 3.6
**Biological environmental parameters of the seawater to be assessed during site survey**

| | To be assessed |
|---|---|
| Nutrient availability:<br>Chlorophyll-$\alpha$ concentration | Shellfish are filter feeders that need phytoplankton for growth and the chlorophyll-$\alpha$ concentration in the seawater is the easiest measuring system to get an indication of phytoplankton availability.<br>• Chlorophyll-$\alpha$ concentration and seasonal variations.<br>**Expression:**<br>in microgram/litre or µg/litre<br>- The data indicates the total concentration of chlorophyll-$\alpha$ of all of the various sizes, including picoplankton (<10 µm) that is too small to be filtered and assimilated by shellfish, so this should be discounted from the total amount available and taken into account when undertaking the assessment.<br>- Nowadays, satellite data is fully available and represents a reliable source of data, but in situ sampling should be periodically undertaken and analysed to ensure that there is an accurate correlation between satellite data and in-situ data (laboratory analysis).<br>- Satellite data is limited to chlorophyll-$\alpha$ determination, while laboratory analysis can be performed for chlorophyll-$\alpha$ and other pigments.<br>- Satellite data refers to surface water while in situ sampling can be made at different water depths. |
| Nutrient availability:<br>Phytoplankton characterization | The parameter assessed above does not give a qualitative indication. Shellfish need a suitable phytoplankton composition for growth and therefore it is important to conduct further investigation into the following factors:<br>• Phytoplankton concentration and related seasonal variations<br>• Phytoplankton composition and related seasonal variations, including concentration of the most representative species/species groups<br>• Phytoplankton size and related seasonal variations |

TABLE 3.6 (CONTINUED)

| | To be assessed |
|---|---|
| Biological pollutants | Like for chemical pollutants the approach is to refer to reports from local authorities or to conduct a census on pollution sources to focus on few analyses.<br>Main pollution sources to consider are:<br>• Presence of sewage related to high population density or terrestrial animal production<br>• Inefficient water treatment<br>As well as chemical compounds, some biological pollutants such as organic matter in suspension or sediments, can enter the nitrogen cycle and phosphorus cycle causing eutrophication.<br>Other main biological pollutants to take in account are:<br>• Bacterial contaminations<br>• Viral contamination<br>• *Norovirus*<br>See previous Section 2.3 and Appendix I about food safety concerns. |
| Algae toxins | During feeding, shellfish can ingest phytoplankton species containing biotoxins that can be harmful for human health. If other wild stocks of shellfish are harvested, or if farms are already operating in the same area, get information from local authorities on the regularity and severity of these events. Toxins effect to ask about will be Diarrheic Shellfish Poisoning (DSP), Paralytic Shellfish Poisoning (PSP), Amnesic Shellfish Poisoning (ASP) and Neurotoxic Shellfish Poisoning (NSP).<br>See previous Section 2.3 and Appendix I about food safety concerns. |

The availability of both real-time and historical data from satellites is a technological revolution that can be of great value when assessing the suitability of a potential aquaculture production site. With the increasing number of satellites, and the progress in sensor technology, both data frequency (temporal resolution) and data accuracy (spatial coverage and resolution) are continuously increasing. The main data available from satellite networks like Copernicus in Europe are the following:

- Seawater temperature at the surface (SST – Sea Surface Temperature) and at a given depth.
- Salinity and Mixed Layer Depth (MLD).
- Winds, waves, tides and currents through (SSH – Sea Surface Height).
- Chlorophyll-α concentration with extrapolation on phytoplankton composition and size or on Primary Productivity (PP).
- Suspended solids and turbidity, with the possibility to distinguish between mass of water from different origins (for instance a freshwater front with suspended solids penetrating offshore clean seawater).
- Dissolved oxygen.
- Euphotic Zone Depth (ZEU).

The spatial resolution, which is the area on earth represented by a single point, is still limited in coastal areas or intertidal zones where the images are the result of the combination between on-earth measurements and off-shore measurements which are performed differently. Nowadays, in fully offshore sites, where the above-mentioned aspect is not relevant, a single point corresponds to a square with sides measuring roughly 300–600 m in length.

The comparison of satellite data with in situ collected data is still necessary to set up the interpretative models and to make the data reliable. But the installation and the maintenance of a permanent on site sampling station at the farm should become unnecessary.

The availability of satellite data, on the one hand, and of new marine hydrodynamic flows modelling systems, on the other, are helping to further refine coastal zone mapping techniques and provide increasingly reliable large-scale studies.

## 3.2 CONSTRAINTS TO BE TAKEN INTO ACCOUNT FOR SITE SELECTION

Constraints are classified as any contributing factor that can prevent or limit the successful operation of bivalve cultivation at the selected location. Due to the open nature of the farming operations, there are many elements that can have an influence on the suitability of a site. The section below outlines these factors and each one should be considered carefully before deciding to progress with the establishment of a farm.

An initial step is to look for any available cartography and technical documentation relating to the site. When possible, contact existing farmers or producer associations to gain insight into the factors that can affect the site based on their past experience of operating under similar circumstances.

Take into account that the potential area of operation for the farm is likely to be of relevance to other users as well. Areas of coastal foreshore and nearshore marine zones can be of use to many diverse stakeholders besides aquaculture production businesses. These can take many forms but include such things as fishermen, moorings for pleasure craft, tourism, local residents, property developers, marine protected zones, sewage treatment discharge outlets and boatyards. Many of these interested parties have completely different priorities when it comes to the use of the available space and, as such, conflicts of interest can occur. As competition for space is fierce in these highly desirable areas, it can be difficult to secure licences to operate a bivalve cultivation operation, especially if it interferes with an already established activity in the relevant location. It is important to engage with not only the pertinent licensing authorities, but also the other local stakeholders, to see if a compromise can be negotiated to allow these diverse activities to exist in harmony. When possible, a "Marine Spatial Planning" exercise should be undertaken. This is a process of assessing the various potential uses for the marine area to maximise economic, social and environmental goals and is usually undertaken by the local authority whilst consulting with the various interested parties. If aquaculture businesses have been highlighted as a positive use of the marine space, then gaining the appropriate operating licences can be easier.

### 3.2.1 Administrative and logistic constraints

Verify:

- The licensing possibilities of the intended site;
- That regulatory compliance for food safety and sustainability do not represent an obstacle;
- If an environmental impact study is required before farming operations can be initiated;
- Seed availability: wild caught seed or hatchery produced seed;
- The authorizations for the access to the farm;
- The proximity to the market;
- The proximity to the laboratory for periodical controls and analysis.

### 3.2.2 Environmental constraints

Verify according to the parameters listed previously:

- The possible impact of geographical and meteorological conditions on the farm and equipment;
- The possible impact of the current environmental situation on product growth, survival and quality;
- The actual possibility to fit with the regulation for consumer safety.

# 4. Overview of the main farming techniques and equipment



## INTRODUCTION

This chapter will provide the reader with a basic understanding of the main farming techniques and equipment that will be needed to operate a mussel production site.

Section 4.1 provides an overview of the possible ways to obtain the seed that is necessary for any farming activity. If mussels breed naturally in the vicinity of the farm, then spat can be collected from the site using the recruitment techniques described in this section of the manual. If there is no locally occurring spat, or the numbers are so low as to render commercial activity unviable, then seed mussel will need to be bought in from other sites or from a hatchery. A hatchery is an establishment where mussels are conditioned and induced to spawn under controlled conditions and the resulting spat are collected, developed and sold on to farms, who then cultivate them until they reach a size that is suitable for sale and consumption.

Hatchery and nursery production techniques are not developed in this manual, but some information is provided in the "Further reading" section at the end of the manual.

Around the world, mussels are produced in many different ways, adapting the farming technologies to the conditions and local aquaculture traditions experienced at each site, and it would be impossible to describe all of these techniques. Nevertheless, the farming systems to grow the mussels can be classified into the main typologies that are briefly described in Sections 4.2, 4.3 and 4.4. Two of the most commonly used techniques for European mussels are then described in detail in Chapters 5 (Bottom cultivation) and Chapter 6 (Suspended cultivation in offshore long-lines).

The different long-line concepts are introduced in Section 4.5, while offshore long-lines to be installed in exposed condition are described in detail in Chapter 6. Some equipment used for grading and other basic operations common to all farming systems are described in Section 4.5.

The production systems used to grow mussels can be grouped into the three following types:

- Off-bottom cultivation
- On-bottom cultivation
- Suspended cultivation

These techniques can be carried out in either intertidal or subtidal zones. This clarification introduces another important distinction between the growing conditions experienced by the mussels:

- Mussels that are grown whilst experiencing the effect of tides, being out of the water twice a day for a variable length of time depending on tidal range and the position in the intertidal zone;
- Mussels that are grown continuously in submerged conditions as occurs in bottom cultivation in the subtidal zone or in long-line cultivation.

As pointed out in the introduction, within these subsets, there are many variations that have been developed by farmers to suit their unique circumstances. In some cases, farmers will use a combination of techniques to maximise the advantages of each system for different stages of grow-out and to allow them to use more of the area within their lease than would otherwise be possible.

The production cycle can be defined as the sequence of processes that are required to grow the mussels from seed to market size and can be divided into the four theoretical steps detailed in the chart below (Figure 4.1). In the following Sections, this logical scheme will be detailed and illustrated for the most common cultivation techniques.

Nevertheless, because recruitment techniques and farming strategies vary according to farming areas and local traditions, there is often a continuous process from seed recruitment through to the production of market-size individuals. As a result, it is frequently impractical to delineate distinct stages within the production cycle. For this reason, in several of the following sections, the production cycle is presented as a single, continuous process extending from seed collection to the final product.

FIGURE 4.1
**Production cycle chart**


## 4.1 PROCURING SEED

At the end of their planktonic stage, mussel larvae settle on suitable substrates available either in the natural environment or within the hatchery (see Section 2.1.2). To facilitate this process and to maximise the number of spat that successfully attach, recruitment devices made from various materials are deployed in the water. These devices provide an appropriate substrate that enhances larval settlement.

In contrast to other bivalves, such as oysters, which lack byssal threads and permanently cement themselves to a fixed surface, mussels attach both to the substrate and to neighbouring mussels by means of their byssal threads. This characteristic makes mussel recruitment considerably more efficient than in other bivalve species. Even after settlement, mussels retain limited mobility, allowing them to adjust their position to optimise feeding and growth conditions, rapidly forming high-density clusters.

A variety of recruitment devices can be employed for seed collection in mussel farming. The most commonly used supports for mussel recruitment are referred to as "rope collectors". These consist of ropes of various types and materials that are submerged in the water prior to larval settlement to provide suitable surfaces for spat attachment and early development. These may include:

- palm, coconuts and hemp fibre ropes;
- frayed ropes and or fuzzy ropes;
- coiled ropes (2–4 strands) to get maximum available surface/m;
- Ropes containing sticks or pegs within the strands, which prevent mussel clusters from detaching when they become too heavy;
- Christmas tree ropes;
- sliced tires (used in China).

Other supports can include suspended mesh nets of various types. In both cases - whether using ropes or nets - weights are required to prevent tangling. An example of mussel seed collection on submerged nets suspended from high-density polyethylene (HDPE) tubes, a system widely employed in northern European countries, is illustrated in Section 4.2.1 (see Figure 4.5).

Furthermore, since spawning occurs annually and the mussel production cycle often exceeds 12 months, in many sites with abundant recruitment, fixation also occurs on existing sea structures and on the previous year's cultivated mussels. This seed can be collected and used for further growth. For instance, it can be easily harvested from headline ropes (Figure 4.2 and Figure 6.30), buoys, predator-protection nets, or any other structural elements of the farm. It may also be recovered from the previous year's mussels following declumping and grading.

The choice of substrate depends on several factors:

- Material suitability and the available surface area;
- Time efficiency of stripping;
- Feasibility of using automated stripping methods;
- Possibility of re-immersion without stripping, and, in such cases, the allowable duration before transferring or harvesting the mussels.

FIGURE 4.2
**Example of wild mussel seed recruitment on a headline rope in the Adriatic Sea, Italy**

In sites where mussel seed settlement is abundant, recruitment on rope collectors can reach densities of 10 000–20 000 mussels/m. However, such high densities may result in reduced growth rates and lower overall yield. The use of supports that promote high recruitment densities typically requires earlier seed recovery and transfer to pre-growing ropes or socks. Conversely, limited recruitment density allows for higher individual mussel growth and permits a longer period before transfer.

The deployment period of the collectors is critical. These should not be placed into the water too early, as this increases the risk of partial or complete coverage by fouling organisms, which reduces the surface area available for mussel larval settlement. Likewise, supports should not be placed too late, beyond the peak spatfall period. Monitoring larval and fouling densities in the water can help determine the optimal immersion timing.

Seed collection is most commonly conducted on the farming site or from nearby natural sites. When recruitment sites are distant from the farm, transportation by boat or truck may be required. In recent decades, climate change and depletion of wild stocks have created challenges in seed collection, leading some producers to source seed from more distant areas. Additionally, increasing pressure from non-governmental organizations (NGOs) to limit harvesting on natural beds has brought greater attention to recruitment using collectors and hatchery-based production under controlled conditions.

To date, the relatively low added value of mussels has rendered controlled breeding and hatchery production largely unprofitable. However, recent changes - including increasingly variable natural recruitment due to climate change and the need to select strains better adapted to new environmental conditions or emerging diseases - have prompted experimental hatchery seed production in Europe and New Zealand, with promising results. Hatchery production also enables the generation of triploid spat, which do not undergo maturation and can be sold year-round.

Within the context of strategic decisions required to ensure a consistent seed supply and the long-term sustainability of production, two particularly relevant issues warrant in-depth consideration. First, how to rebalance the value chain in light of the significant increase in seed costs. Second, how to leverage knowledge of genetic diversity and selective breeding to manage species distribution, control hybridization, and enhance resistance traits to specific environmental factors.

FIGURE 4.3
**Example of mussels on the sea bed in the Kingdom of the Netherlands**



## 4.2 ON-BOTTOM CULTIVATION

"On-bottom cultivation" or "bottom cultivation" can be defined as the cultivation of the shellfish directly in contact with the bottom, on what are known as mussel "beds" or "lays" (Figure 4.3). The mussels are not held in any form of containment device and are harvested either by dredge, by rake or by hand. This traditional technique is commonly used in the United Kingdom of Great Britain and Northern Ireland and in the Kingdom of the Netherlands.

In contrast to off-bottom cultivation, which is primarily conducted in intertidal areas, on-bottom cultivation can be implemented in both intertidal and subtidal zones. An example of on-bottom farming is described in detail in Chapter 5, while the key features and main challenges of mussel on-bottom aquaculture in the Kingdom of the Netherlands are summarised below.

### 4.2.1 Mussel on-bottom extensive farming in the Kingdom of the Netherlands

*Introduction and history*

The main production areas are located in the Wadden Sea and the Oosterschelde. The first concessions, or "plots," for mussel cultivation date back to 1870, when the government issued the initial licences. Since then, numerous changes have occurred in farming techniques, production areas and management strategies. Major marine engineering projects and geomorphological changes have underpinned this evolution.

Since the 1970s, mechanisation has enabled increased production, although output has remained constrained by limited space and the availability of seed. Production peaked at 46 000 t in 2018 and was approximately 30 000 t in 2022. Production and harvesting are highly mechanised, carried out by a fleet of specialised 30–35 m vessels, with a crew of five to manage all operations (Figure 4.4). The production areas are extensive, and the distances covered during operations are often considerable.

*Seed procurement*

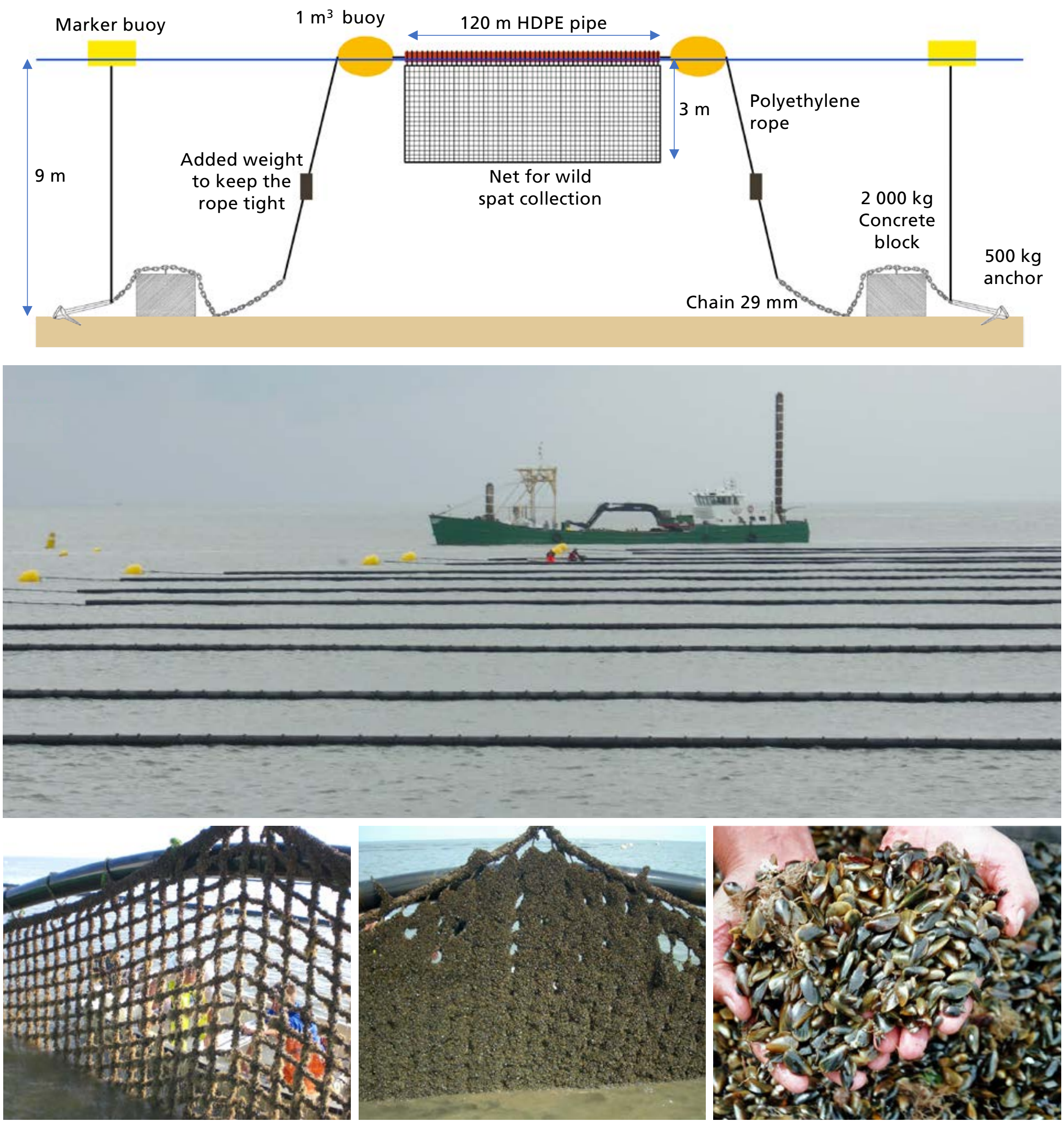
Seed harvesting on natural beds is carried out by dredging in subtidal areas during spring and autumn. This activity is now strictly regulated, based on periodic monitoring and in accordance with agreements among all relevant stakeholders.

When collectors are used, maximum recruitment is typically observed between May and June, and settlement may continue throughout the summer. The ropes or nets employed for recruitment (Figure 4.5) are stretched between poles for limited periods, generally from March to November. Depending on seasonal trends, one to three seed harvesting events may occur annually.

Seed from collectors is harvested using suction with Venturi-type pumps while the recruitment plots remain submerged.

FIGURE 4.4
**Workboats and equipment used in the Kingdom of the Netherlands**
(a) Example of mussels harvesting boat; (b) on-board equipment; and (c) example of dredges

FIGURE 4.5
**Example of mussel recruitment in Kingdom of the Netherlands**
Bottom photos, from left to right: small seed on net, big seed on net; and final collected seed






The harvested seed is then transferred to specially equipped vessels for transport to on-growing cultivation plots. Sowing is performed through openings along the sides of the boat, from which the water-mixed seed is released onto the seabed as the vessel moves. In a single operation, up to 80 000 kg of seed can be transferred.

*On-growing*

Over time and with accumulated experience, the areas designated for seed recruitment and on-growing have been more clearly defined. Site selection is influenced by several environmental factors, including sediment quality, which is closely linked to currents, salinity, turbidity and plankton availability. The risk of mussels being displaced by currents and wave action is also a critical consideration in determining the most suitable locations.

After seeding, mussels are not handled again until harvesting, which is carried out by dredging (Figure 4.6). The on-growing cycle typically lasts two to three years, with harvesting occurring between summer and autumn.

Mussel cultivation vessels are 30–40 m in length and capable of transporting up to 100 t of product. They are designed for long-distance navigation, as cultivation areas are extensive and often far apart. Starfish and crabs are removed onboard prior to landing.

### *Constraints*

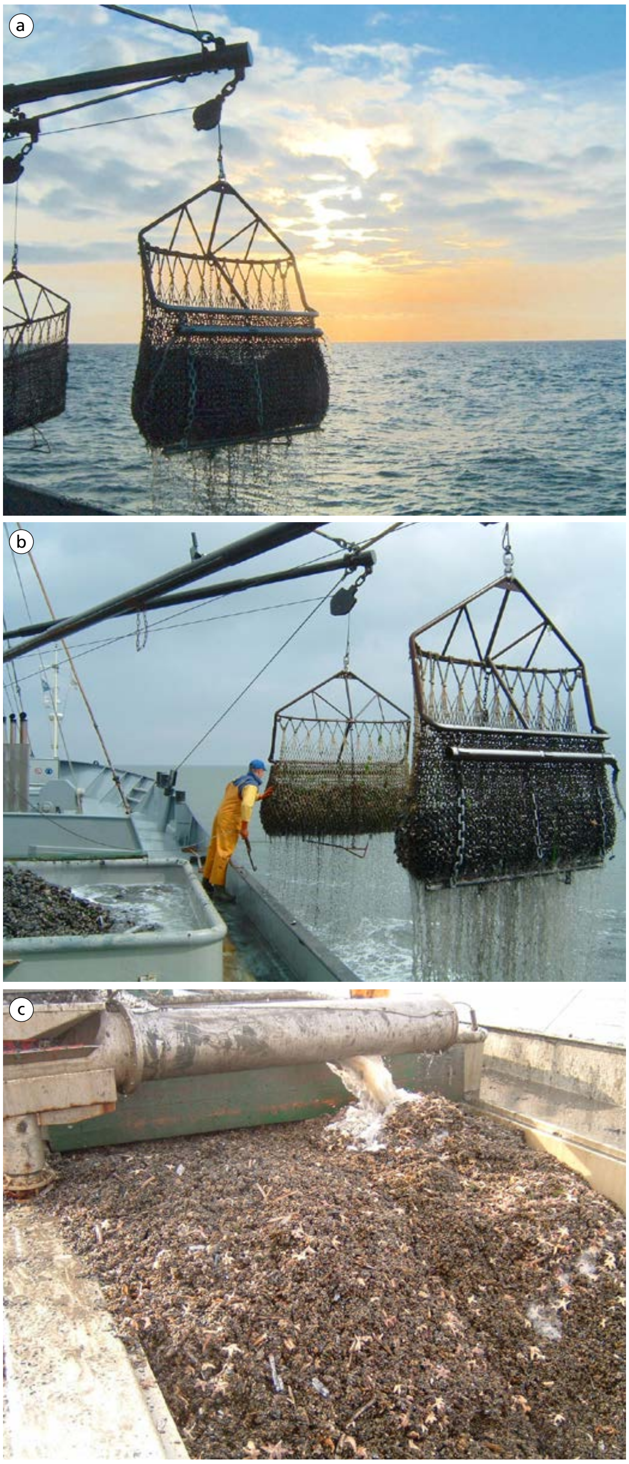
One of the main limitations of on-bottom mussel farming lies in its inherent nature as an extensive form of aquaculture, in which mussels are highly dependent on environmental conditions and seasonal variations.

Another limitation is the need to balance environmental and socio-economic sustainability. In this context, the seed supply strategy is particularly critical. Recruitment costs are considerable - approximately six times higher than harvesting from natural beds - which has prompted careful evaluation of the actual impact of fishing on wild stocks. Studies comparing areas open and closed to seed harvesting have shown that, in closed areas, densities remained low because the seed, although not harvested, was likely lost due to natural factors such as storms and predation. These studies also demonstrated that biodiversity in natural beds and cultivation plots is very similar. Furthermore, transferring seed to cultivation plots does not appear to significantly affect the overall ecosystem stock.

However, there is concern that a gradual shift from harvesting seed on natural beds to increased reliance on collectors could lead to higher total biomass, potentially intensifying competition for food and compromising the productive capacity of the system as a whole.

From a farming perspective, the seed collection and transfer techniques described above still require optimisation, as survival rates during and after transfer remain suboptimal. Efforts are also underway to mitigate predation through the use of devices such as “starfish mops” or “crab pots.” Overall, rising production costs underscore the need to improve yields.

FIGURE 4.6
**Mussel dredging (a and b) and the harvested product (c)**



Finally, adapting this complex and fragile system to the effects of climate change represents a major challenge for sustainable mussel farming

## 4.3 OFF-BOTTOM CULTIVATION

Off-bottom cultivation can be defined as the farming of shellfish using equipment that raises them above the seabed. The most common off-bottom method is the *bouchot* system, in which mussels are supported on poles, with the lowest individuals positioned less than one metre above the seafloor. Another method, typically employed for seed collection, involves suspending ropes between 0.5–1 m above the seabed.

### 4.3.1 Mussel off-bottom farming on *bouchot* in France

*Introduction and history*

A *bouchot* is defined as an ordered alignment of vertical poles, which are partially or fully exposed at low tide (Figure 4.7). This traditional mussel farming technique has been practised along the French coast for several centuries, with strategies varying depending on the production area. Mussels cultivated using this method are sold under the generic name *Moules de bouchot*. Since the 1950s, *bouchot* cultivation has developed primarily in Normandy, particularly in the Bay of Mont Saint-Michel.

From 2008 to 2020, French mussel production declined from approximately 80 000 t to 62 000 t, with *Moules de bouchot* accounting for roughly 75 percent of the total production. In 2018, the production of *Moules de bouchot* in Normandy and Charente reached 38 000 t, representing 77.5 percent of the national total of 49 000 t.

The tradition of cultivating mussels on *bouchots* dates back to 1235. According to historical accounts, an Irishman named Patrick Walton was shipwrecked along the French coast that year. As the sole survivor, he settled in the area and initially made a living by capturing birds using a net suspended above the sea and supported by large stakes driven into the mud. Walton observed that mussels attaching to these poles grew faster and were of superior quality compared to wild mussels. Consequently, he began cultivating them by planting lines of stakes for mussel attachment and growth, naming these stakes *bouchots*.

The current and most widespread production strategy involves growing mussels from natural spat, initially on ropes and subsequently on vertical wooden stakes planted in the foreshore. The rows of poles are aligned parallel to one another and may be arranged in single, double or triple rows. Production areas are accessed at low tide, either on foot or using tractors, barges or wheeled boats. This intertidal production

FIGURE 4.7
***Bouchots* are exposed to air with the falling tide in Normandy, France**

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method, with frequent exposure to air and sunlight, promotes shell hardening and develops a particularly strong adductor muscle.

### *Seed procurement*

In Normandy, along the Channel coast, natural mussel reproduction is limited. As a result, spat collection is carried out in spring (March-May) further south along the Atlantic coast in Charente, using ropes stretched horizontally over stakes planted in the foreshore. The ropes, typically consisting of 3–4 strands, are made from natural coco or hemp fibres. In favourable years, spat densities of up to 20 000–25 000 mussels/m can be collected.

Once the spat has settled, the ropes are either transferred to Normandy in May-June or used on-site for the remainder of the rearing cycle. Additionally, on the Atlantic coast, stakes bearing mussels from the previous year are often colonised by new spat, which is harvested and transferred to "socks' that are subsequently rolled onto new stakes.

### *On-growing*

On the Channel coast, spat ropes transferred from the Atlantic coast are installed on so-called *chantiers*, where the mussels continue to grow for approximately 4–5 months (Figure 4.8). At the end of summer, the ropes are retrieved, cut into sections, spiralled,

FIGURE 4.8

**Mussel seed ropes on the intertidal zone in Maine Père et Fils, France**

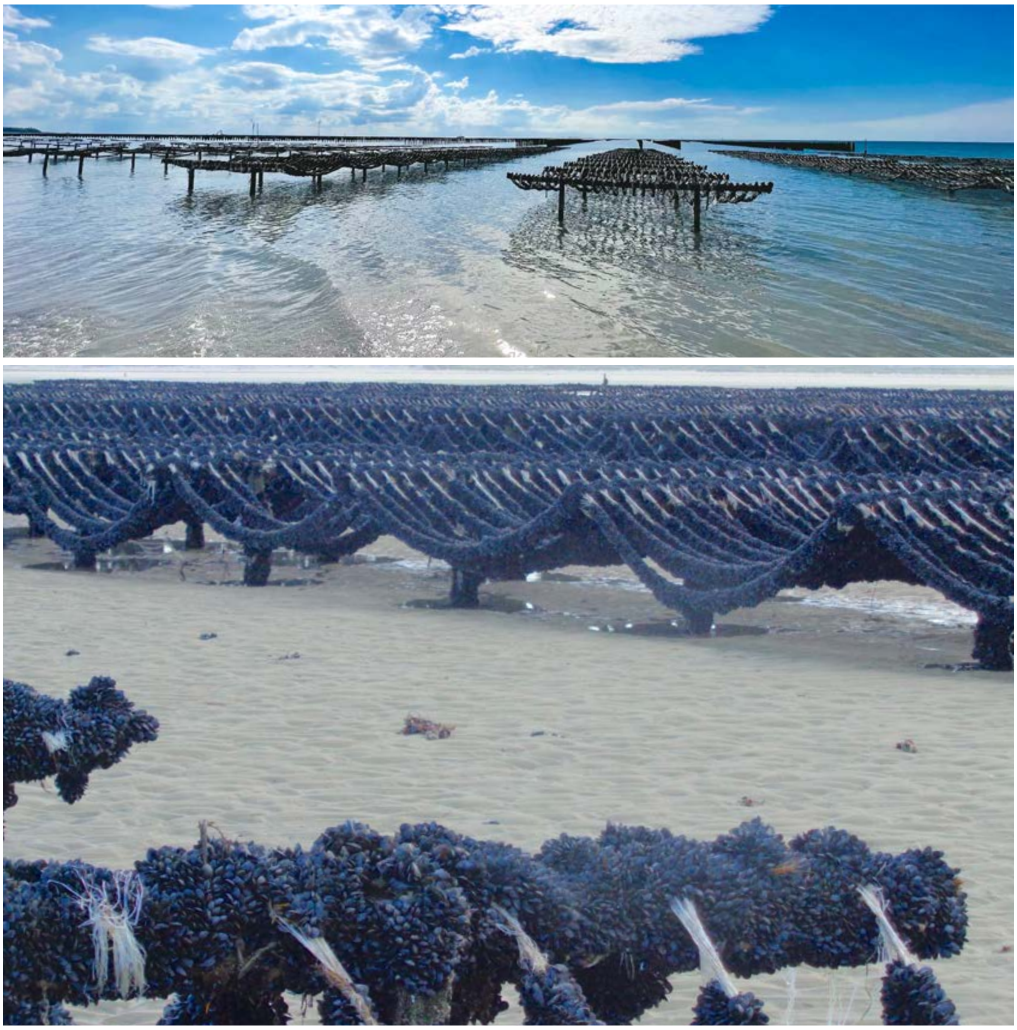

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FIGURE 4.9
**Mussels seed ropes spiralled on wooden poles (*bouchots*) in Maine Père et Fils, France**

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and fixed to the poles (Figure 4.9), where they remain for an additional 10–12 months. Depending on their size, the mussels are subsequently harvested either to fill new poles or for sale. Overall, for a given year of spat recruitment, the rearing period on *bouchots* does not exceed 24 months. Beyond this period, the growth rate of the remaining mussels is low, and the resulting product is considered of mediocre quality. The official marketing period extends from mid-June to the end of February; however, if quality requirements, such as size and meat content, are not met, the season may be shortened.

In Normandy, the *chantiers* typically measure approximately 5 × 100 m and are located between rows of poles in the upper foreshore (see Figure 4.8). The ropes, generally 100 m in length, are laid horizontally about one metre above the seafloor and are exposed to air at low tide. The number of ropes per chantier varies; as a general rule, approximately three *chantiers* are required to seed one kilometre of *bouchots*.

On the Channel coast, rows of poles are consistently oriented perpendicular to the shore and arranged in parallel within the intertidal zone (see Figure 4.7). The configuration of the lines (single, double or triple), the spacing between lines, and the number of poles per line vary according to the production area, the degree of mechanisation, and the slope of the foreshore. *The Moules de bouchot* designation specifies the following limits: 350 stakes/triple line of 100 m, 250 stakes/double line of 100 m, and 200 stakes/single line of 100 m.

Stakes are traditionally made from oak with the bark left intact but are increasingly being replaced by square stakes (10 × 10 cm) of exotic wood, which are better suited to mechanised harvesting (Figure 4.10 and Figure 4.11). Poles are installed by driving them into the sand using a pressurised water hose. On average, stakes are renewed every five years. In Normandy, the portion of each stake available for mussel attachment may not exceed 3.5 m above ground level. For 4.5 m-long poles, with 2 m buried and 2.5 m above ground, approximately 3–3.5 m of small mussel rope is required to fully cover a single pole.

Throughout the rearing period, the stakes are carefully cleaned at their base and fitted with protective devices to prevent benthic predators from climbing and reaching the mussels (Figure 4.12). A minimum distance of 30 cm must be maintained between the ground and the mussels, ensuring a quality free of sand product.

FIGURE 4.10
**Mussel seed ropes on the intertidal zone in Maine Père et Fils, France**

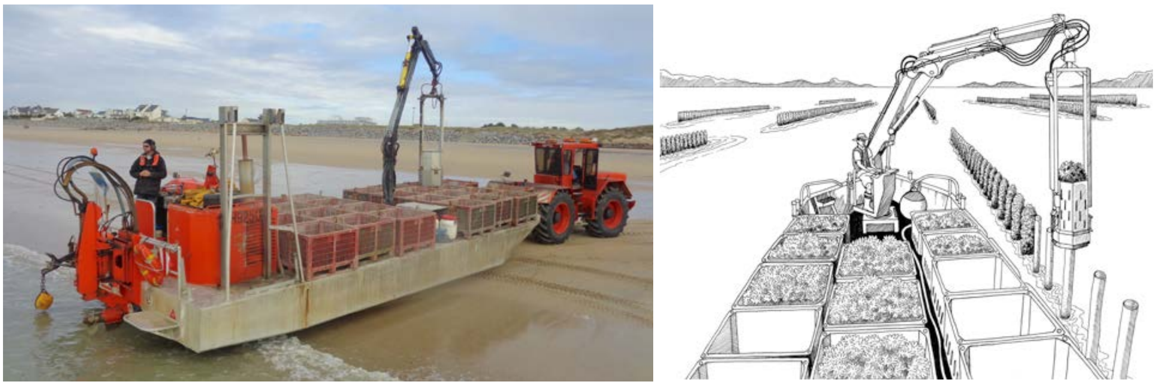

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FIGURE 4.11
**Harvesting mussels from *bouchots* poles**

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FIGURE 4.12
**Lower portion of the pole devoid of mussels and fitted with a predator-exclusion device**

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During the rearing period on *bouchots*, protective netting is applied to the poles to prevent losses due to waves and swell (Figure 4.13). This operation is referred to as *catinages*. Concurrently, mussels may be harvested, placed in tubular nets, and used to seed new poles in an operation known as *boudinage*.

In Normandy, after the ropes are spiralled around the poles, it takes several months for the mussels to fully cover the pole, forming a thick and uniform sleeve. Following this initial growth, 3–4 *catinages* are typically required, with each operation repeated every 3–4 months. Final production per pole can reach 30–60 kg of mussels, with an average of approximately 90–100 mussels/kg.

On the Atlantic coast, where growth rates are higher, catinage is performed less frequently. However, the poles are thinned more regularly to regulate mussel density, promote uniform growth and minimize

FIGURE 4.13
**Mussels on the *bouchot* poles covered with a protection net**



losses. Spat and juvenile mussels recovered through this process are transferred into tubular nets (*boudinage*), which are then spiralled onto new poles. As observed with spat ropes, the mussels rapidly migrate out of the nets, forming a continuous sleeve around the piles.

### *Constraints*

The primary constraints in cultivation include predation by Atlantic dog whelk (*Nucella lapillus*), European spiny spider crabs (*Maia squinado*), European green crabs (*Carcinus maenas*), starfish (*Asterias rubens*), as well as fish such as seabream and birds including eider ducks, scoters and gulls. Infestation by *Mytilicola* may also occur during long-term farming. Fouling is controlled through periodic removal of epiphytic algae. Recently, a weakening of byssal threads has been reported, resulting in increased losses, although the underlying cause remains uncertain.

The commercial season typically spans 7–8 months, from mid-June to mid-February. Expansion of production areas, along with the number, density, and height of stakes, is strictly regulated according to the trophic capacity of the environment. Nevertheless, climate change and increasingly stringent certification requirements, as outlined in Section 2.2, are making it progressively more challenging to optimize the balance between product quality, environmental sustainability and economic viability.

## 4.4 SUSPENDED CULTIVATION

Suspended cultivation is the most widely adopted method for mussel farming worldwide. In shallow, protected waters, mussels have traditionally been grown on structures consisting of vertical poles staked into the seabed, supporting one or more beams from which ropes or socks containing mussels are suspended. Typically, these beams remain above the water surface. This traditional system persists in some lagoon areas, where the practice has been transmitted across generations.

In deeper waters or more exposed sites, mussels are instead suspended from floating structures, such as rafts or long-lines. Accordingly, the supports used to hold ropes or socks with mussels are highly variable. For clarity, they can be categorized as follows:

- *Simple staked supports*: Poles driven into the seabed, as observed in the Thau Lagoon in France and the Po River Estuary in Italy.
- *Long-lines in sheltered coastal areas*: This configuration is the most commonly employed in China and other countries with protected sites.

- *Offshore long-lines*: Designed for moderately to highly exposed sites, such as in the Adriatic Sea in Italy, where farms are located 2–3 nm from the coast.
- *Floating rafts* (>300 m²): For example, the *bateas* in the Rías of Galicia, Spain, or smaller mussel rafts used along the northern Atlantic coast of the United States of America. These rafts typically rotate around a single mooring line.
- *Large floating mussel rafts with mooring grids*: Similar in design to fish cages, as used in the United States of America.
- *Submersible rafts*: Recently developed in the United States of America, these rafts feature pipes that can be filled with air or water to adjust buoyancy.

The supports where mussels are attached, commonly referred to as "droppers," can also vary significantly (Figure 4.14):

- *Simple ropes*: Mussels attach directly to the rope via their byssal threads without nets or additional support. This method is generally used for seed recruitment or early on-growing stages.
- *Cotton-wrapped ropes*: Mussels, either freshly declumped or in small clusters, are tightly wrapped in cotton nets with mesh sizes smaller than the shell width, allowing mussels to attach to the rope and each other. The cotton nets disintegrate after a few days. Nets can be simple wrappings or tubular, with mussels inserted manually or mechanically.
- *Tubular plastic nets*: Mussels are introduced manually or mechanically into polyethylene nets, which support the weight of the mussels. Mesh sizes are adapted to growth stages. Finer cotton nets may also be used initially to prevent early losses.
- *Adherent tubular nets*: Placed later in the growth cycle to prevent detachment and loss of heavier mussels.
- *Protective nets*: Tubular or other nets surrounding droppers, but not in direct contact with mussels, serving usually as protection against predators.
- *Ropes with transverse pegs or sticks*: Pegs inserted across the rope strands provide additional attachment points to support mussels as they gain weight during growth.
- *Socks with polyethylene netting and transverse pegs*: Similar to ropes with pegs, these socks facilitate mussel retention as individual mussels increase in mass.

FIGURE 4.14
**Typologies of droppers in mussel culture**

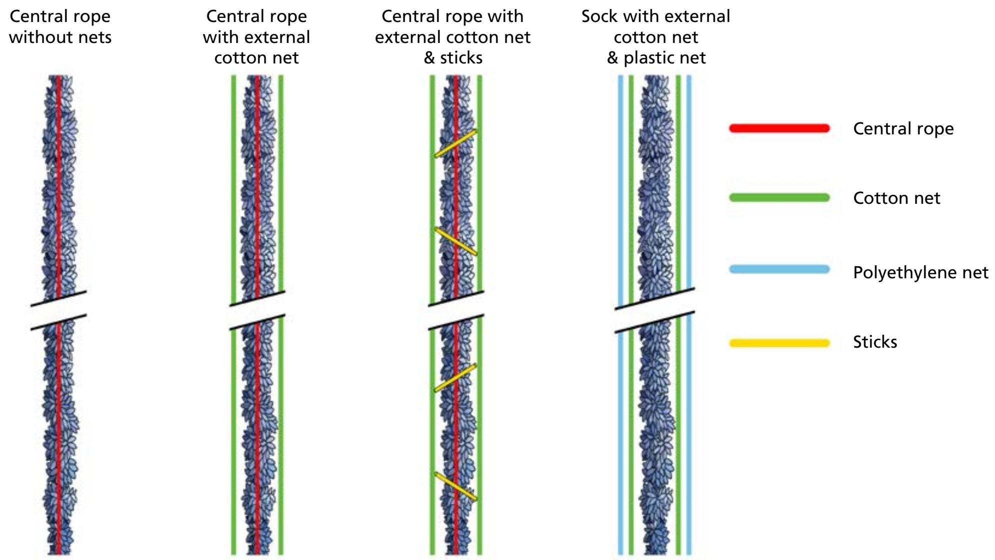
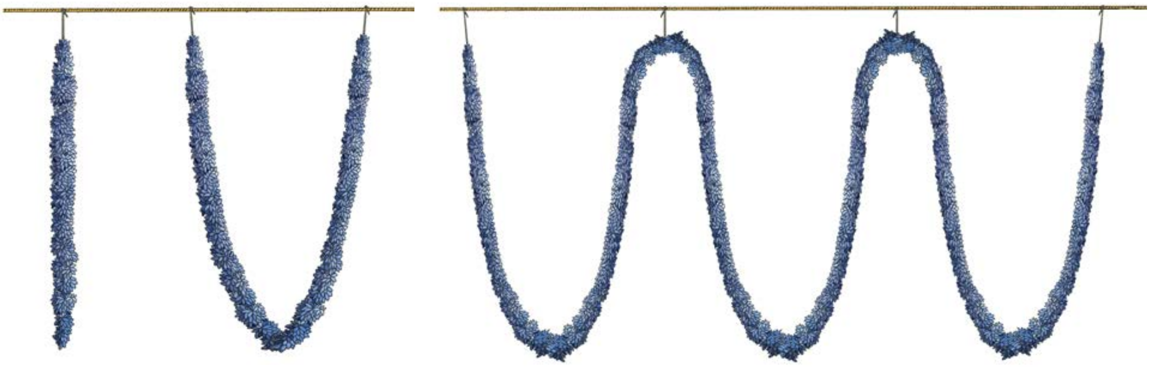


FIGURE 4.15
**Possible arrangement of mussel culture droppers on support lines**




Furthermore, the droppers, whether composed of ropes or polyethylene nets, may be configured as single, double, or continuous lines, with their length varying according to the farming area and corresponding water depth (Figure 4.15).

Finally, each producer may adopt a wide range of combinations of the techniques described above, selecting and adapting them as deemed most suitable to local environmental conditions, farming objectives and operational constraints.

### 4.4.1 Suspended cultivation on *bateas* in Spain

*Introduction and history*

Mussel farming in the *rías* of Galicia, along the Atlantic coast in northern Spain, developed after the Second World War and currently comprises approximately 3 400 floating platforms, known as *bateas* (Figure 4.16). The development and success of this activity are largely due to the exceptional phytoplankton productivity of the coastal waters.

Winds blowing from land toward the sea generate upwelling phenomena, bringing deep, nutrient-rich waters to the surface. This process stimulates intense phytoplankton blooms that coincide with the end of the mussel breeding season and the onset of early growth. These winds also facilitate wide larval dispersal throughout the surrounding marine environment. Mussels produced in this region are marketed under the Protected Designation of Origin (PDO) *Mejillón de Galicia*.

Between 2019 and 2023, production in Galicia - representing approximately 98 percent of Spain's national mussel output - declined from 255 500 to 178 000 t

FIGURE 4.16
**Examples of mussel rafts or *bateas* culture in Galicia, Spain**

(Jacumar data), corresponding to a 30 percent reduction. This decrease is mainly attributed to the effects of climate change on marine environmental conditions.

Up to the period 2000–2010, most production was directed to the processing industry (canned and frozen products), with peak sales occurring during summer months. More recently, increasing competition from Chile in European markets has driven a shift toward fresh product marketing, both domestically and for export, with harvesting now concentrated primarily in the autumn-winter period. Between 2000 and 2024, the share of production destined for processing is estimated to have declined from 27–60 percent.

### *Seed procurement*

Mussel spat is traditionally collected during winter from rocky intertidal zones bordering the *rías* by manual scraping, and also through the use of recruitment ropes suspended beneath the *bateas* from March to July each year. In favourable conditions, recruitment yields can reach 10–15 kg of seed per rope, or approximately 1.5–1.75 kg/m of rope.

Seed collected from natural rocky substrates is often preferred by producers, as it is considered to exhibit stronger attachment capacity and greater resistance during the on-growing phase.

### *On-growing*

The *bateas* are floating rafts covering an area of approximately 300–500 m² (Figure 4.16). They are traditionally constructed from eucalyptus wood and typically equipped with four to six floats positioned beneath the structure and connected to a single mooring point located on one side. The mooring system consists of ropes, a chain, and a mooring block that ensures the stability of the raft under varying hydrodynamic conditions.

Originally, the floats were made entirely of wood; however, modern designs employ steel floats coated with polyester, fibreglass-reinforced polyester, or polyethylene improving durability and buoyancy control (Figure 4.17a).

The wooden frame, which forms the working platform at the surface, is composed of main longitudinal beams supporting the floats, overlaid by secondary transverse beams arranged perpendicularly. The entire structure is further reinforced by lateral side beams, which serve as mooring points for service vessels, and by a central beam from which the anchoring system (bow) extends.

The rearing ropes (droppers) are attached to smaller cross-supports fixed perpendicularly to the secondary beams (Figure 4.17b). These supports distribute the weight of the mussels evenly and facilitate maintenance and harvesting operations.

FIGURE 4.17
**Mussel *bateas* construction details**
(a) Floats under the main wooden frame; and (b) Secondary wooden beams and hanging ropes

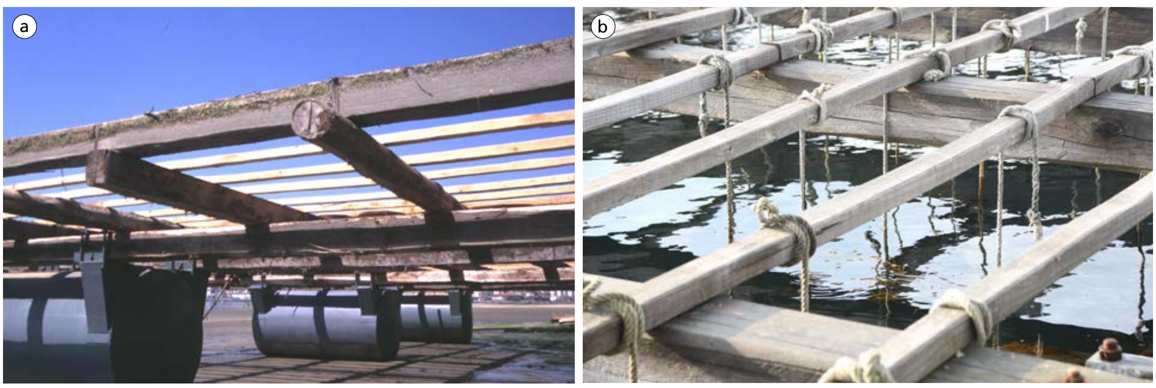


FIGURE 4.18
**Mussel socking and wrapping onboard**
(a) Mussel socking onboard; (b) Socking into fine-mesh cotton tubular net; and (c) Wrapping cotton net around mussel rope



A single *batea* supports between 300 and 500 ropes, each measuring 5–15 m in length. Some ropes are designated for seed collection, while the majority are used for on-growing (fattening ropes generally measure 10–12 m). The average annual production per *batea* ranges from 40–80 t, depending on site conditions and management strategies adopted by the producer. At the end of the production cycle, the mean yield is estimated at approximately 20 kg/m of on-growing rope, although in some cases, individual ropes may reach up to 300 kg.

The first socking operation, using seed collected from natural rocky areas, is carried out during the winter period. After 4–6 months, the ropes are lifted for a first thinning. During thinning, mussels are detached from the ropes and re-socked at a lower density onto new ropes. Typically, each initial rope yields 2 to 4 new ropes, depending on mussel density and growth conditions. In certain cases, the resulting biomass increase can be even higher. Throughout the production cycle, ropes are periodically lifted, thinned, and re-socked one or two additional times to maintain optimal growth and minimize losses.

Socking consists of simultaneously feeding mussels and the supporting rope into fine-mesh cotton tubular nets (Figure 4.18). This operation is largely mechanized, employing adjustable endless-screw (auger) machines. The net temporarily holds the mussels together and around the rope until they attach to it and to each other by means of their byssal threads. After several days, the cotton net degrades and disintegrates naturally.

Whereas ropes were formerly made from esparto or other natural fibres, they are now predominantly constructed from nylon or polyethylene to ensure durability and resistance to marine conditions. Some producers also use plastic pegs or sticks, inserted transversely between the rope strands at regular intervals of approximately 40 cm, to prevent mussels from detaching as they gain weight. Ropes obtained from recycled fishing nets or used ropes can also be used.

For harvesting, ropes are lifted from the water using specialized service vessels equipped with cranes. During lifting, a collection basket is positioned beneath the ropes to recover any mussels that may become detached during the operation (Figure 4.19).

Once the commercial size of 7–10 cm has been reached, the mussels are sorted by size and destined for marketing.

FIGURE 4.19
**Mussel harvesting**
(a) Lifting mussel ropes; and (b) Harvesting mussel from ropes fitted with transverse pegs




### *Constraints*

Current climate change trends appear to be causing a weakening of wind regimes and a reduction in upwelling intensity, accompanied by increasingly frequent periods of drought. In addition, the rise in average sea temperatures has resulted in an earlier onset of spawning, creating a temporal mismatch between the periods of larval abundance and phytoplankton availability, which negatively affects recruitment success.

An increase in predation by gilthead seabream (*Sparus aurata*) on natural mussel beds has also been observed, contributing to a progressive decline of wild stocks. Furthermore, harvest suspensions due to the occurrence of toxic algal blooms (HABs) are becoming increasingly frequent, further constraining the stability and profitability of mussel production in the region. The frequency of suspension periods is also associated with increasing heavy rainfall events.

## 4.4.2 Suspended cultivation in long-lines in the Adriatic Sea

Suspended mussel cultivation using offshore long-line systems is a traditional practice in the Adriatic Sea, along the Italian coast (Figure 4.20). An example of cultivation employing droppers composed of mesh socks is described in detail in Chapter 6.

It is noteworthy that the main mussel farming technique used in China is based on a similar long-line system, employing floating or sub-surface long-lines from which single droppers of 2–4 m in length are suspended. The work vessels used in these operations are also comparable in design, featuring lateral star-wheels that enable the boat to move along the headline as it is lifted above the water surface for sock deployment or retrieval.

FIGURE 4.20
**Example of a long-line mussel farm in the Adriatic Sea**

### 4.4.3 Other suspended cultivation systems

Suspended mussel farming represents by far the most widespread production technique globally, due to its high productivity, adaptability to different marine environments, and efficient use of the water column. The method allows optimal exposure of mussels to plankton-rich surface waters while minimizing benthic predation and risks of sediment accumulation on mussels.

In addition to the well-known Mediterranean and Atlantic systems, several noteworthy examples illustrate the diversity of suspended culture practices worldwide. In New Zealand, extensive use is made of continuous rope systems, where mussels are grown on uninterrupted droplines extending several metres below the surface. This technique allows for mechanized handling, efficient thinning, and high stocking densities, resulting in substantial yields of the endemic New Zealand green-lipped mussel (*Perna canaliculus*).

In Chile, one of the largest global producers, mussels are cultivated on floating long-line systems in the sheltered fjords and channels of the southern regions (notably Chiloé and Los Lagos). These farms are characterized by large-scale operations and processing infrastructure, and high levels of export-oriented production, primarily of the Chilean mussel (*Mytilus chilensis*).

Similarly, in China, the world's leading mussel producer, suspended farming is carried out using floating and sub-surface long-lines, typically equipped with 2–4 m droppers. The system benefits from high nutrient availability, favourable hydrodynamic conditions, and technological innovations such as the use of star-wheel vessels that facilitate efficient sock deployment and harvesting operations.

Overall, the success of suspended mussel farming in these regions highlights its technical flexibility, economic viability, and potential for adaptation to diverse environmental and operational contexts.

## 4.5 OVERVIEW ON COMMONLY USED EQUIPMENT

This section introduces the different long-line configurations that can be used for farming mussels and some equipment that is common to all systems of cultivation.

### 4.5.1 Long-line typologies and components

*Typologies*

Long-lines comprise all the components required to support a main rope (headline) within the water column at a predetermined depth. The headline, which runs parallel to the sea surface, serves as the primary structural element supporting various cultivation devices, such as droppers, socks, or spat collectors. It is maintained at the desired depth through an array of buoys or floatation units, while anchors and mooring lines ensure system stability under hydrodynamic forces.

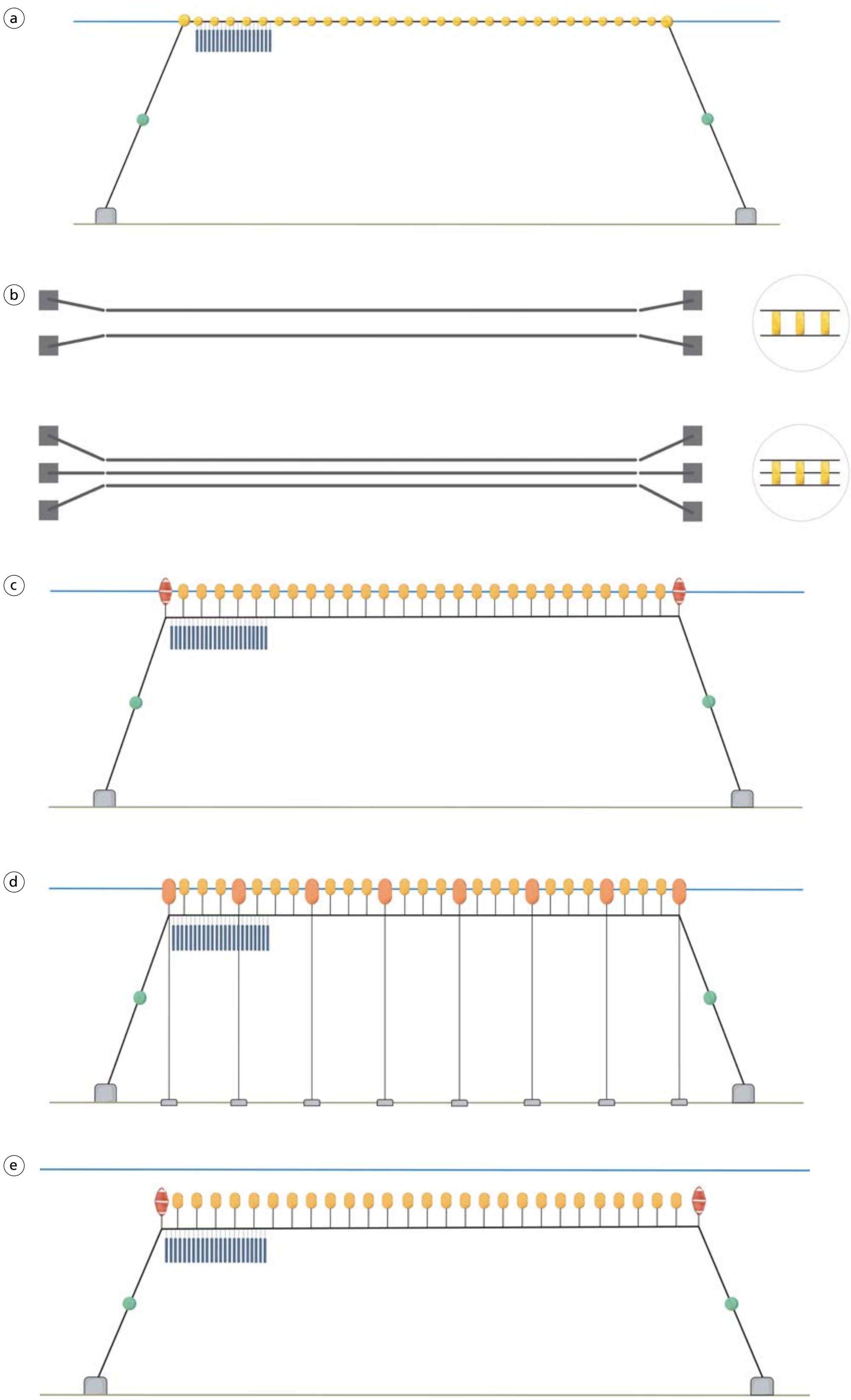
The three principal configurations of long-line systems are classified according to the depth of the headline and associated buoyancy elements (Figure 4.21):

- "Floating" when both headline and buoys remain on the surface;
- "Sub-floating" when only the buoys stay on the surface, whilst the headline is suspended a few metres beneath (see Figure 6.3);
- "Submerged" when both headline and buoys remain under the surface, so that nothing is visible from the boat.

From the sea bottom to the surface, a long-line consists of:

- The anchorage devices to which the mooring lines are linked;
- The mooring lines that are maintained under tension by buoys installed at different levels;
- The headlines that support the cultivation devices, which are fastened to the mooring lines at the upper end towards the surface;

FIGURE 4.21
**Different type of long-line structures**
(a) Floating long-line; (b) Multi-headlines floating long-line; (c) Sub-floating long-line; (d) Sub-floating long-line with intermediate legs; and (e) submerged long-line



- The buoys of different shapes and sizes that keep the whole system under tension in a single plain.

From this basic composition, some variations must be mentioned:
- The presence or not of intermediate mooring lines, also called intermediate legs;
- The possible use of parallel headlines with reduced distance between them.

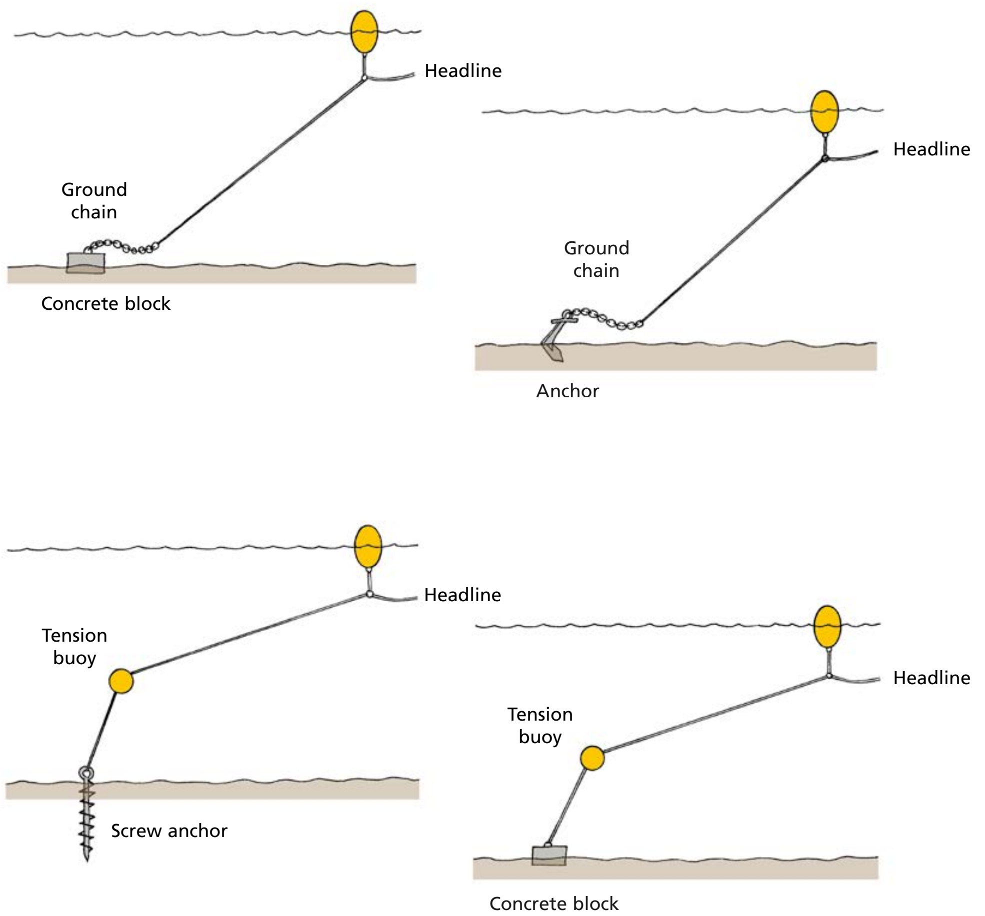
### *Components*

The commonly used components to build long-lines are listed below:
- Anchoring devices (concrete blocks, anchors, screw anchors, etc.);
- Ground chain or submerged buoys to allow the structure to be correctly tensioned;
- Headline ropes and mooring line ropes;
- Surface buoys of different shapes and sizes;
- Shackles with bolt, nut and safety pin, thimble and bulldog grip.

Different anchoring systems can be implemented to allow the long-line to adapt to the forces applied to it by currents and waves (Figure 4.22). These systems will allow the elongation of the mooring line when applied forces increase.

Mooring lines can be designed with a ground chain or with an intermediate submerged buoy. In the first case, the mooring line will be kept under tension between the surface buoys that push up and the heavy stainless steel ground chain that pulls

FIGURE 4.22
**Long-lines mooring systems**



down. When the forces applied on the system increase, the chain is lifted from the bottom with consequent elongation of the mooring line. In the second case, by using an intermediate submerged buoy, the lower part of the mooring line will be kept under tension by the vertical force applied by the buoy. When the forces applied on the system increase, the angle of the mooring line at the level of the submerged buoy increases with consequent elongation of the mooring line.

The estimation and calculation of the applied forces, the choice of the most suitable system and the sizing and design of the mooring line will have to be done by specialised engineers. In some cases, in typical marine conditions, it will be possible to replicate existing standardised mooring systems.

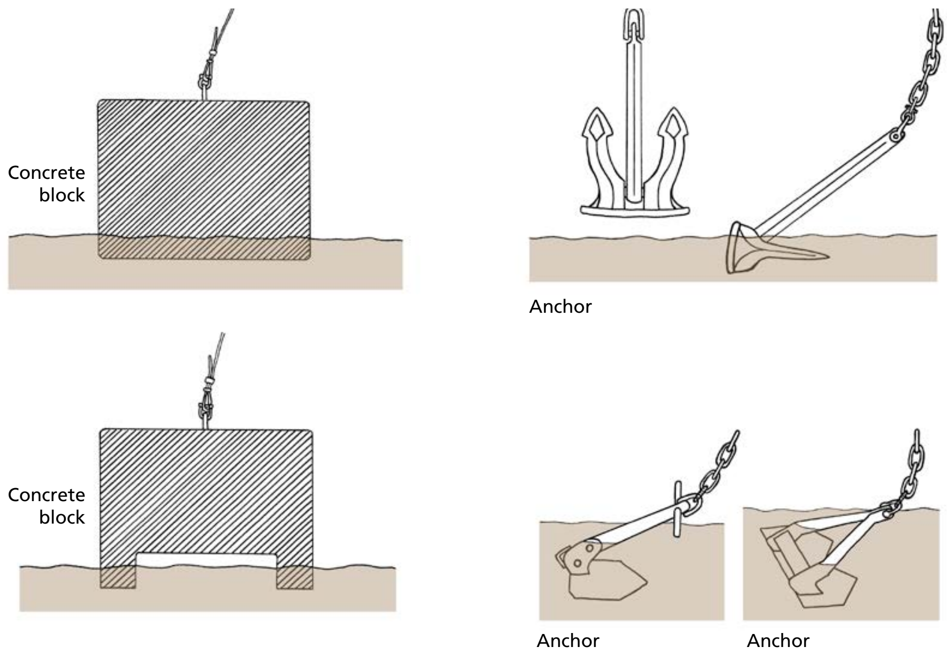
### *Concrete blocks and anchors*

The weight and the characteristics of concrete blocks or anchors is part of the calculation and design above (Figure 4.23). It is recommended to always consult expert companies to undertake these calculations. Under sizing can be deleterious and make all the equipment unusable.

Reinforced concrete blocks for anchoring can be built on site and then deployed in the chosen positions on the seabed. There are two main typologies: a simple cubic block or a concave cavity block where the lower surface is partially empty. In all cases, the total weight will have to be sufficient to counteract the traction forces applied to the long-line and to ensure that the block cannot slip on the seabed. Concrete blocks are recommended for sandy or muddy seabeds.

Many anchors, designed for fish cages and long-lines, are available on the market. As stated above, an expert should do the size calculation, with regard to the total weight and to the inclination of the anchor/mooring line.

FIGURE 4.23
**Long-lines anchoring devices**




### *Buoys*

A wide variety of buoy shapes and volumes are available on the market. Because buoys are often bulky and costly to transport, farmers and farm designers typically prioritize locally available products.

While the shape, volume, and positioning of buoys have only a limited influence on the final quality of the mussel product, they can have a significant effect on yield. In particular, strong or frequent hydrodynamic forces (kickbacks) transmitted through the buoys may cause mussels to slip along the rope or detach from the central net, resulting in partial or total loss of the stock to the seabed. Proper selection and arrangement of buoys are therefore critical to maintaining rope stability and optimizing production efficiency.

The buoys that keep the headline in position can be used underwater or on the surface. In the first case, they should be filled with polyurethane foam to avoid the walls collapsing under the pressure they are subjected to depending on the depth they will be situated. In the second case, except for buoys of primary importance to the stability of the whole system, filling with pressurised air is sufficient.

The surface buoys are usually made from moulded plastic and can be spherical, bi-conical, or cylindrical. The shape, the position and the level of immersion will determine the way the buoys move vertically in the water as well as the range of these movements. Consequently, the buoys' movements will have an effect on the attachment of the mussels to the socks. For instance, a bi-conical buoy that is half submerged will have more sudden movements compared to the same buoy that is almost fully submerged. In the same way, the stress on the whole long-line will be reduced in the case of submerged long-lines.

In some cases, floats can be homemade from HDPE pipes. These buoys are particularly suitable for exposed sites. Furthermore, their shape avoids abrupt movements under the effect of waves, reducing the risk of breakage of the long-lines and mussels' detachment.

Beyond the characteristic of a single buoy, the number of buoys along the headline is another important factor in managing the whole system. When using large volume buoys with a greater distance between them, the mussel socks near the buoy will be submitted to completely different conditions when compared to another mussel sock that is more distant. Under these circumstances, mussel socks situated near to the buoys are frequently damaged. By using numerous smaller buoys, this scenario can be avoided, but the installation and maintenance is much more time consuming.

### 4.5.2 Mussel declumping and grading equipment

As introduced in Section 2, mussels produce byssal threads, which enable them to attach both to substrates and to one another, forming clusters. At the same time, as in many other bivalve species, individuals within the same batch exhibit variable growth rates, necessitating periodic grading to prevent excessive size heterogeneity.

Under typical growing and marketing conditions, achieving uniform batch sizes requires that mussels be separated from each other and from the substrate as a prerequisite for subsequent size selection (grading).

Regardless of the farming technique employed, declumping and grading equipment form the foundation of effective farm management. While the specific machinery may differ between countries or operators, the underlying principles described in the examples below remain consistent. Numerous variations and small adaptations are possible to accommodate particular operational requirements. Consequently, it is recommended to consult multiple specialized suppliers when designing facilities to compare equipment options and select those that best meet specific needs.

The equipment described can be operated either onboard workboats or in land-based facilities, depending on the production system and operational preferences.

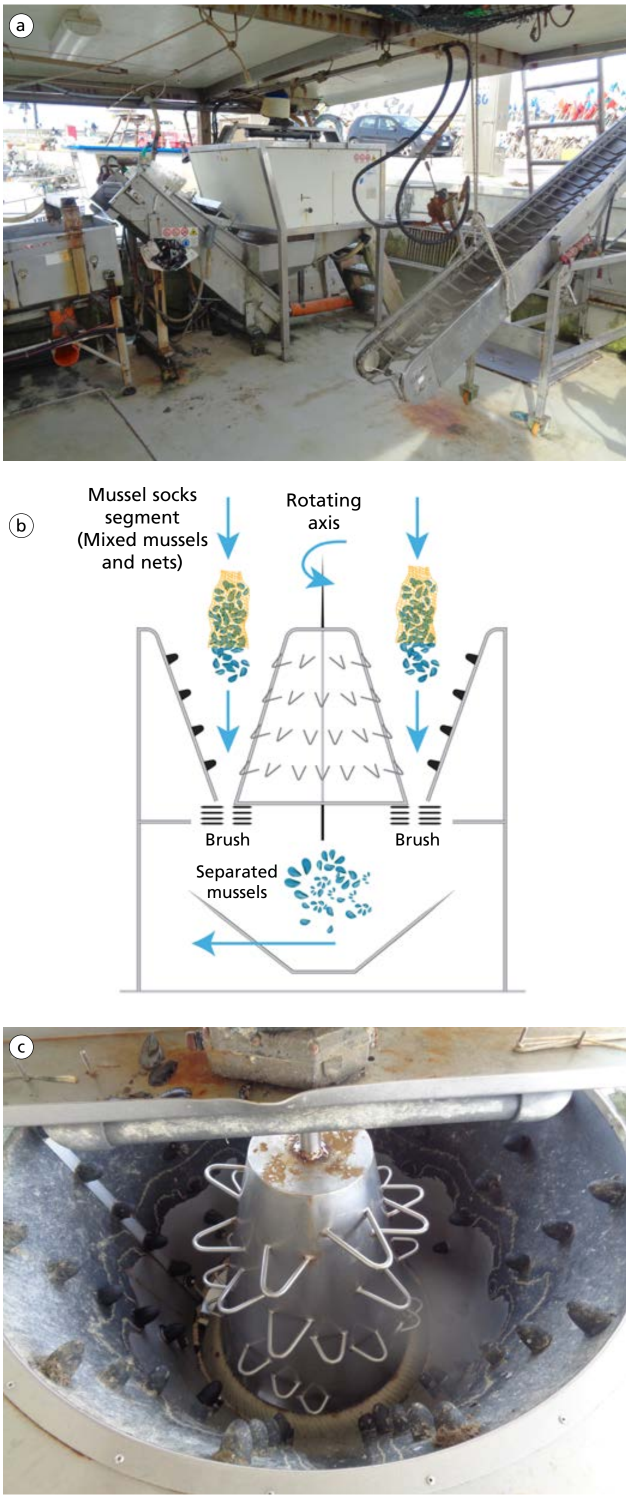
#### *Conical declumper*

Declumping is the process by which mussels are separated from each other and from the plastic net, preparing them for grading and subsequent processing. In operation, mussel clumps are deposited into the top of the declumping machine. As the internal cone rotates, it brushes the mussels against protruding knobs attached to the outer inverted cone hopper (Figure 4.24).

As the mussels catch on these knobs, their byssal threads are broken, allowing individual mussels to be separated. The mussels then fall through the gap around the central cone at the bottom of the hopper. Once separated, they are conveyed onto grading equipment for size assessment, while the plastic nets are manually removed by the operator.

A water spray bar located at the top of the declumper, together with the brush positioned at the base of the cone, helps to clean the mussels as they tumble through the machine, ensuring both efficient declumping and preliminary washing.

FIGURE 4.24
**Mussel conical declumper**
(a) Declumper external view; (b) Diagram showing the section; and (c) Declumper internal view

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### *Graduated vibrating mussel grader*

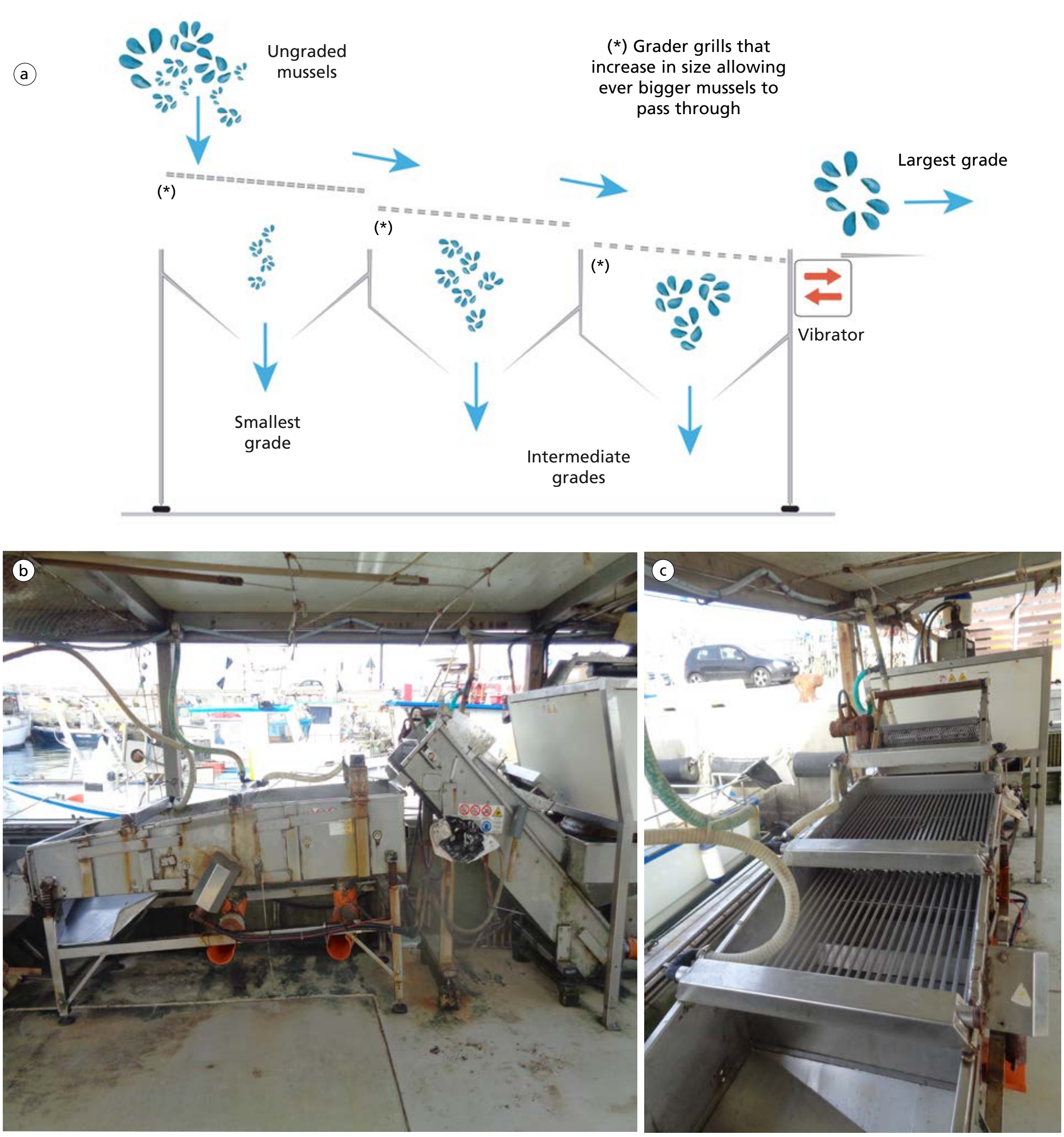
The vibrating grader separates declumped mussels based on size by conveying them over a series of parallel bar grills with progressively larger apertures (see Table 4.1). Grading is conducted horizontally, with an operator positioned in front of each grill to assist in fully separating any mussels that remain partially clumped (see Figure 6.34).

Mussels first fall onto the smallest-aperture grill, allowing only the smallest individuals to pass through, while larger mussels continue to the next grill under the combined effects of vibration and manual guidance by the operator. This process is repeated over successive grills with increasing bar spacing (Figure 4.25).

The number of grills depends on the grader model; in the example described, there are three layers, producing four distinct size grades. The grills are slightly inclined downward, so that the feeding end is higher than the exit end leading to the subsequent grill or collection chute. In some models, the height and angle of inclination can be adjusted to optimize mussel movement.

The combined action of the inclination and vibrations generated by electric motors conveys the mussels across the grills. Additionally, the grills are interchangeable, allowing the grader to be adapted for sorting different mussel size ranges as required.

FIGURE 4.25
**Horizontal vibrating mussel grader**
(a) Diagram showing the movement of mussels through the grader; (b) and (c) Horizontal vibrating grader






This grading system, as illustrated in the examples below, relies on mussel thickness as the primary selection criterion. Due to their shape, mussels naturally orient themselves horizontally when falling onto the grill, aligning parallel to the bars. They pass through the bars only if their thickness is smaller than the spacing between them.

Commercial size specifications vary depending on production region, farming techniques and consumer preferences. For example, in Mediterranean markets, mussels weighing 20–25 g typically have a shell thickness of 20–25 mm. Smaller market sizes, around 10–15 g, correspond to thinner mussels.

An example of a set of interchangeable grills for sorting Mediterranean mussels is presented in Table 4.1. This set allows grading of mussels from an average weight of 0.5–1 g (thickness 5–6 mm) up to 20–25 g (thickness 20–25 mm), providing flexibility to meet varying commercial requirements. This table is provided for illustrative purposes only. Individual farmers may select grills with spacing tailored to their specific needs,

TABLE 4.1
**Grader grills with parallel bars**

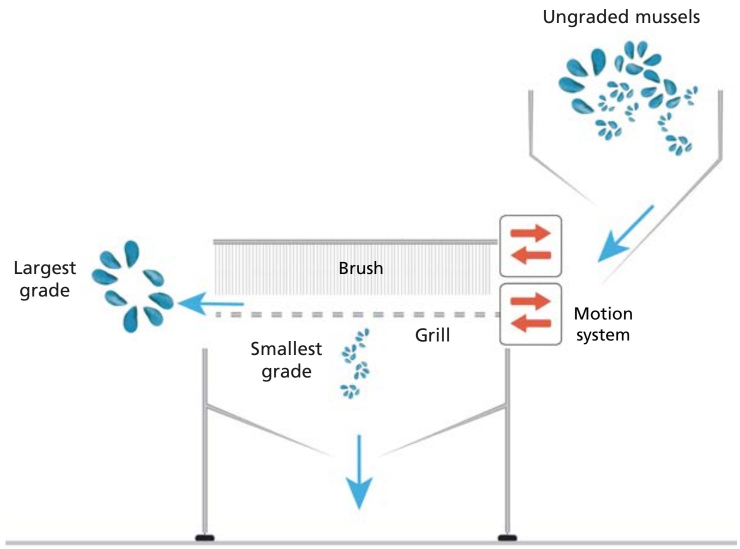
| Space between the parallel bars (mm) | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 |
|---|---|---|---|---|---|---|---|---|---|

including intermediate sizes not listed in Table 4.1, to suit their production system and market requirements.

### *Straight brush grader*

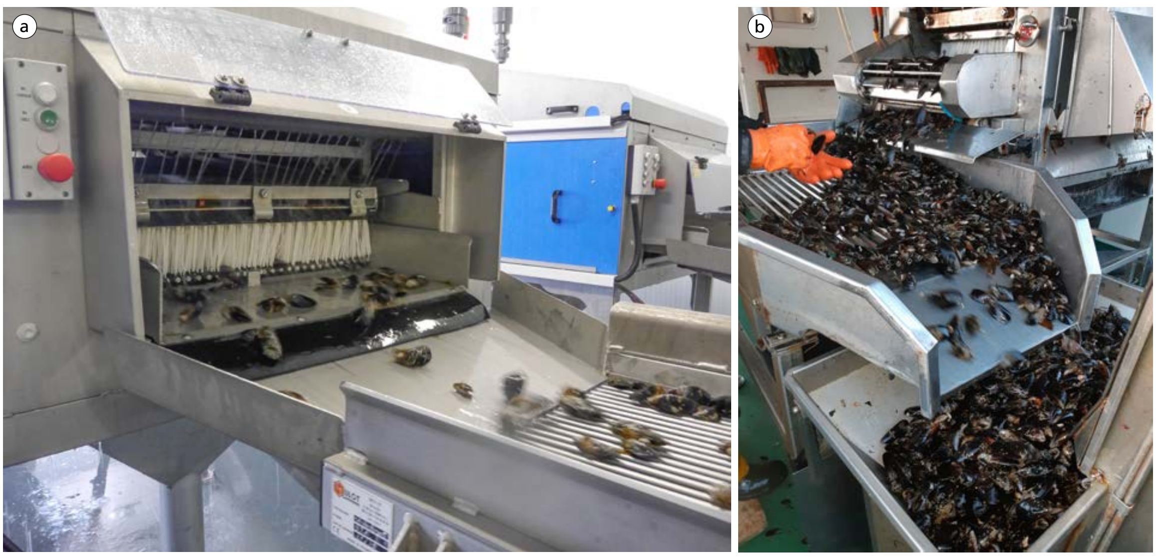
Separated mussels are deposited into a hopper at one end of the grader. Inside the metal housing, a grill composed of parallel metal bars is positioned beneath a set of brushes. These two elements move in opposite directions, and as the mussels come into contact with the brushes, they are swept across the bars and through the grader's grill (Figure 4.26). Undersized mussels pass through the grill and are collected in a box located beneath the grader, while larger mussels exit via the chute and either proceed along the grading line for further processing or are collected in a separate box.

FIGURE 4.26
**Straight brush mussel grader**
Diagram showing the movement of mussels through the grader




A straight brush grader or a straight brush cleaner can be associated with a single grill horizontal grader as illustrated in Figure 4.27.

FIGURE 4.27
**Examples of straight brush cleaner (a) and single grill vibrating grader (b)**

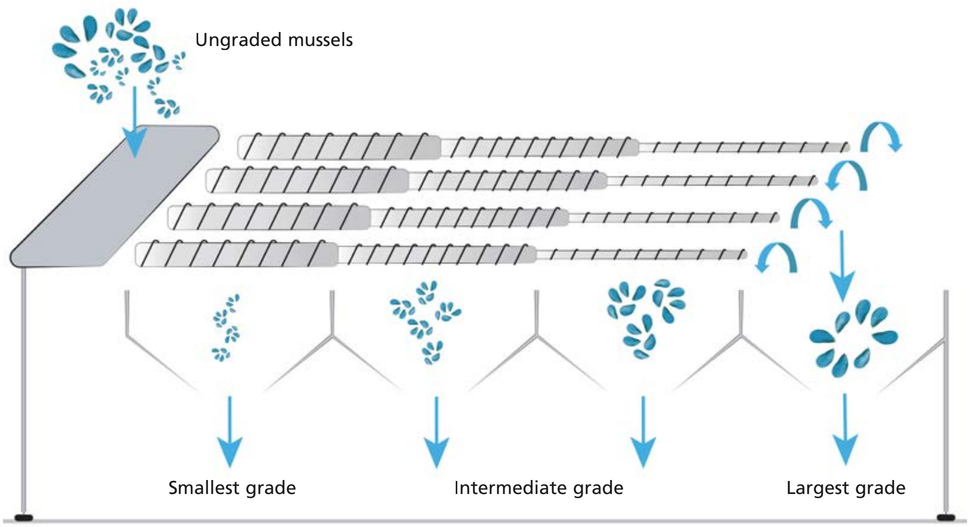


### *Rotating parallel bars grader*

This grader can only be used once the mussels have been declumped and separated. The grading mechanism consists of divergent parallel bars of gradually decreasing diameter, each equipped with a helical metal strip running along its length (Figure 4.28). As the bars rotate, they convey the mussels along the grader. At the entry point, where the mussels first drop onto the bars, the gaps between the bars are very narrow, allowing only the smallest shells to pass through. As the mussels' progress along the grader, the spacing between the bars gradually increases, enabling progressively larger mussels to fall through the gaps, with only the largest shells reaching the end of the grader. Each size grade is collected beneath the bars, either in boxes or onto conveyors, which transport the mussels for further processing. This design ensures a consistent and efficient separation of mussels by size, minimizing damage and optimizing downstream handling.

FIGURE 4.28
**Parallel bars mussel grader**
(a) Diagram showing the movement of mussels through the grader; and (b) Parallel bars mussel grader

(a)

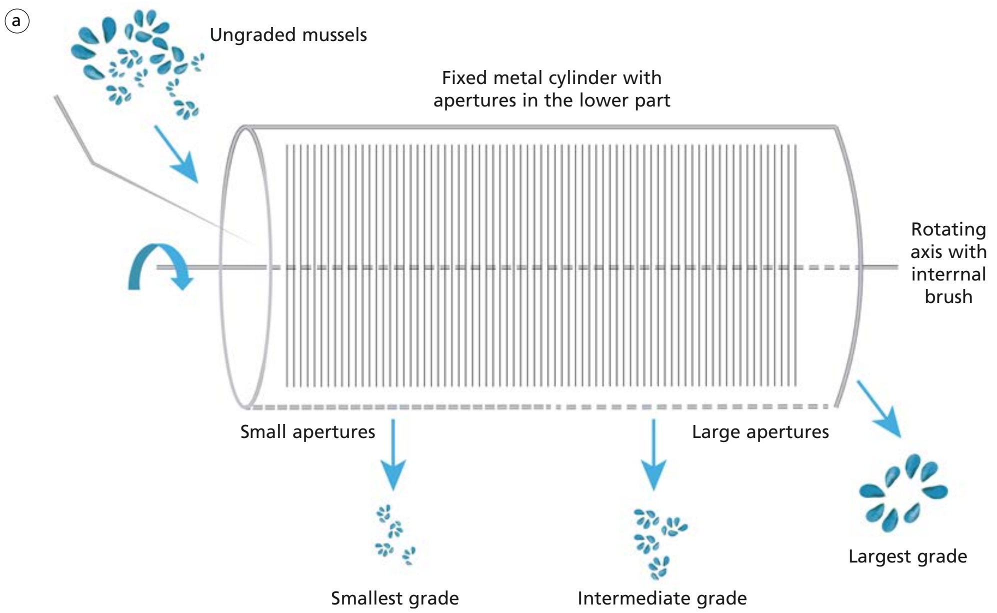



(b)

### *Rotating grader with internal rotating brush*

The rotating brush grader consists of a metal tube containing a helical brush that rotates along its length. Mussels are fed into one end of the tube and gradually moved forward by the rotation of the brush. The bottom of the tube is divided into two sections of parallel metal bars. In the first section, the bars are narrowly spaced, allowing only the smallest mussels to fall through. In the second section, the bars are slightly farther apart, enabling slightly larger mussels to pass through. The largest mussels continue to the end of the tube, where they are discharged. Beneath each section, a collection box receives the mussels according to their size grade, resulting in three distinct size categories (Figure 4.29). This design ensures efficient separation of mussels by size while minimizing damage during handling.

FIGURE 4.29
**Rotating grader with internal rotation brush**
Diagram showing the movement of mussels through the grader




## 4.5.3 Other equipment

### *Bagging machine*

If the harvested mussels are intended for sale as live shellfish, they must first be placed into bags or crates for offloading. They are then transported to a controlled land-based facility for further depuration and, if required, subsequent packaging (Figure 4.30). This ensures that the mussels remain alive and safe for consumption while meeting hygiene and quality standards.

### *Weighing elevator*

This machine features a conveyor belt that transports shellfish into a weighing unit, which can be pre-programmed to dispense an exact target weight of mussels (Figure 4.31). Once the desired weight is reached, the conveyor automatically stops, and the mechanical jaws holding the mussels open to release them into the receiving container. The weighing elevator can be used in any cultivation system where it is important to accurately measure and dispense precise quantities of mussels, ensuring consistency in packaging, stocking, or further processing.

FIGURE 4.30
**Mussel bagging machine (a) and filled mussel bags ready for transportation (b)**


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FIGURE 4.31
**Mussel weighing elevator**

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# 5. On-bottom cultivation in the intertidal or subtidal zone



## INTRODUCTION

Bottom cultivation means that the mussels are grown loose on the seabed or fundus. They are sown directly onto the ground and are not enclosed by any form of bag or basket. It is the simplest form of mussel farming, requiring the least amount of equipment, husbandry techniques and manual handling. It also most closely replicates the conditions in which mussels naturally grow and has been practised by humans for thousands of years. By sowing mussels onto predefined areas, known as "beds", the farmer is essentially creating a manmade mussel reef, imitating the natural structures that mussels create when they settle and cluster together on the seabed. The low-tech

FIGURE 5.1
**Dutch mussel dredging vessels**

nature of this cultivation system means that it is the simplest to set up and manage. However, the relative lack of control over the stock and its exposure to predation and environmental factors means that the mortality rate is higher than in other techniques and therefore a higher input of seed mussels is required to yield the desired amount of market size product.

## 5.1 SITE SELECTION

When selecting a site for bottom cultivation, there are several main factors that need to be considered.

### 5.1.1 Water depth and tidal range

Mussel beds should be situated in either intertidal or relatively shallow subtidal locations (<15 m). Below the depth of 15 m, the process of dredging becomes more challenging and inefficient. Also, below this depth, the availability of phytoplankton can decrease as there is less sunlight penetration which is an essential element that these organisms need to live, grow and reproduce. A reduction in this vital food source results in slower growth rates and a reduction in the quality and quantity of meat that the mussel produces. There will be areas where turbidity is very minimal and therefore light penetration will allow suitable levels of phytoplankton to exist at greater depths. However, under average conditions the 15 m depth guide is a suitable reference point. There are merits and constraints associated with subtidal or intertidal sites, but both can produce favourable results.

The principal advantage of subtidal beds is that the stock remains permanently submerged and can therefore filter-feed continuously. This promotes faster growth, enabling the mussels to reach marketable size in a shorter period of time. Shortened grow-out periods improve cash flow by facilitating earlier revenue generation, and they also decrease cumulative exposure to environmental and biological stressors that can induce mortality. Considering that it typically takes 18–36 months, depending on environmental conditions, to produce a market-sized mussel, substantial time and effort are required to replace any stock lost to mortality. A site that supports faster production therefore reduces vulnerability to these inherent risk factors.

However, because subtidal mussels are never exposed to air, they have little need to close their shells regularly, which results in weaker adductor muscles. This compromises their ability to withstand prolonged periods out of the water and ultimately leads to a shorter shelf-life - an important consideration for mussels sold in the shell. Their reduced shell-closing strength also limits their ability to resist predators that attempt to pry the shells open. Furthermore, the rapid growth rate generally produces thinner, weaker shells, diminishing their resistance to predation and their robustness during mechanical processes such as dredging and grading.

Mussels grown on intertidal beds, that are regularly exposed to the elements, develop extremely strong adductor muscles and thicker shells and can therefore maintain themselves out of the water for a greater length of time, ensuring a superior quality product for longer. The process of exposing the mussels to the air by moving them from the subtidal to the intertidal zone is known as “hardening”. Having a site where both subtidal and intertidal cultivation can be performed in close proximity can be advantageous.

Predation will occur on both intertidal and subtidal beds but the severity of the losses will depend upon the population and type of species that exist in each of the zones. It is more likely that higher losses to predation will occur on the subtidal beds, because voracious predators such as shore crabs (*Carcinus maenas*) and starfish (*Asterias rubens*) have permanent access to the mussels.

### 5.1.2 Structure of the seabed

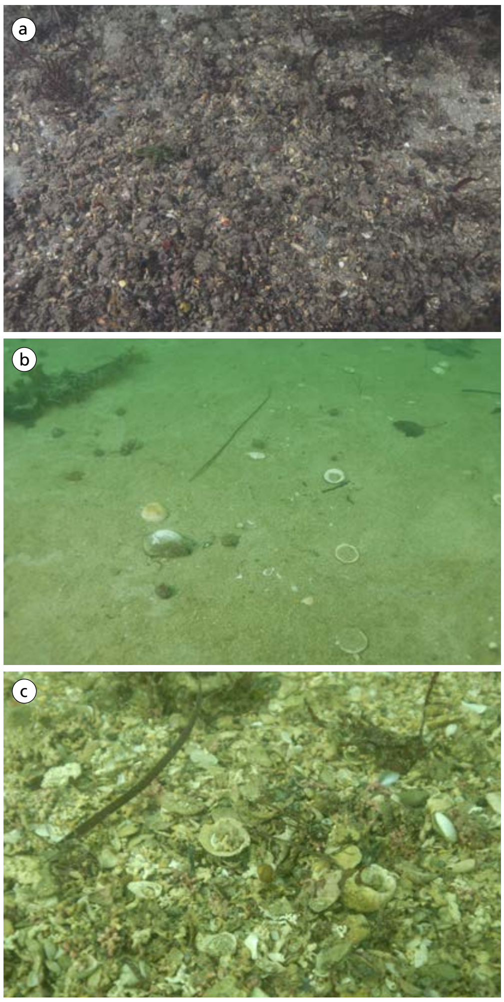
Because mussels lie directly on the seabed or fundus, ensuring that they are deposited onto the appropriate substrate is a crucial factor to ensure the establishment of a productive mussel bed. A suitable substrate is important not only for mussels that are transplanted from hatcheries and sown onto the seabed, but also for promoting natural spat settlement from existing wild populations.

Although the marine environment has a wide range of substrate types, only some are conducive to mussel cultivation. Mussels are generally less demanding in their substrate requirements than many other bivalve species. This flexibility is largely due to their production of byssal threads, which enable them to anchor not only to the substrate but also to neighbouring individuals, forming a cohesive mussel matrix that overlays the underlying seabed.

As mussels filter suspended particles from the water, they produce large amounts of faeces and pseudo-faeces that accumulate on the seabed over time, somewhat altering the original substrate. By extending and retracting their byssal threads, mussels can lift and reposition themselves above this layer of detritus, maintaining good access to the water column for feeding. This adaptive movement allows them to thrive on softer, muddier substrates that would be unsuitable for other bivalves, such as oysters.

The most suitable substrate for mussel beds is a mixture of gravel, pebbles, muddy sand, and old shell material, as shown in Figure 5.2. This combination provides a stable, supportive surface for adult mussels and an ideal settlement surface for mussel spat. Mussels will also naturally recruit and grow well on rocky ground. However, if the stock is to be harvested using dredges, rocky substrates are unsuitable because the dredging gear can snag on the uneven surface.

FIGURE 5.2
**Examples of substrates suitable for mussel bed establishment**
(a) Small pebbles and gravel on sand; (b) Firm sandy bottom; and (c) Old shells

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### 5.1.3 Tidal flow and fluvial currents

The position of mussel beds relative to tidal flow and fluvial currents determines the availability of nutrients as well as the salinity regime created by the mixing of freshwater and seawater. These hydrodynamic conditions also influence water temperature and dissolved oxygen concentrations. Together, these factors directly affect mussel growth rates and the overall quality of the harvested product.

Although no single formula can define the optimal site for mussel cultivation, a steady, moderate water flow is generally advantageous. Continuous water movement will deliver a regular supply of suspended food particles and help reduce the effects of eutrophication, including hypoxia. An adequate flow will also assist in dispersing faeces and pseudo-faeces produced by the mussels, preventing excessive accumulation on the beds. The impacts of HABs, which are closely linked to eutrophication and hypoxic conditions, are described in detail in Section 3.2 of this manual.

Conversely, excessively strong tidal currents can hinder feeding by moving phytoplankton past the mussels too rapidly for effective filtration. This reduces feeding efficiency and slows growth. A current velocity between 0.2 and 2 knots (10–100 cm/s) is generally considered suitable for sustaining optimal feeding and growth conditions. While mussels can survive outside this range, their growth performance is typically diminished.

#### 5.1.4 Exposure to wave action

Subtidal beds are largely unaffected by wave action, as they lie below the main dynamic energy of the waves. Intertidal beds, by their nature, are more susceptible to wave action, particularly at exposed coastal sites. This is especially true at locations where the prevailing wind direction blows directly onto the shoreline. As the tide rises and falls over the bed, waves can break directly onto the exposed mussels, potentially causing shell damage. This can leave them vulnerable to predation and unable to retain seawater within their shells during emersion, both of which can lead to mortality.

The repeated impact of waves and the resulting high-energy water movement in the breaking zone can also displace mussels from the beds. Displaced mussels may be carried to areas of the foreshore that are inaccessible to dredging vessels, necessitating manual recovery, which is less efficient. Sites exposed to this type of dynamic sea state can also be challenging for dredging operations. There is not only a safety risk to the crew but also a potential for damage to the vessel. Operation of deck equipment, dredging, and recovery of the dredges onboard can become very difficult if wave heights are excessive.

The ideal location for a mussel bed is therefore in protected bays and estuaries that are not exposed to the forces of breaking waves.

## 5.2 FARM DESIGN

### 5.2.1 Farming beds

Once a suitable area of ground has been identified for the mussel beds, there are three main actions to be undertaken before any stock can be sown onto the seabed: mapping and marking the beds, preparation of the ground and the removal of predators.

*Mapping and demarcation of the mussel beds*

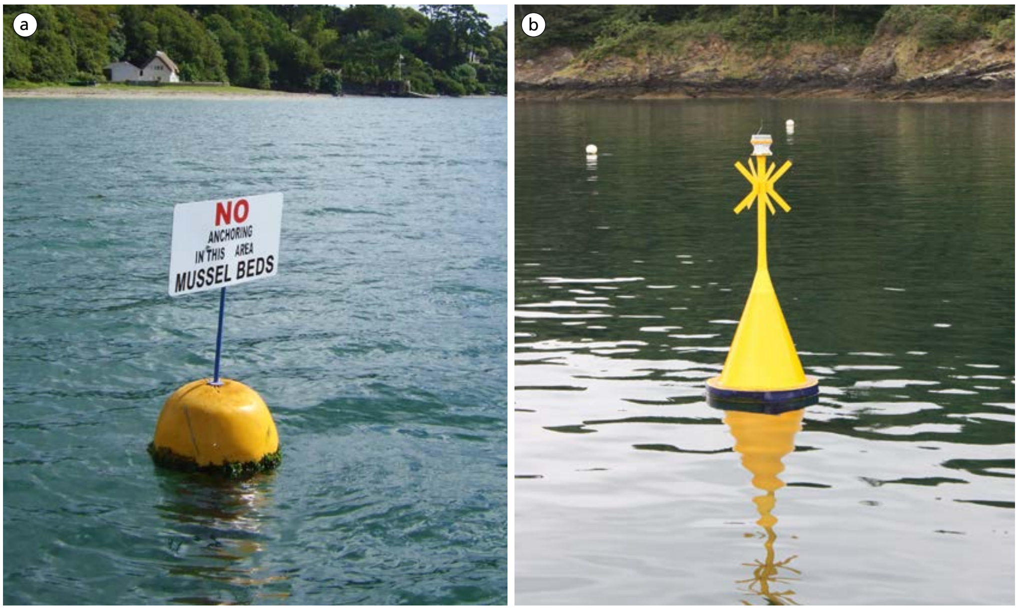
The beds can be mapped and marked using both electronic and physical navigational aids. This not only enables the farmer to know precisely where the mussels have been laid but also informs other water users to exercise caution when navigating the area and indicates where anchoring should be avoided. Anchoring by other vessels can pose a significant risk to mussel beds. When a boat anchors, it typically deploys a chain four times the maximum water depth. For example, a vessel anchoring in 10 m of water will deploy 40 m of anchor chain. As the tide ebbs and flows, the vessel swings around the anchor point, causing the chain to sweep the seabed in a circular pattern. Mussels can therefore be damaged not only at the anchor drop point but also along the path where the chain is dragged. Clearly marking mussel beds, both physically and on electronic charts, helps alert other water users to the presence of the crop and discourages anchoring in these areas.

*Physical mussel bed markers*

Markers can come in different forms, but the two main ones used are navigational buoys and wooden or metal poles. Navigational buoys are deployed around the perimeter of the mussel beds and will usually display signage warning of the product on the seabed. The signs typically contain text such as: "Mussel beds – No anchoring" or something similar (Figure 5.3a).

Another method of marking the beds is the use of wooden or metal poles that are driven into the ground on the outer extremities of the beds. They need to be long

FIGURE 5.3
**Navigational markers**
(a) Navigational markers indicating that there are mussel beds on the seabed; and
(b) "Special Mark" navigational buoy






enough that they are still exposed at the top of the highest astronomical tide and can also often have signage attached to them.

If other mussel aquaculture equipment in the same zone could pose a navigational hazard, buoys known as "Special marks" are deployed. These are an internationally recognised marker, always coloured yellow, and often equipped with a yellow flashing light or a yellow "X" on a pole above the buoy (Figure 5.3b).

Figure 5.4 shows a workboat dredging a mussel bed within the area indicated by navigational markers.

FIGURE 5.4
**Illustration of workboat dredging for mussels**
The bed is marked by navigational buoys situated at the four corners of the production zone

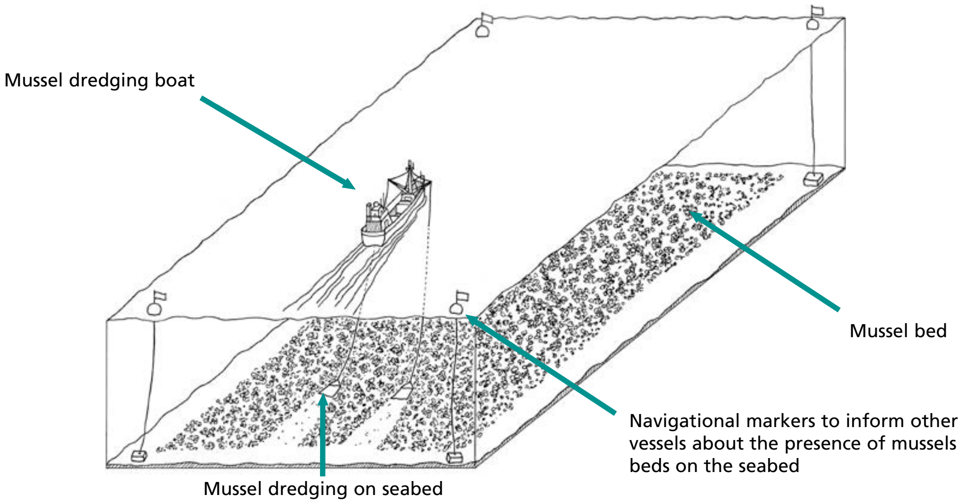
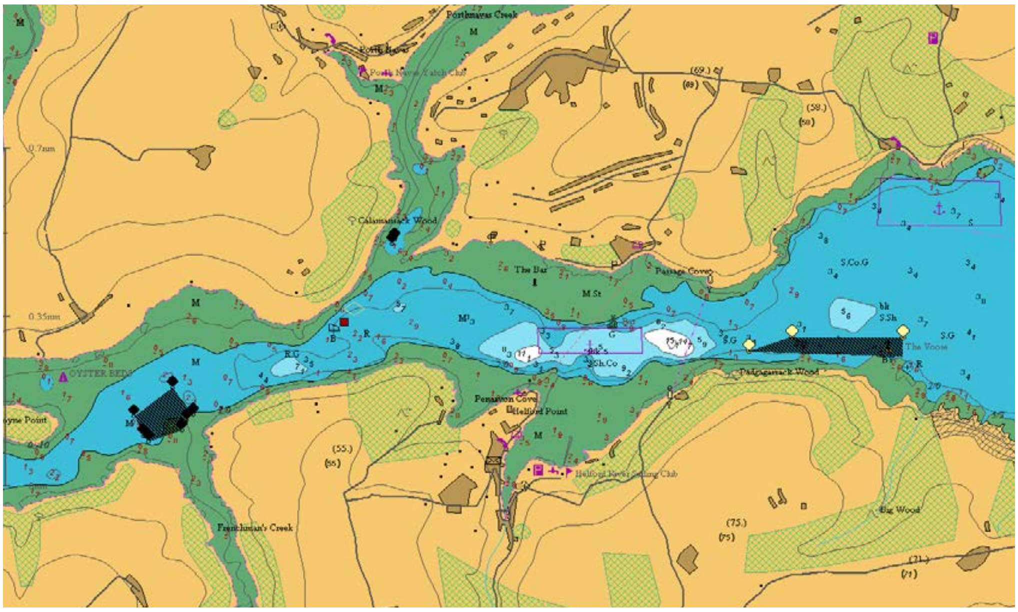


FIGURE 5.5
**Electronic chart plotter showing position of mussel beds (black, shaded areas) within an estuary**






*Electronic navigational aids*

Electronic navigational aids use Global Positioning System (GPS) or the even more accurate Differential Global Positioning System (DGPS) coordinates to pinpoint a position on the earth's surface. It is possible to use navigational instruments such as Chart Plotters to precisely mark out the areas on which mussels are sown (Figure 5.5 and Figure 5.6). Mussel farm operators should inform the local navigational authority about the position of their beds. These can be included on the electronic charts that are used by other vessels and can therefore warn other water users that there are mussels on the seabed in a given area. Usually, the communication of the geographical coordinates of the farm and of the markers used is part of the licensing procedure.

When re-laying or harvesting the stock, it also allows the boat skipper to know precisely where they need to be and to ensure that no mussels are missed. Some systems will show a "Track", which is an electronically generated line on the chart plotter indicating exactly which course the boat has taken when moving over the mussel beds. The skipper can refer to these "Tracks" to ensure that no ground has been missed and therefore minimise the mussels left behind after dredging.

FIGURE 5.6
**Electronic chart showing detail of mussel beds separated into three different zones**




## *Preparation of the fundus*

Before laying any mussels onto the beds, it is important to ensure that the ground is in the best possible condition to allow the mussels to thrive. If the ground has not been used for mussel beds previously, then it is likely that there will be a build-up of general marine debris, seaweed and possibly excessive sediment. It is recommended to survey the intertidal beds at low tide to assess the necessary action required to be undertaken in order to clear the beds prior to sowing. Any debris, such as old tyres, tree branches, plastic bags or other such items, should be removed by hand as they will interfere with the dredges and impede efficient use of the beds. It is also worth noting any areas of particularly soft ground where sedimentation has occurred. When undertaking this survey, it is a good idea to take a handheld GPS unit so that any areas of concern can be logged. Subtidal beds will need to be surveyed by diving on them and any bulky debris removed using lift bags that can be collected at the surface by a boat.

*Removal of predators*

It is impossible to eliminate all causes of predation from a mussel bed due to their exposed nature. However, it is wise to limit the number of potential predators in the area and thus limit the number of mortalities that they can cause. Bear in mind that, by laying large amounts of mussels onto a relatively compact area, it will undoubtedly attract unwanted attention from animals that feed on them, so the operation of removal should be an ongoing process throughout the cultivation cycle. By introducing an increased food source, the farm is potentially boosting the numbers of predators that the area can support, unnaturally raising their population numbers. It is therefore important to control these increased numbers by removal. The aim of this process of removal is not to completely decimate the number of predators, as it is important to maintain a thriving and balanced ecosystem around the mussel beds. The goal is just to limit the numbers so that mortalities do not cause the bed to become unviable. There is a comprehensive list of mussel predators in Table 2.4 of Section 2.1.4, while in this section the manual will describe the techniques required to remove two of the most voracious: crabs and starfish.

#### Crabs

The best way to remove crabs from the area of the mussel beds is by deploying crab pots around the periphery. Pots should be baited with crushed mussels or waste products from fish processing and distributed along a continuous line around the beds. They should then be recovered by boat on a regular basis, every few days (Figure 5.7). The reduction in crab numbers will decrease mortalities and, depending on the type of

FIGURE 5.7
**Crab pot being hauled from an area around the mussel beds**

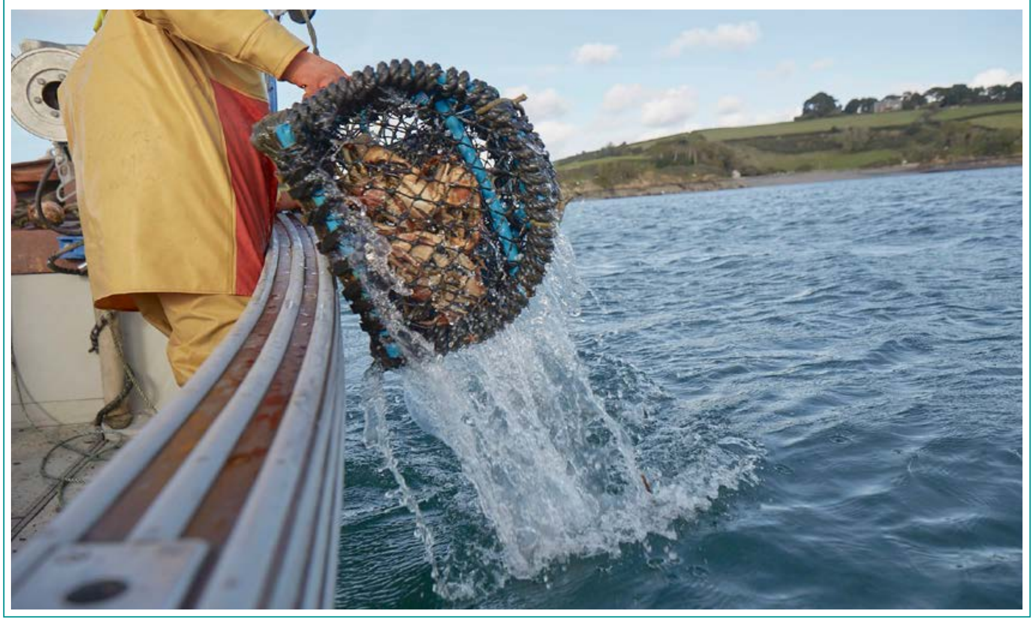


FIGURE 5.8
**Typical crab pot design**

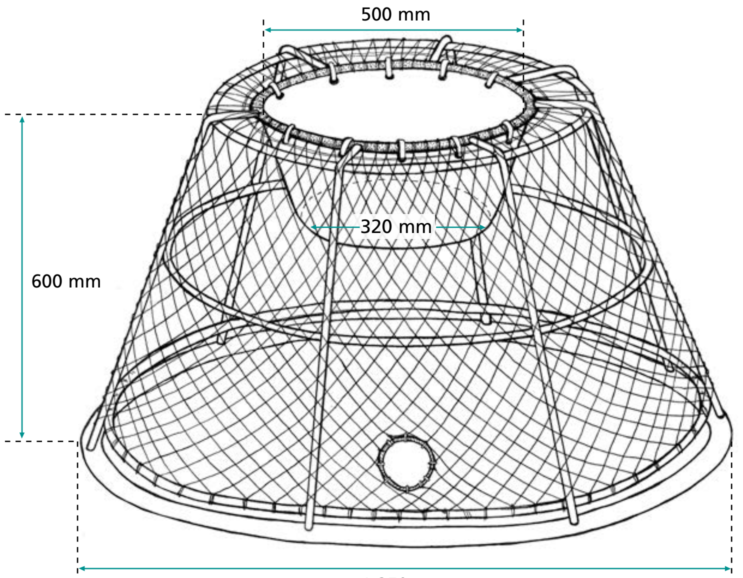
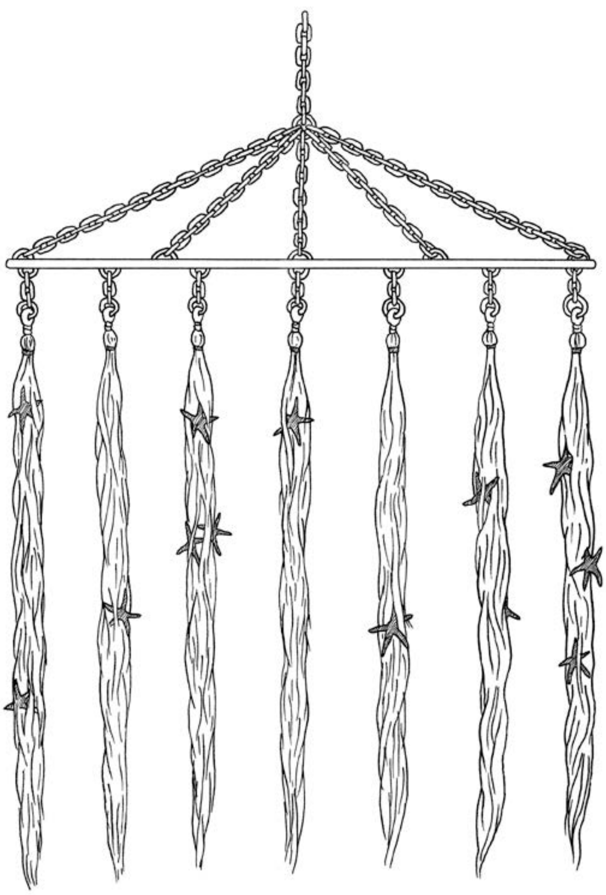



FIGURE 5.9
**Mop used to remove starfish from farmed mussel beds**



crab that is caught, could provide another income stream if they are of commercial value. If there are many crabs present initially, then this process can be done every few hours to reduce the population. Figure 5.8 shows an example of a widely used design for a crab pot used commercially and for this purpose.

### Starfish

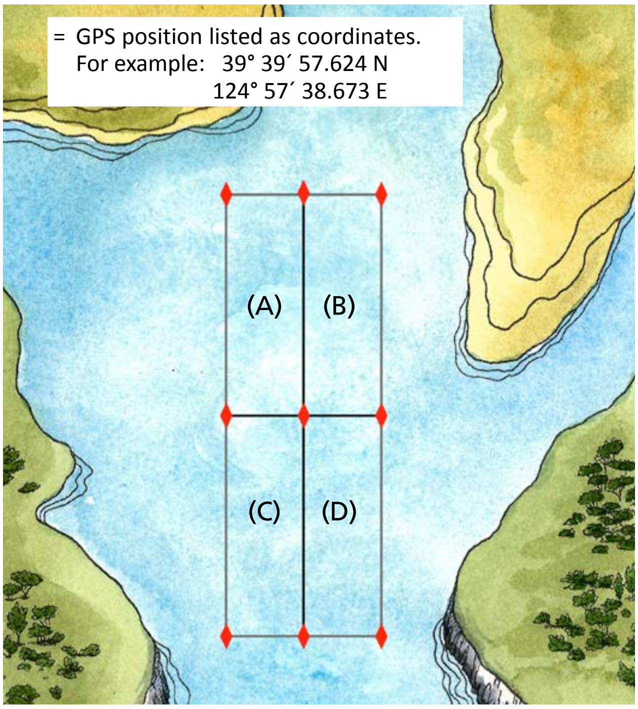
Starfish can also be removed using pots or traps in a similar fashion to crabs. However, the most efficient means of removal is by using a piece of equipment known as a starfish mop (sometimes referred to as a Faubert mop). Usually, the apparatus is made up of a triangular metal frame, like the front end of a dredge, with several mops attached to it (Figure 5.9). These mops, that are usually made up of frayed rope material, are trailed across the seabed in a similar fashion to dredging. As they traverse the mussel beds, the starfish become entangled in the fabric of the mops and can then be raised to the surface and deposited into containers on-board the workboat.

## 5.2.2 Farm layout

Each farming area will have its own unique set of factors that will determine how the beds will be laid out to maximise the production potential. There will be areas that will be better for encouraging fast growth but not necessarily good for fattening the mussels to obtain a product with a superior meat to shell ratio. Some beds will be intertidal and some subtidal which will have an effect on growth rates and on their shelf-life when removed from the water. Mussels should be placed onto the beds that are most suitable for attaining the desired result, whether that be encouraging seed mussels to grow quickly or fattening larger mussels to prepare them for market. When designing the layout of the farm these different farming strategies should be considered.

Another important aspect to consider when designing the layout is dividing the beds into different areas so that mussels of different sizes can be laid onto them at different times of the year. If the farmer wishes to harvest mussels throughout much of the year, then this strategy will allow the operator to harvest stock that has attained market size from one area without disturbing smaller stocks that were laid later in the year and that can be left to grow further. It is a more efficient way of harvesting because it prevents dredging up a proportion of mussels that will then have to be re-laid back onto the beds. For example, a farmer has four beds A, B, C and D as seen in Figure 5.10. Seed mussels are laid onto each bed at different times of the year: bed A – January, bed B – April, bed C – July, bed D – October. Under standard growing conditions, beds A and B would be ready to be harvested during the late summer and early Autumn, while beds C and D would be harvested during the following season. Having the stock separated in this way prevents double handling and targeted harvesting ensuring the most efficient use of bed space.

FIGURE 5.10
**Mussel bed subdivided into different areas with GPS coordinates**
Seed mussels is laid onto the beds (A), (B), (C) and (D) at different times of the year, thereby allowing the stock to reach marketable size at staggered points throughout the growing season




### 5.2.3 Farm access

*Tractor or alternate 4-wheel drive vehicle*

It is possible to use a tractor and trailer to access and work on mussel beds that are intertidal, arriving as the tide ebbs and working over the low tide until the water floods back in and covers the mussels. The trailer should be of a suitable size and sturdy construction to be able to safely carry the weight of mussels that are deposited onto it. If the beds are located in an area where access requires crossing a foreshore that has a soft substrate, then it is recommended to fit wider tyres to prevent the trailer from becoming stuck. Some trailers will also be fitted with a crane to assist in the handling of containers, into which the mussels have been deposited. Tractors are particularly suitable for operations that are harvesting mussels by hand from areas of foreshore that have suitable road access to allow for the transportation of the stock back to the processing facilities.

*Workboat and basic on-board equipment*

The workboat or dredging vessel is the central component of the farming operation. It is therefore essential that the selected vessel is appropriately designed and sized to match the intended production volume, species mix and farm location. If the vessel will be used exclusively for sowing and harvesting bottom-cultivated mussels, a purpose-

FIGURE 5.11
**Mussel dredging vessel for medium- to large-scale production, fitted with derricks to deploy the dredges**




built, highly specialised vessel should be employed to efficiently perform these tasks.

For most medium- to large-scale operations, these vessels typically range from 25–40 m in length and 8–10 m in width and are capable of harvesting with either two or four dredges (Figure 5.11).

However, many smaller farms - particularly those cultivating multiple species such as mussels, oysters and seaweed - require a general-purpose workboat that can be adapted to the differing operational needs associated with each culture type (Figure 5.12). The workboat effectively serves as the "tractor of the sea." Beyond specialised tasks such as dredging, it must also be capable of carrying out a wide range of other operational activities. For this reason, flexibility in both layout and functionality should be built into the vessel's design.

A wide variety of workboat configurations is available, and the farm operator should ensure that the chosen vessel meets the specific requirements of their site.

For small-scale production where hand dredges are used for harvesting, many of the features found on larger workboats are unnecessary, and the vessel size can be scaled down accordingly (Figure 5.13). Hand-dredge harvesting can be performed from vessels as small as 4 m in length, powered by a 10 hp outboard motor.

FIGURE 5.12
**Drawing of a general-purpose workboat used for shellfish farming, featuring dredges deployed from derricks and a crane for handling catch and equipment**

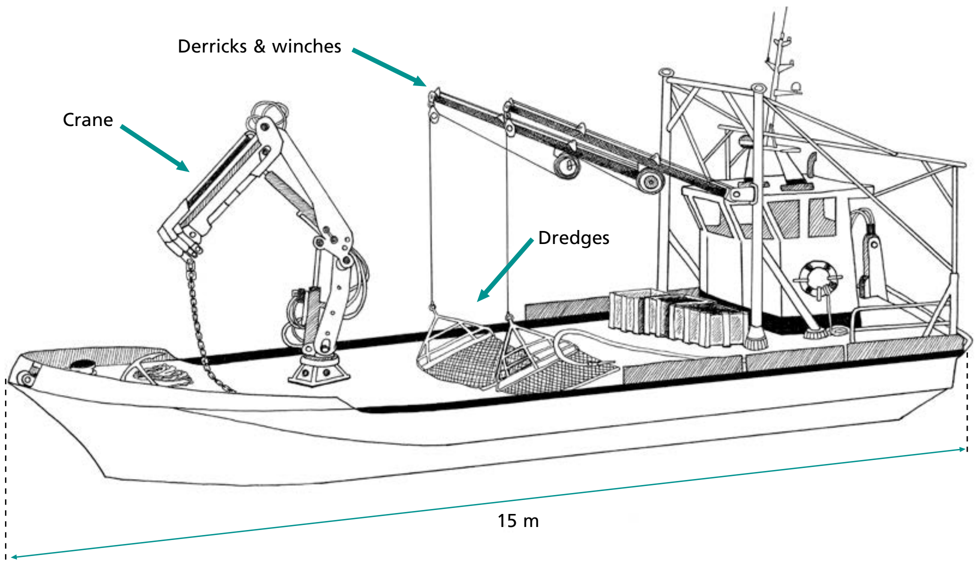


FIGURE 5.13
**Example of general-purpose workboats with shallow draft and open deck space suitable for small-scale shellfish cultivation**

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However, the main features of the ideal workboat for medium- to large-scale production are as follows:

*Shallow draft workboat*
The draft (or draught) of a ship's hull is the vertical distance between the waterline and the lowest point of the hull (the keel). It represents the maximum depth of any part of the vessel below the waterline. Draft determines the minimum water depth in which a ship or boat can safely operate.

Workboats used in mussel farming typically operate in intertidal or relatively shallow subtidal zones. As the tide ebbs, water depth over the beds decreases - disappearing entirely in intertidal areas and becoming progressively shallower in subtidal areas. Tidal range varies greatly worldwide: in extreme cases it may reach 16 m or be as little as 0.1 m, though more commonly it falls between 1–6 m.

Because tidal fluctuations directly affect water depth over the mussel beds, vessels can only operate when the tide is sufficiently high. To maximise the available working window, it is advantageous for the vessel to have a shallow draft, typically 1 m or less, allowing access to the beds during the widest portion of the tidal cycle (Figure 5.14).

FIGURE 5.14
**Vessel with shallow draft**

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Even larger workboats, up to 40 m in length, are therefore designed with drafts between approximately 1.5–2.8 m. Some production sites maintain consistently deep water over the beds, in which case shallow draft is less critical, but such conditions are the exception rather than the norm.

*Hull shape*

One way of minimising the draft is to design the hull with a flat bottom (Figure 5.15). Not only does this allow the vessel to operate in shallow depths, but it also allows it to be dried out on the beds or foreshore without the boat tipping over. This allows it to be moored comfortably in locations where the water completely recedes and is also useful when loading and unloading equipment and mussels when the tide is out, as the deck will remain relatively horizontal depending on the ground below it. The same shallow draft and stability can also be achieved using multihull and pontoon style hulls.

Flat hulls are also more stable when operating in calm waters so will provide a better working platform on deck under these conditions. However, in choppy conditions, flat-bottomed vessels become less stable than traditional rounded or V-shaped hulls, so it is important to tailor the vessel's design to the particular environment in which the beds are located.

*Deck space*

On specialised dredging vessels, the deck layout is designed around the area where the dredges are brought inboard and the mussels are deposited. Depending on the vessel's size and configuration, this arrangement provides space for any onboard processing equipment, as well as sufficient hold capacity to store the harvested mussels (Figure 5.16a).

For a general-purpose workboat, which must perform a wide range of tasks, an adaptable deck layout is essential. In most cases, a flat, open deck is recommended so that it can be easily reconfigured to suit operational requirements whether dredging, grading, moving equipment, or transporting harvested product (Figure 5.16b).

FIGURE 5.15
**Flat bottom hull workboat**

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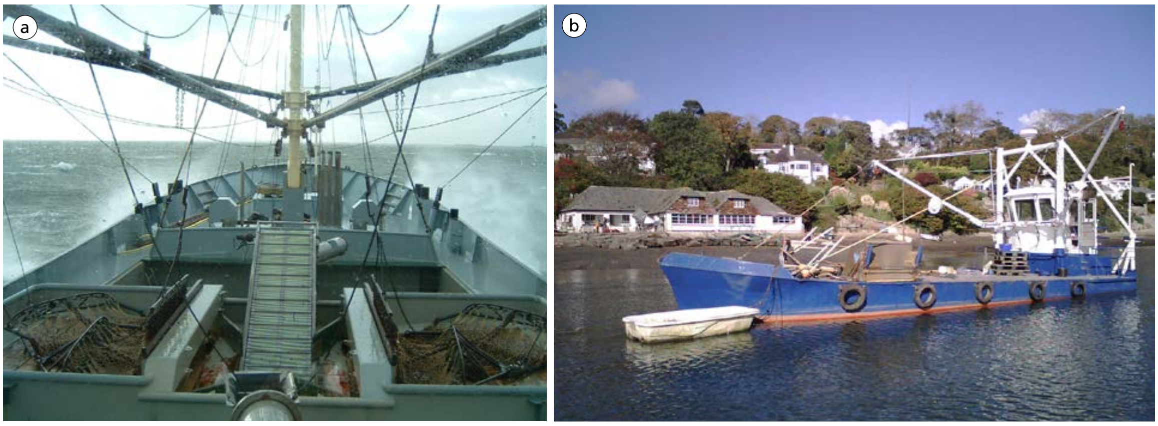
FIGURE 5.16
**Examples of deck layouts on dredging vessels**
(a) Deck space on specialist mussel dredging vessel; and (b) Flat, open deck space on general purpose workboat.






*Derricks and winches*

A derrick is a metal arm that pivots out from the vessel and is used to lower and raise the dredges into and out of the water (Figure 5.17a). Winches control the cable attached to the dredges, allowing them to be deployed onto the seabed during harvesting and raised when bringing the mussels back onboard. The winch cable must be of sufficient length to accommodate the maximum depth over the beds.

Typically, vessels are equipped with two derricks, one on each side. Larger workboats may have four derricks - two shorter and two longer - allowing the simultaneous deployment of four dredges. Both derricks and winches are hydraulically powered, with control levers located in the wheelhouse for the skipper (Figure 5.17b). The levers are arranged in pairs, port and starboard, enabling simultaneous control of both winches or both derricks.

*Crane*

Many of the workboat's operations involve moving heavy loads on and off the vessel. Consequently, a crane with adequate reach and lifting capacity is essential for the efficient running of the farm (Figure 5.18). Typical lifting tasks include offloading harvested mussels and handling onboard processing equipment.

FIGURE 5.17
**Shellfish workboat lifting equipment**
(a) Derrick with hydraulic winch attached; and (b) Control levers for the derricks and winches in wheelhouse

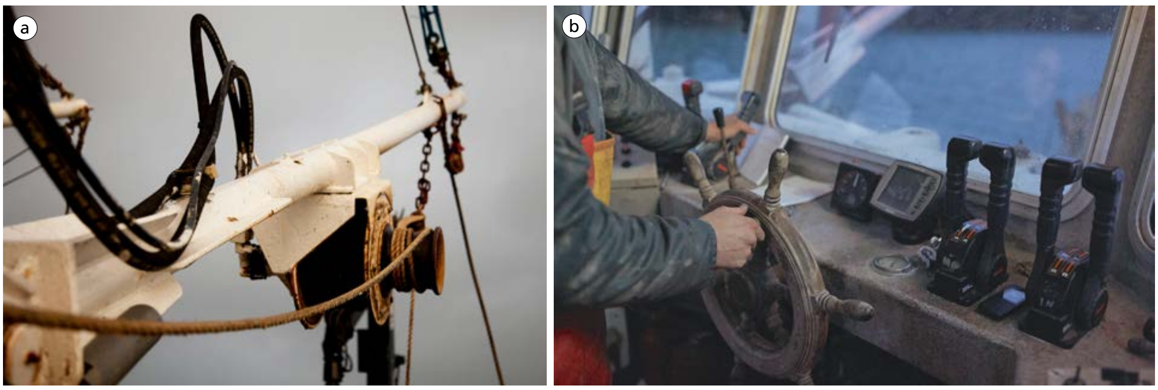


FIGURE 5.18
**On-board crane used to lift farming equipment and harvested mussels**

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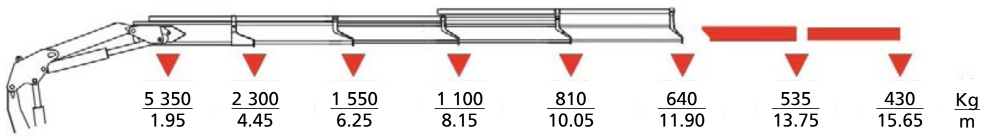
FIGURE 5.19
**Example of lifting capacity of a 10.4 tonnes/metre crane**
As the crane is extended, the lifting capacity diminishes

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A crane's lifting capacity is expressed in tonnes per metre. For example, the crane shown in Figure 5.19 is rated at 10.4 t/m, meaning it can lift 10 t at a 1 m radius from its central rotation point. The diagram also illustrates how lifting capacity decreases as the crane's telescopic boom extends outward from the base.

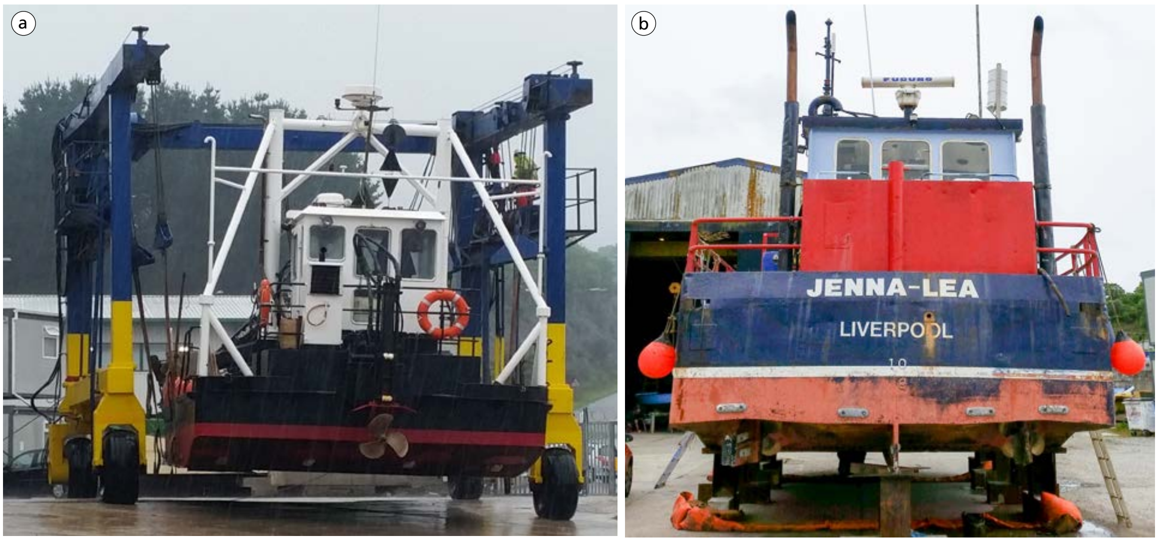
The crane's specifications and use must be compatible with the vessel's stability to ensure safe operations and prevent capsizing. Each vessel has a maximum allowable angle of roll (side-to-side movement), beyond which stability is compromised. Professional advice from a marine surveyor should be sought regarding vessel stability during lifting operations.

Not all vessels are equipped with cranes, particularly when suitable shore-based lifting facilities are available for offloading harvested molluscs.

*Propulsion system*

When dredges are towed across the seabed, they generate a certain amount of resistance. As the dredges fill with shellfish, their weight increases, which in turn increases drag. Because of this, it is crucial that the vessel is equipped with a propulsion system capable of maintaining a consistent towing speed even when the dredges are fully loaded. The system should therefore prioritise pulling power and torque over maximum speed. While various propulsion systems exist, the most commonly used is the diesel engine. The general workboat described in this section uses a variation of this setup: a diesel

FIGURE 5.20
**Examples of workboat propulsion systems**
(a) Vessel with hydraulic propulsion system; and (b) Vessel with twin propellers





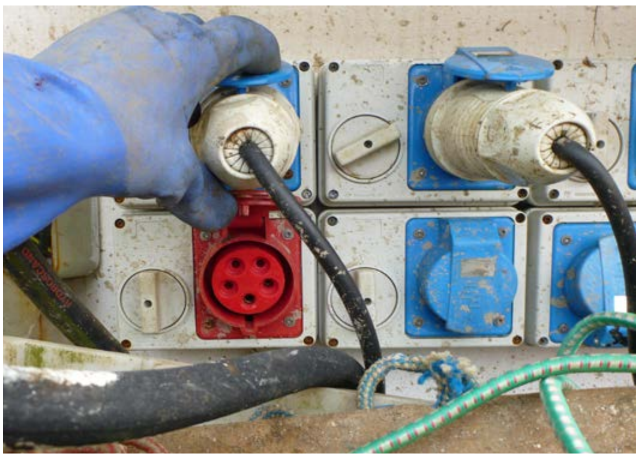

engine powers a hydraulic pump, which in turn drives the propeller (Figure 5.20a). It features a 6-L marinized truck engine producing 230 hp at 2 100 RPM.

Some vessels are equipped with twin engines driving two propellers, one on the port side and one on the starboard side (Figure 5.20b). This configuration provides greater torque, which is particularly advantageous during dredging. It also improves manoeuvrability and allows the vessel to safely return to shore in the event of an engine failure, running on the remaining unit.

*Navigation and communication system*
The use of chart plotters has been discussed in the previous section of this chapter entitled “Electronic navigational aids”. It is also necessary for the vessel to be equipped with Very High Frequency (VHF) radio so that it is possible to communicate with other water users in the area. This is especially important whilst undertaking dredging activities because, when the dredges are on the seabed, the vessel is limited in ability to manoeuvre and therefore use of the VHF to warn other vessels can help to avoid potential collisions or entanglement. The VHF should be always monitored on Channel 16, which is the international distress frequency and is also used by vessels to initiate communications before switching to another channel.

*Electrical power*
Some of the items of processing equipment may require either single or three phase electrical power (Figure 5.21). When installing a generator to produce this power it is recommended that the operator purchases one with a higher power specification than the bare minimum that is required. This will allow for the use of equipment that was not initially needed. Also, certain pieces of

FIGURE 5.21
**Waterproof electrical sockets for powering deck equipment**



equipment require a larger amount of power to start them which drops down once they are running, so this must be factored into the installation calculations.

*Hydraulic power*
Hydraulic power can be used to power the crane, winches, derricks, water pump and in some cases the propulsion system itself. It can also be used to power other items of processing equipment. It is therefore an integral part of the vessel's operating system and, as with the electrical power system, must be designed with plenty of extra capacity to allow for the expansion of its use.

*Specific on-board equipment*
There are two options for processing the mussels that are dredged from the beds. Either they are loaded from the dredges directly into containers and transported back to the shore-based facilities for grading or they are graded on-board the workboat itself.

Dredging the mussels from the bed will commence when the majority of them are of a suitable size to be harvested. However, the growth rate of the individual mussels will vary over the season and so, when harvesting takes place, there will be a variety of sizes landed in each dredge. These need to be separated out, and only the mussels that have attained a minimum market size will be landed for further processing. The rest of the slower growing stock that is under the minimum size needs to be re-laid back onto the beds to allow it to grow on. This is achieved using the grading equipment. The advantage of undertaking this process on-board the vessel is twofold. Firstly, it means avoiding the unnecessary transportation of the smaller stock from the beds to the shore-based facilities and back again saving time and double handling. Secondly, the mussels can be returned immediately to the water, which will reduce any potential mortalities from the grading process.

FIGURE 5.22
**Mussel hand dredge**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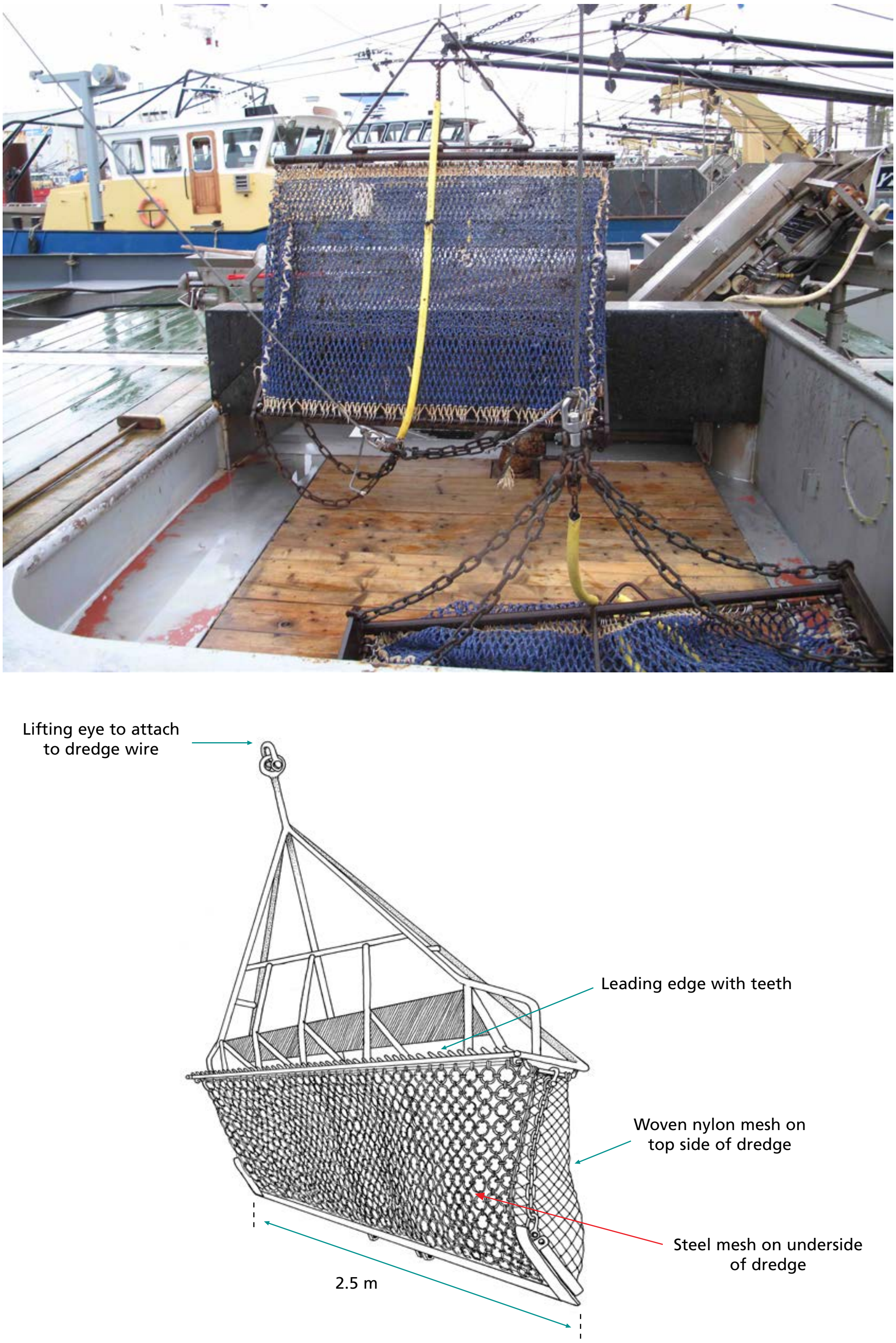
### Dredges

These are used to harvest the mussels from the beds. They are designed to be non-invasive to the base substrate. The leading edge of the dredge cuts through the faecal and pseudo-faecal layer that mussels create below them without damaging the fundus underneath. They can vary in size and design depending on the vessel that they are being deployed from. Here are two examples, one being a small manual dredge that can be recovered by hand (Figure 5.22) and the other being a larger design that would require recovery by mechanical winches (Figure 5.23).

FIGURE 5.23
**Example of a large mussel dredge**






## Hopper

After the vessel has completed a pass over the bed and the dredges are full, they are swung inboard on the derricks. The dredges are then opened, and the mussels are deposited into a hopper (Figure 5.24). The hopper must be sufficiently large, at least as wide as the dredges and with enough volume to accommodate the contents of both,

FIGURE 5.24
**Example of hopper on the deck of a workboat**
Once the mussels enter the hopper, a chain belt conveys them through high-pressure water jets, depositing them into the hold or into bulk bags



so that the dredges can be offloaded and redeployed while the crew processes the harvested mussels and the skipper makes another pass over the beds.

This equipment typically includes a chain belt system that conveys the mussels through water jets to clean them, depositing the product into the hold or into bulk bags. The belt is designed with openings that allow smaller mussels to fall through, which can then be redistributed onto suitable beds to continue growing to market size.

*Heavy-duty plastic pallet boxes or bulk bags*
Mussels can be loaded directly into heavy-duty plastic pallet boxes or bulk bags (Figure 5.25). These can then be lifted directly off the boat to be processed ashore.

FIGURE 5.25
**Mussels stored in large heavy-duty bulk bags**

## 5.3 FARMING PRACTICES

### 5.3.1 Strategy for the introduction of the seed

In this section, the manual will describe the strategy for the introduction and handling of seed that is specific to bottom cultivation on mussel beds. Seed can be dredged from beds where natural spatfall occurs or collected by means of spat recruitment equipment such as suspended ropes before being distributed onto the cultivation beds. Suspended rope culture is dealt with in Chapter 4 of the manual where seed collection by this method is described in detail.

*Collection of naturally occurring mussel seed from the sea bed*

Seed mussels are defined as specimens that are below minimum market size (<45 mm). When collected from the wild, seed sizes can vary considerably depending on nutrient availability, climatic conditions, and the length of time the spat have settled before being located and harvested. Typically, the minimum size of collected seed is approximately 5–10 mm.

Mussel spat settle in areas with suitable substrate, both in intertidal and subtidal zones. While seed beds can form at depths of up to 50 m, the majority are found in shallower waters (<20 m), making them readily accessible for dredging vessels. These beds are often ephemeral, and although conditions may initially support spat settlement, they may not provide the circumstances required for mussels to develop into mature adults. Key limiting factors include predation, siltation, storm damage and population density. In areas with optimal settlement substrate, densities of up to 100 000 spat/m$^2$ have been recorded. Excessive settlement results in intense competition for food; without sufficient phytoplankton, and to a lesser extent zooplankton, the mussels cannot obtain the nutrition required for survival and growth. Therefore, harvesting seed from these beds does not negatively impact natural populations, as the majority of spat would otherwise be lost.

Prolonged larval durations, often driven by climatic conditions such as lower water temperatures or reduced food availability, can keep mussel larvae in the planktonic phase for up to two months. During this extended drift period, larvae may be transported considerable distances, sometimes more than 100 km, from their original fertilisation site before settlement occurs. Following settlement, juvenile mussels form dense, cohesive mats or "carpets" bound together by their byssal threads, typically accumulating on a layer of faeces and pseudo-faeces.

Although seed mussels can occur across a broad tidal gradient, it is generally inadvisable to collect seed from the upper intertidal zone for transplantation. Mussels in this region spend prolonged periods exposed to air and have highly restricted feeding opportunities. Despite appearing similar in size to newly settled spat, individuals from the upper foreshore may be several years old. Extended exposure to such limiting conditions induces metabolic down-regulation and adaptive energy conservation strategies. As a result, even when transplanted to subtidal, nutrient-rich environments, these mussels frequently remain stunted and exhibit poor growth performance.

For reliable growth and optimal cultivation outcomes, prime seed should be sourced from the lower intertidal or sublittoral zones, where mussels benefit from more consistent immersion, improved feeding conditions, and substantially higher growth potential.

*Period and quantities*

Seed mussel is generally harvested and transplanted from late spring through late summer, although operations can extend beyond this period if seed availability and prevailing environmental conditions are suitable. Transplanting during summer aligns the seed with maximum primary productivity, when phytoplankton abundance is highest. This timing enables rapid somatic growth and facilitates the formation of a dense, cohesive mussel matrix, stabilised through extensive byssal-thread attachment, before the arrival of autumn and winter storm events, when hydrodynamic stress is greatest.

The volume of seed collected should be matched to the surface area of the cultivation beds and the expected mortality rate during the grow-out phase. Many farms utilise a baseline expectation of a 1:1 biomass return, where one tonne of seed ultimately yields one tonne of market-size mussels. Thus, a sowing of 100 t of seed is projected to produce approximately 100 t at harvest. Under optimal environmental conditions, such as favourable temperatures, sustained phytoplankton availability, low siltation and effective predator control, returns of 1:3 or higher are achievable.

Return ratios are influenced by multiple factors, including hydrodynamic exposure, food availability, sedimentation and predation pressure. Shore crabs (*Carcinus maenas*) and starfish (*Asterias* spp.) are typically the dominant predators on subtidal mussel beds, and increased investment in their removal or mitigation directly improves survival and biomass accumulation.

It is important to recognise that even a 1:1 return corresponds to individual survival rates of well under 10 percent. For example, 1 kg of seed contains approximately 800–5 000 spat, depending on seed size. In contrast, 1 kg of market-grade mussels contains roughly 60 individuals, highlighting the natural thinning that occurs as the population self-regulates through mortality, density-dependent growth, predation and displacement.

*Seed size and density*

The size of seed laid onto the beds can have a significant influence on the final market-size stock harvested. Smaller seed (5–10 mm) will generally produce a better yield when considering the tonnage conversion to market-size mussel. Although smaller seed is more vulnerable to predation and siltation, the higher number of individuals per kilogram typically compensates for these losses, resulting in a greater overall tonnage of saleable product compared to larger seed.

However, in areas with particularly high predation pressure, larger seed (30–35 mm), with more robust shells capable of resisting attacks from crabs and starfish, may achieve better outcomes. Larger seed also remains on the cultivation beds for a shorter period because of its initial size, reducing exposure to risks over time. It is therefore important that the farm operator trials different seed sizes and sowing strategies across various beds to gather site-specific data. What works effectively on one farm, or even on one bed, may not be suitable for another. Building this knowledge base over time will help the operator understand the diverse factors influencing a successful seed strategy and may ultimately lead to a methodology that maximises production output.

When determining the appropriate density of seed to lay onto the bed, three main factors must be considered: predation, competition for food and seed size. Beds sown at low densities often experience higher mortality due to predation, as mussels in low-density settings cannot form protective clumps using their byssal threads. In contrast, mussels laid at higher densities can aggregate more effectively, improving their collective defence. However, excessively high densities force a larger number of individuals to compete for available food, resulting in reduced growth rates and, in severe cases, mortality. A balance must therefore be achieved between these opposing pressures.

Because each production site has unique environmental and nutritional characteristics, it is not possible to prescribe exact density figures suitable for all farms. Sites with high phytoplankton availability and strong water exchange may support sowing densities as high as 100 t/ha, whereas sites with moderate conditions typically require lower densities. Under average conditions, a density of 20–30 t/ha is recommended. Smaller seed will require more space to grow than larger seed and should therefore be laid at lower densities.

*Laying seed mussels onto the beds*

When sowing seed mussels, it is important to achieve an even spread across the entire bed. This ensures that each individual has equal access to food, promoting uniform growth throughout the stock. Before distribution, the seed mussel should be separated into individual shells using a de-clumping machine to prevent excessive clustering on the seabed.

When distributing mussels from a vessel, sowing should take place when there is sufficient water depth between the surface and the seabed (a minimum of 3 m). This allows the mussels to disperse as they fall, promoting an even spread across the bed.

Depending on the type of vessel used, there are several methods for sowing the mussels. Some purpose-built mussel barges have systems that flush seed out of the hold at a controlled rate, allowing the operator to manage the density landing on the bed. Other vessels use hoses to wash the seed overboard from the deck. On smaller boats, the operation may be carried out manually, either by brushing mussels overboard, if deck design permits, or by tipping them directly from collection bags. Regardless of the method, the vessel should maintain a steady forward speed (2–3 knots) during sowing. This movement helps ensure even distribution of seed across the bed.

It is also important to minimise the time harvested seed spends out of the water before sowing. This is especially critical for seed collected from subtidal beds, as it will be the first time these mussels have been exposed to air and they are completely unaccustomed to it. The entire process should ideally be completed within 24–36 h. During this period, the seed should be kept cool, damp, and at a temperature similar to that at the site of origin to prevent mortality from desiccation. Reducing the out-of-water time during transfer from the seed bed to the cultivation zone helps minimise potential losses.

Some farms with both intertidal and subtidal beds choose to initially lay seed in the intertidal zone. Exposure to air during part of the tidal cycle induces a "hardening" process, during which the mussels strengthen their adductor muscles by repeatedly closing their shells while out of the water. Because they cannot feed continuously, growth slows, allowing them to develop thicker shells that provide better protection from predators once they mature and are transplanted to subtidal cultivation beds. Birds feeding in intertidal areas tend to target mussels over 30 mm in length, as the energy required to break the shell is only justified when the nutritional return is sufficient. Smaller seed is therefore less targeted, giving it time to strengthen its defences.

### 5.3.2 On-growing strategy and technique

In this section, the manual outlines the actions required for effective management of the cultivation beds and the mussel stock placed on them, from seed through to market size. This includes the physical tasks that must be carried out, as well as guidance on the most efficient strategies for maximising the productive use of the beds.

*Recommended frequency in dividing and/or grading batches*

Depending on the cultivation strategy adopted, mussels are generally only graded when they are transferred from one bed to another or during harvest. For example, as discussed in the previous section, seed mussel that is initially laid on intertidal beds for a first season to initiate the hardening process would ideally be moved to deeper, subtidal beds for the grow-out phase. In these subtidal locations, mussels can feed continuously, promoting faster growth and improving meat yield in the final market-size stock.

To facilitate this transfer, and where a purpose-built dredging vessel is used, the stock is harvested from the intertidal seed bed and processed through the onboard grading equipment. This involves passing the mussels over a belt or metal grill with graded openings, allowing mussels of different sizes to fall into separate holds or containers positioned beneath the grader (grading equipment is described in more detail in Section 4.5.2 of this manual). The smaller and larger part-grown mussels can then be re-laid onto separate beds, ensuring that stocks of similar size are grouped together.

This approach allows the operator to harvest the larger, faster-growing mussels first, giving the smaller stock additional time to reach market size. It also ensures that mussels of comparable size are harvested simultaneously, improving operational efficiency and product uniformity.

### *Recommended densities depending on product size*

The harvesting density figures assume that a high percentage of individual seed mussels will be lost due to predation and other environmental mortality factors. This mortality rate can be in the region of 90 percent. As previously stated, many bottom-cultivation farms operate on the basis that if 1 000 kg of seed is laid onto the beds, the final yield will be approximately 1 000 kg of market-size mussels. In exceptionally favourable years, the yield may increase to as much as 3 000 kg for every 1 000 kg of seed sown.

However, when considering that 1 kg of small seed may contain up to 5 000 individual mussels, and that 1 kg of market-size mussels contains roughly 60 individuals, it becomes clear that extremely high mortality rates are inherent in this production method. Because of these losses, bottom-cultivation fisheries are only financially viable when seed can be harvested at no cost or at minimal cost, and the use of hatchery-produced seed, which must be purchased, is unlikely to be a feasible option.

TABLE 5.1
**Initial sowing densities and expected final harvest densities relative to mussel seed size**

| Seed size (mm) | Initial density (kg/m²) | Harvest weight (kg/m²) |
|---|---|---|
| 5–20 | 2–3 | 2–10 |
| 20–35 | 3–5 | 3–15 |

### *Recommended frequency for removal of predators*

The techniques used for the removal of predators (crabs and starfish) are discussed in Section 5.2.1. Although predation by birds can be the cause of significant losses from intertidal beds, there is no effective means of preventing this. Therefore, in areas where large predatory bird populations exist, it is recommended to use subtidal beds where possible or make allowances in the projected harvesting volumes for the anticipated losses.

TABLE 5.2
**Recommended frequency of removal of predators from mussel beds**

| Species | Frequency of removal |
|---|---|
| Crabs | Throughout the year, especially during times of population growth brought about by locally favourable conditions. Pots (Figure 5.7) can be lifted and emptied every few hours during peak periods or every few days during low population density months. |
| Starfish | Throughout the year, especially during times of population growth brought about by locally favourable conditions. It is important to monitor the population densities and adjust the removal schedule accordingly. During peak periods, it is good practice to drag the starfish mops (Figure 5.9) over the beds once a week as mass invasions can occur quickly. Starfish can move at an average speed of 1 m/minute. |

## 5.3.3 Dredging techniques

Dredging is arguably the most important technique to master when operating a bottom cultivation site. In this section, the manual will describe the approaches required to achieve this successfully.

### *Preparation whilst approaching the bed*

Before lowering the dredges onto the bed, it is essential to position the workboat correctly and ensure the dredges are properly set up. The vessel should begin its approach at least 50 m before reaching the start of the bed, giving the skipper sufficient time to select the correct course and achieve the desired speed. Maintaining good forward momentum is critical to ensure that, when the dredges contact the seabed, the vessel does not stall. An approach speed of approximately 2–3 knots is recommended, allowing the workboat to maintain a dredging speed of roughly 1–2 knots over the bed.

During the approach, the dredges must be correctly positioned and prepared. The leading edge and mouth should be oriented toward the bed, and the trailing-edge jaws must be properly locked. When checking the locking mechanism, it is important to remove any debris that could prevent the jaws from closing completely. Failure to do so can result in a frustrating situation where, at the end of a run, all the harvested mussels pass back through the belly of the dredge onto the bed.

Once the dredges are locked, they are extended over the sides of the vessel using the derricks and lowered into the water so that they are just below the surface, positioned behind the stern. As the bow of the vessel approaches the bed, the dredges are further lowered using the winches to ensure they make contact with the seabed before reaching the outer edge of the bed. This ensures that no mussels are missed along the perimeter.

### *During the tow*

The two most important elements to consider whilst dredging are speed and the angle of the dredge cable.

#### *Speed*

As noted above, it is important to maintain forward momentum when moving across the beds. As the dredges fill with mussels, the vessel will naturally slow due to the increased resistance on the seabed. The skipper must therefore increase engine revs while traversing the bed to maintain speed and prevent the boat from coming to a standstill.

However, excessive speed can cause the dredges to skip across the seabed, resulting in significant loss of mussels. A speed of approximately 1knot is appropriate when harvesting beds that are densely populated. As the density of mussels decreases with continued harvesting, increasing the speed to around 2 knots allows the vessel to cover a larger area, helping to maintain an efficient harvesting rate.

#### *Angle of dredge wire*

The angle of the dredge wire determines the angle at which the dredge contacts the seabed. The correct wire angle is critical for proper engagement with the bed and, consequently, for efficient mussel harvesting. When operating correctly, the leading edge of the dredge should pass beneath the mussels and cut through the layer of pseudo-faeces on which they rest.

If the wire is too short, the dredge will not engage firmly with the seabed and will skip over the mussels. Conversely, if the wire is too long, the dredge will dig into the seabed with excessive force, potentially becoming bogged down and causing the vessel to stall (Figure 5.26).

As a general guide, the length of the wire under water should be approximately 3–4 times the water depth. For example, in 4 m of water, the wire should be between 12–16 m, resulting in a wire angle of roughly 70°–75° (Table 5.3). With experience, the skipper can sense whether the dredge is skipping or digging too deeply and adjust the wire length accordingly.

A useful tip for beginners is to mark a reference line on the wheelhouse window with masking tape at the desired angle. As the cable runs from the end of the derrick to the water past the wheelhouse, the skipper can use this visual guide to monitor and maintain the correct dredge angle.

FIGURE 5.26
**Drawing illustrating the effect of different lengths of dredge wire on the interaction between the dredge and the seabed**
(a) Wire too long: dredge will dig into the ground and become bogged down, potentially causing the vessel to stop. (b) Submerged section of the wire set at good length (3 to 4 times the depth of water): Dredge will make good contact with the bed and harvest mussels efficiently. (c) Wire too short: Dredge will not engage firmly with the ground and it will skip over the mussels

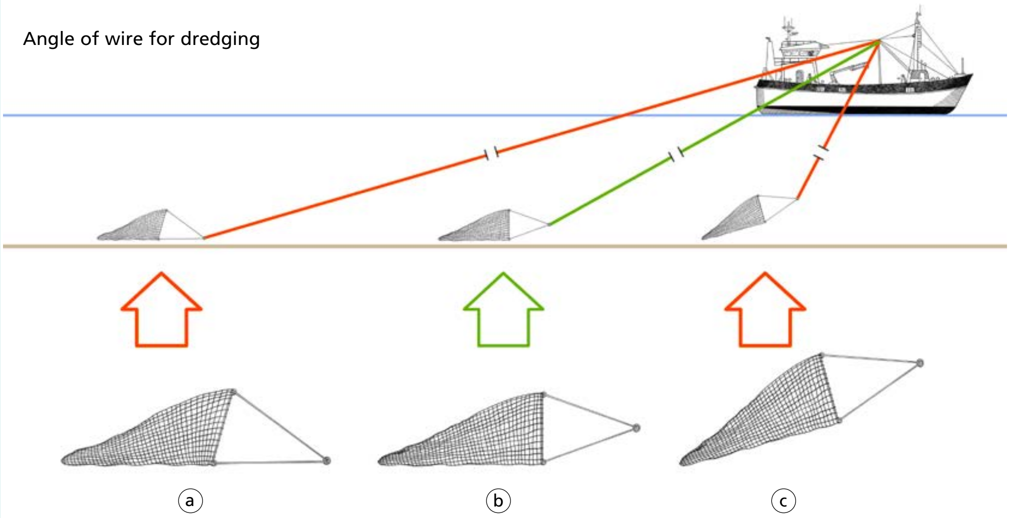



TABLE 5.3
**Table showing the relationship between water depth, wire length and angle of the dredge wire when undertaking dredging operations on the mussel beds**

| Depth of water (m) | Length of dredge wire (m) should be 3 to 4 times water depth | Angle of dredge wire (°) |
|---|---|---|
| 2 | 6–8 | 70° to 75° |
| 4 | 12–16 | 70° to 75° |
| 6 | 18–24 | 70° to 75° |
| 8 | 24–32 | 70° to 75° |
| 10 | 30–40 | 70° to 75° |

### *At the end of the tow*

It is imperative that the skipper continues to tow the dredges all the way through to the end of the bed to ensure that no mussels along the edge of the culture area are missed. The dredges trail a considerable distance behind the vessel, which varies depending on the water depth over the bed. For example, in 4 m of water, the leading edge of the dredge will be approximately 16 m behind the stern, so the skipper must account for this distance before beginning to haul in the dredges.

Both the port and starboard dredges should be winched in simultaneously to maintain a straight course. Raising only one dredge will cause the vessel to veer to one side, increasing the risk of a cable becoming entangled in the propeller. Once both dredges reach the surface, the skipper can safely change course.

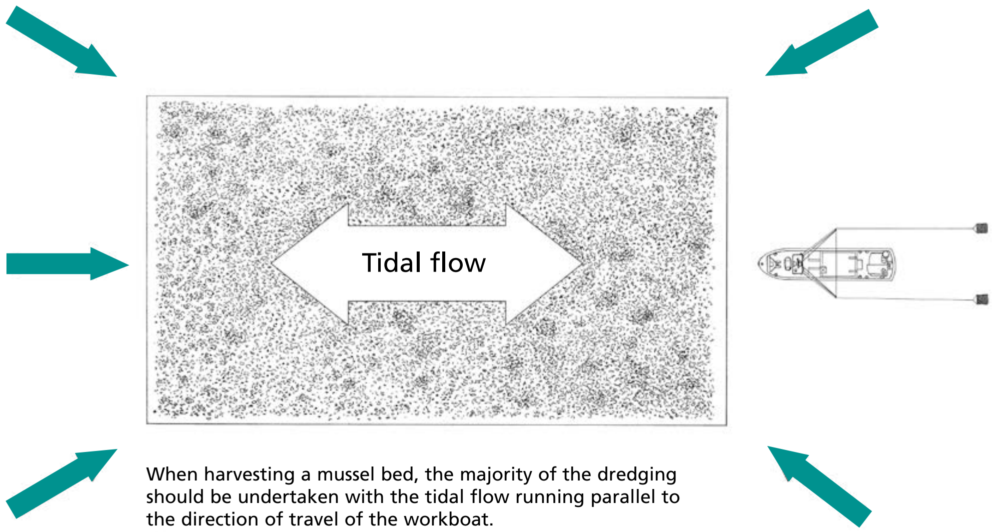
Before bringing the catch on board, the winches can be used to repeatedly lower and raise the dredges in and out of the water to remove as much excess mud and silt as possible. Once the mussels are relatively clean, the derricks can be swung inboard, and the dredges emptied either onto the grading line or directly into containers for offloading and processing ashore.

### *Vessel course over the beds*

When beginning to harvest a bed, the workboat should be steered along a course parallel to the longest side of the bed, working in straight lines both with and against the tide. Once the main bulk of mussels has been removed in this manner, the skipper should approach the bed from different angles, criss-crossing it in a diagonal pattern.

During harvesting, the dredge creates furrows in the seabed, leaving ridges alongside these tracks. These ridges can contain substantial quantities of mussels, and the most efficient way to recover them is by steering the workboat on a diagonal course across the bed (Figure 5.27).

FIGURE 5.27
**Diagram showing dredging from different angles of approach to bed when harvesting mussels**




When harvesting a mussel bed, the majority of the dredging should be undertaken with the tidal flow running parallel to the direction of travel of the workboat.

Once the bulk of the mussels have been cleared from the bed, it is then imperative to alter the angle of dredging, running diagonally to the tidal flow so that any mussels that remain are captured.

## 5.3.4 Harvesting strategy

Harvesting will take place from beds when the average individual size of the mussels has exceeded the minimum required size to be placed on the market. Harvesting can take place throughout the year depending on the condition of the mussels.

However, when the primary spawning event of the year occurs in late Spring, the exact timing of which is highly dependent on an increase in water temperature, harvesting should be avoided. During this period, gametes are released into the water and the meat can become deflated and thin thereby negatively affecting its quality. Secondary spawning events can occur over the summer period, depending on climatic and biological factors, so it is important to monitor the stock during this period and only harvest when the quality is of a sufficient standard.

Harvesting can be undertaken by dredging on the subtidal beds as described in the previous section. On the intertidal beds, harvesting should be done using a combination of dredge and hand picking. Once the number of mussels being recovered by each tow of the dredge has fallen dramatically, it becomes inefficient to continue gathering the mussels in this way. At this point, it is better to wait until the tide drops to reveal the bed and then harvesting can continue by hand. When done correctly, dredging is a very effective way of harvesting but there will always be mussels left behind, so picking by hand is the only way to ensure that the remaining stock is recovered.

### *Fit with market demand*

There will be certain times of year when the demand for mussels will peak. This can be due to certain public holidays, feasts and festivals or merely tradition. When considering harvesting and production strategy, it is important to take these times of intense demand into consideration to ensure that the farm is holding enough market size stock to fulfil this requirement.

### *Quality assessment*

When undertaking the final grade of the mussels before they are sold, the quality of the product must be thoroughly assessed. This will involve analysing the key factors that the customer will be concerned with: size, meat quality and taste, meat to shell ratio and exterior appearance if they are being sold into markets that will serve them in their shell. All of these aspects are discussed in detail in Section 2.2. Depending on which market they are being sold into, they can all play a part in determining the price that the mussels will demand. It is worth noting that, under normal circumstances, the price per kilo will increase as the size and meat to shell ratio increases.

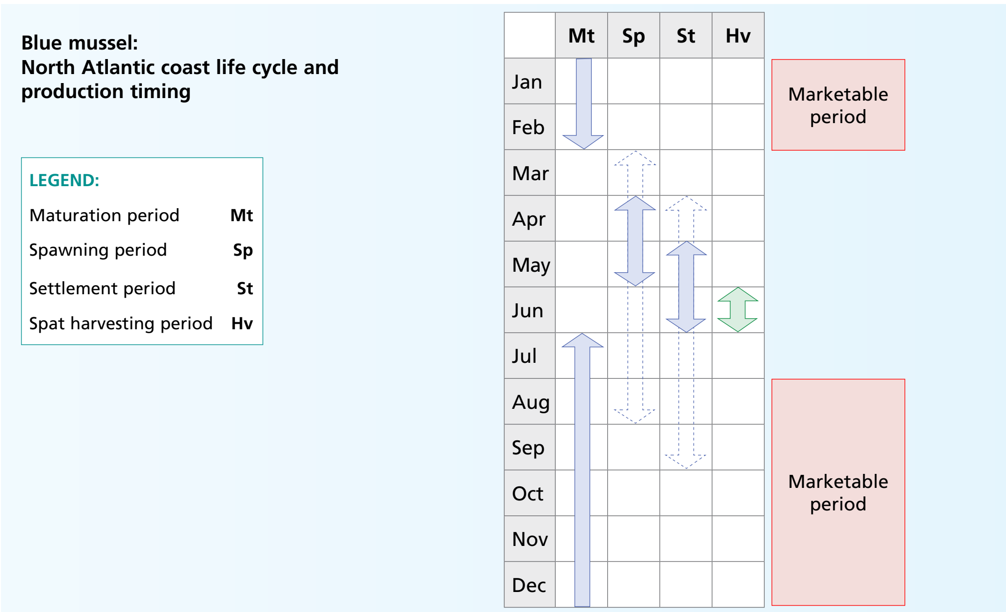
### *Handling and storage practises*

Due to the nature of the dredging process, the mussels are exposed to a certain amount of disturbance and stress, especially when they are discharged from the dredges into boxes on the deck and then when they are tipped from the boxes onto a grading or sorting line. Although these impacts are unlikely to cause mortality directly, except in molluscs with weaker shells, it is recommended to rest the mussels in seawater after these processes and before they are dispatched. This can be done by either placing them on intertidal foreshores or suspended in ventilated pallet tanks suspended from a raft or by depositing them in storage ponds or tanks where seawater is circulated through the shellfish by pumps.

## 5.3.5 Farming calendar

The farming calendar in Figure 5.28 refers to the reproduction and settlement timing of blue mussels in the North Atlantic region as described in Section 2.1 of the present manual.

FIGURE 5.28
**On-bottom blue mussel production cycle and farming schedule in the North Atlantic region**



### 5.3.6 Maintenance

There are a number of tasks that the operator should undertake on a regular basis to ensure that all of the equipment used to produce the mussels is maintained to a correct standard. The marine environment is particularly harsh on equipment and so to gain the maximum longevity and safe operation of the cultivation apparatus, regular checks and servicing should be mandatory. Some of the items that should be checked on are listed in Table 5.4.

*Workboat engine checks*

Each day, before starting the engine of the workboat, all of the oil levels (engine, gear, box, hydraulic), coolant level and fuel level should be checked to ensure that the vessel is fit to go to sea. Once the engine is running, the saltwater cooling system should be inspected to ensure that the correct flow is occurring.

TABLE 5.4
**Maintenance chart featuring daily, weekly, monthly and annual maintenance tasks**

| Task | Frequency |
|---|---|
| Workboat engine checks | Daily – Before use. |
| Check dredge for holes in metal and nylon mesh | Daily – Before use. |
| Check dredge cable for signs of fraying | Daily – Before use. |
| Fresh water wash-down of equipment | Daily – After use where possible. |
| Greasing | Weekly or monthly – Particular attention should be paid to equipment that is used on a daily basis. |
| Hydraulic hose replacement | Weekly – Check for signs of wear and abrasion. |
| Hydraulic valves and fittings | Monthly – Check for signs of corrosion and to ensure that the protective coverings are still valid. |
| Shackles and strops | Monthly – Check for signs of wear and abrasion. |
| Anodes inspection and replacement | Quarterly inspection – Replace anodes as necessary. |
| Servicing the workboat engine | In line with the manufacturer's guidelines regarding engine hours and usage. |
| Workboat hull inspection and upkeep | Annually – Check hull integrity, apply antifoul, replace anodes as necessary. |

*Check dredge for holes in metal and nylon mesh*

Dredges are usually constructed with steel mesh on one side and polypropylene mesh on the other side of the belly. The steel mesh is the one that is in contact with the seabed whilst dredging operations are underway. As such, it experiences wear and will need replacing when the mesh becomes thin or damaged. Tears can appear in the polypropylene mesh as well. These can normally be repaired using rope until the material becomes too damaged and then it will also need replacing. Running repairs on both types of mesh are essential and inspection of these items should be carried out every day before dredging commences. Any large holes in the mesh will result in mussels passing through and lead to lower catches and missed stock.

*Check dredge cable for signs of fraying*

The steel cables that are attached to the dredges and are used to haul them in by the winches can become worn and frayed. The main area of wear is usually along the length of cable that runs through the pulley blocks that it passes through towards the end of the derricks. As soon as fraying is visible, it is recommended to cut this section off so as to minimise the risk of losing the dredge whilst it is underwater being towed along the seabed. The cable should also be greased on a regular basis to minimise the effects of corrosion. Even with careful maintenance, it is possible that a cable will break during dredging due to the forces applied to it during operations. A separate rope and small pick-up buoy can be attached to the dredge before deployment so that, in this eventuality, it can easily be located and recovered.

*Freshwater wash-down of equipment*

Any equipment that is exposed to salt water should be washed down with freshwater after use when possible. Even items built of stainless steel can rust in certain conditions although not as swiftly or seriously as regular steel. Equipment with moving parts can get clogged up with debris and salt deposits from activities such as grading so it is recommended that they are cleaned on a regular basis.

*Greasing*

Regular greasing of any components that require lubrication should be carried out in line with the manufacturer's recommendations.

*Hydraulic hose replacement*

If the operator is using any pieces of equipment that are powered by hydraulics, such as the crane and derricks, then all hydraulic hoses should be checked for wear and abrasion on a regular basis. Hoses that are exposed to the elements, particularly ultraviolet light (UV) and salt water, will perish over time. If a hose bursts whilst under pressure it can create a dangerous situation for anybody working in the vicinity of the stricken piece of equipment. Also, the consequent loss of hydraulic oil into the water around the boat will have a negative effect on the environment and must therefore be avoided at all costs.

*Hydraulic valve and fittings protection*

Many of the metallic fittings, such as the hose connectors and the hydraulic valves themselves, are prone to corrosion and should be protected from the elements as much as possible. Where possible, they should be wrapped in corrosion prevention sealing tape or spray to maintain their integrity.

*Shackles and strops*

All lifting gear must be checked for signs of wear and replaced when necessary. Particular attention should be given to any shackles that are used on a daily basis for dredging and lifting as they will incur the most attrition. As well as checking for wear, the operator should also ensure that all shackle pins are tightened and secured. Any shackles that are used for these operations should be tested and certified to ensure that they are suitable for this purpose and for the forces that will be applied to them.

*Servicing the workboat engine*

Mechanical breakdowns of any propulsion unit at sea can have serious consequences for the crew of the vessel, so it is imperative that regular servicing of the main engine is carried out in line with the manufacturer's guidelines.

*Workboat hull inspection and upkeep*

The hull of the vessel spends the majority of its existence submerged in salt water. As such, depending on the construction material used, corrosion and deterioration can take place and so it is vital to regularly check that the integrity of the hull is maintained to ensure that there is no danger of water ingress. The vessel should be lifted out of the water to allow a full inspection of the hull to occur. An annual application of antifoul is recommended to protect the hull. This also reduces biofouling which will maximise the hydrodynamics of the vessel and thereby reduce fuel costs. If the hull is of metal construction, then anodes must be checked and replaced when their effectiveness has been reduced through galvanic corrosion.

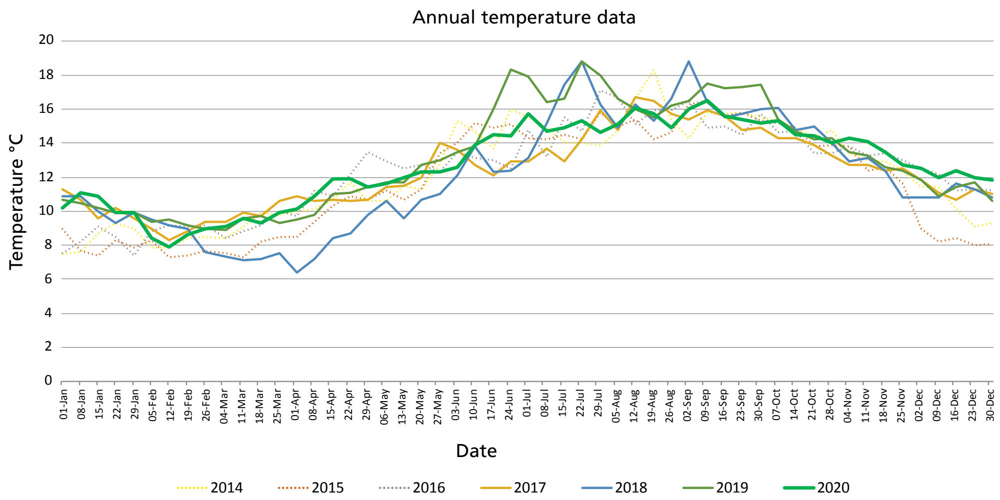
### 5.3.7 Monitoring and traceability

*Data collection*

It is important to collect comprehensive data on the aquaculture production area in order to develop a detailed understanding of the environmental and operational factors that influence mussel growth.

As each season passes, the data collected can be analysed and used to predict expected growth rates, serving as a valuable tool to guide the operator in decisions regarding stock management and harvesting. Parameters that can be monitored include water temperature (Figure 5.29), salinity, monthly mussel growth rates, monthly meat-to-shell ratios, and monthly mortality figures.

FIGURE 5.29
**Example of annual water temperature data graph**






*Stock charts*

Stock management charts are an essential tool for keeping track of the mussels that are in the production cycle and determining what actions need to be taken and when to maximise the production capacity and quality of the product. An example of a stock management chart can be seen in Figure 5.30 below.

FIGURE 5.30
**Mussel bed stock chart**

| A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| Mussel bed name | Species | Date seed mussel laid | Average size of seed (mm) | Density at time of dispersal (kg/m$^2$) | Expected harvest date | Comments |
| B | *Mytilus edulis* | 22.08.23 | 15 | 3 | 01.03.25 | Starfish present on beds |

## 5.4 MAIN CONSTRAINTS

As mentioned previously, one of the main constraints of this particular technique is the general exposure of the mussels to both physical and environmental threats. As they are not enclosed by any cultivation equipment, they have no protection from predation or from boats anchoring or going aground on the beds and causing damage to the shells. In the case of a negative environmental event, they are unable to be moved quickly out of harm's way because of the dispersed nature of the stock. Because the beds are situated in the intertidal or shallow subtidal zone, they are exposed to any contaminants or excessive freshwater run-off from the land and, as such, can suffer from highly variable water quality issues. They are thus more likely to be closed for harvesting operations due to these factors when compared to cultivation systems that are situated further from the shore. They are also more easily accessible and therefore more prone to human intervention with issues such as theft and tampering with the stock being a possibility.

### 5.4.1 Environmental constraints

Intertidal and nearshore sites, such as the locations necessary for bottom cultivation, are by their nature highly impacted by environmental influences issuing from the land next to which they are situated. There are a number of different factors that must be considered when discussing these issues:

*Salinity*

Due to the proximity of freshwater sources such as rivers, the salinity at these sites can vary substantially depending on seasonal rainfall and its effect on fluvial discharge and terrestrial runoff. An increase in freshwater inflow into an estuarine or nearshore environment will reduce salinity levels. Salinity is a key factor influencing mussel filtration rates; under typical conditions, lower salinity slows filtration, which can, over an extended period, reduce growth rates.

Freshwater entering a waterbody does not immediately mix with the saltwater, often leading to stratification. Because freshwater is less dense than seawater, it naturally floats above the denser saline layer. The degree of mixing between these layers is influenced by tidal range and currents, wind speed and direction, bathymetry, and the rate of fluvial discharge. In extreme cases, a distinct wedge of freshwater can form at the surface, with minimal mixing with the underlying saltwater. If mussels remain within this low-salinity wedge for an extended period, mortality can occur due to salinity falling below their tolerable range.

*Water quality*

Water quality is influenced by the level of contaminants entering the marine environment. These contaminants can originate from a variety of sources, including sewage overflows, agricultural runoff, discharges from industrial facilities, coastal mining activities, and pollutants introduced by other marine users. The impact on water quality varies depending on the nature of the contaminant.

For example, sewage overflow and runoff from agricultural operations involving animal manure can increase levels of Escherichia coli in the water. This poses a health risk to humans consuming fresh, untreated bivalves that have been filtering the contaminated water. Such contamination can also result in temporary or permanent closure of production areas if the local regulatory authority determines that the harvested product is unfit for human consumption (see Section 2.3 and Appendix I).

Because bivalves are filter feeders, they are particularly vulnerable to waterborne contaminants. It is therefore essential for farm operators to be aware of potential pollution sources in the vicinity of the farm and to have a management plan in place to address contamination events.

*Eutrophication*

Eutrophication is the process by which a body of water becomes enriched with excessive nutrients, leading to an unnatural proliferation of algae and marine plants. As these organisms die and decompose, bacteria that consume them use up oxygen and release carbon dioxide, resulting in hypoxic conditions. Marine organisms, including bivalve molluscs, rely on dissolved oxygen to survive, and depletion to critical levels can cause mass mortality in the affected area. The carbon dioxide released during decomposition also lowers the pH, leading to acidification of the water. Among other consequences for the broader marine environment, these conditions can negatively affect mussel growth, reproduction, larval development, settlement, and shell formation.

### 5.4.2 Conflicts for site availability and licensing

Areas of coastal foreshore and nearshore marine zones can serve a wide range of stakeholders beyond aquaculture businesses. These include, for example, moorings for pleasure craft, tourism operators, local residents, property developers, marine protected areas, sewage treatment discharge outlets, and boatyards. Many of these stakeholders have very different priorities regarding the use of available space, which can lead to conflicts of interest.

Competition for space in these highly desirable areas is often intense, making it challenging to secure licenses for bivalve cultivation, particularly if the proposed operation interferes with established activities. It is therefore important to engage not only with the relevant licensing authorities but also with other local stakeholders to explore potential compromises that allow these diverse activities to coexist harmoniously.

# 6. Offshore long-line cultivation



## INTRODUCTION

This chapter focuses on long-line farming conducted in offshore conditions providing all the main farming techniques and equipment that will be needed to operate a long-line farm. Farming takes place in net socks, or drops, into which the mussels are introduced and then hung along the headline at regular intervals (Figure 6.1).

FIGURE 6.1
**Offshore long-line farm in the Adriatic Sea, Italy**

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This cultivation technique is relatively recent and has developed after World War II as a result of the availability of new farming equipment and techniques suited to growing mussels in exposed conditions.

Compared to on-bottom farming (see Chapter 5), investment is higher, farm design more complex and farming operations more time-consuming despite the automation of certain production processes. These challenges require a different approach with regards to the organisation and economy-of-scale of the entire farming operation.

The techniques detailed in this chapter are those employed in commercial farms operating in the Adriatic Sea at water depths ranging between 10–20 m. In the case of open ocean locations, the culture structures, materials and farming activities described in the subsequent sections of this chapter would need to be redesigned to allow farming to take place in more exposed conditions and tested before undertaking any significant investments. In the case of relatively sheltered sites, the reliability and the resistance of long-lines will be less important, while minimizing operational costs will be the determining factor in the viability of a farm.

## 6.1 SITE SELECTION

### 6.1.1 Overall approach

All the conditions and environmental parameters listed and described in Chapter 3 will have to be carefully considered when selecting a site to establish a long-line operation. If no farming activities exist or have been previously carried out in the identified area it is advisable to consult a site expert and analyse available historical data on weather and sea conditions.

If an identified site presents similar conditions to those described for the Adriatic Sea, this production technique can be considered fully standardised and tailored for offshore farming. Nevertheless, the existence of on-site logistical support and the availability of equipment and service suppliers will have to be assessed.

An entrepreneurial approach will be required to maximise the chances of success, with a thorough analysis of the financial investments required to set up and run the farm. This approach is strongly recommended, regardless of whether the farmer intends to undertake much of the operation set-up on his own or opts to purchase a ready-to-operate and "all inclusive" farm, noting that long-lines will require regular maintenance and logistical support. "Economies-of-scale" are relevant at all production scales, regardless of whether the farming operations are small or large.

Some key criteria will have to be considered when selecting a site to establish a commercial farm:

- The exposure of the farm site must not be excessive, whereby the relationship between water depth, maximum wave height and average wave period must be suitable.
- According to the envisaged long-lines design and workboat dimensions, the number of days that the farm cannot be accessed due to adverse weather conditions should not exceed 50–60 days/y.
- The seabed slope should not be too steep or uneven as to impede the installation of the long-line mooring system.
- Suitable landing facilities must be available in the vicinity and the time to reach the farm from the nearest harbour must not be excessive.

### 6.1.2 Water depth, tidal range and exposure

In relatively exposed offshore sites, the depth of the water column stands as the pivotal parameter and primary limiting factor when assessing the suitability of a location for long-line farming. It is important to take into consideration the following observations:

- If the average depth of the site is less than 10 m, the available space for installing farm structures and suspended cultivation devices will be suboptimal. This situation may result in farmed mussels coming into contact with the sea floor, which is undesirable.
- Conversely, when the average depth of the site exceeds 30 m, underwater diving operations become exceedingly demanding. The extended decompression periods required under these circumstances will significantly prolong installation and maintenance efforts, thereby adversely affecting production costs. In this case, investment will be also higher due to the longer mooring ropes.
- The average water depth is closely linked to the local tidal range, thus exerting a direct influence on the feasibility of the farming endeavour.
- Wave height and wave period exhibit a partial dependency on the average depth of the water column. This factor contributes to the overall assessment of site suitability.
- Sites with depths greater than 10–15 m and high turbidity may encounter reduced light penetration. These environmental conditions can diminish phytoplankton availability, thereby impeding the growth of the farmed mussels.

A thorough understanding of these depth-related considerations is essential for making informed decisions regarding the feasibility of long-line mussel farming in exposed offshore sites.

Furthermore, exposed open sea sites characterized by high tidal ranges pose significant challenges when it comes to designing mooring systems capable of accommodating the substantial fluctuations in the distance between the sea surface and the sea floor, stemming from the cumulative impact of the maximum tidal range and maximum wave height. Engaging in farming under such extreme conditions appears impractical and economically unviable when considering the utilization of existing, well-established farming equipment and techniques.

Relative wave height and the occurrence of breaking waves tend to increase as water depth decreases, while wave period exhibits a proportional increase with greater depths. Regardless of the water depth, both wave height and wave period also depend on the fetch and wind forces affecting the designated production area. The combination of these parameters leads to a wide range of potential conditions that require site-specific evaluation. Along the Adriatic Sea shoreline, characterized by shallower depths ranging from 10–20 m, limited fetch distances of less than 500 km, and short storm durations not exceeding 72 hours, conditions result in concise breaking waves with significant heights measuring less than 6 m. In contrast, the vast expanse of the Atlantic coast features deeper waters and longer fetch distances, resulting in waves characterized by extended periods and infrequent breaking, with significant heights exceeding 8 m. Regarding the resilience of long-line systems in the face of storms, it is important to note that waves with comparable significant heights, yet shorter and more turbulent, can cause more substantial damage than their elongated, non-breaking counterparts.

Ultimately, the exposure level of a selected farming site depends on the coastal configuration and geographic location. Sites situated within relatively sheltered bays or coastal regions where fetch distances and prevailing storm winds are limited should be the preferred choice.

### 6.1.3 Sea bottom

Installing moorings for farm structures becomes challenging when the sea bottom exhibits irregularities, a steep slope profile, or rocky terrain. In cases where water depths feature vertical variations exceeding 3–5 m on short distances, each mooring line must be of a specific length corresponding to its position on the seabed. The associated installation costs and ongoing maintenance of moorings in such locations are likely to be excessively high. In areas with a sharply inclined seabed, it may be difficult in install the desired number of long-line units within the mooring depth range of 10–30 m. Furthermore, in areas with rocky substrates, there exists a risk of concrete blocks or anchors slipping or shifting from their initial positions.

### 6.1.4 Currents, water quality and nutrients

In offshore locations, even in areas with larger tidal ranges, tidal currents tend to be lower when compared to intertidal or subtidal zones. In offshore conditions, the currents, which are mainly influenced by geophysical configurations of the coast, typically remain below one knot. When selecting a site, it is advisable to opt for one where the average current speed preferably exceeds, 0.4–0.5 knots (equivalent to 20–25 cm/s).

Moving farther offshore, away from anthropogenic activities and river discharges, generally leads to improved water quality characterized by reduced eutrophication and pollution levels. This improvement can offer a significant advantage in terms of minimizing contamination risks and enhancing meat quality. However, this shift also leads to lower plankton concentrations, which can limit both growth and meat content. In the site selection process, when determining the distance from the shore, striking a balance between these parameters becomes crucial. It is important to note that excessively oligotrophic waters should be avoided to ensure optimal conditions for cultivation. Chlorophyll-α concentrations of more than 1–2 µg/L are recommended.

## 6.2 FARM DESIGN

As mentioned in the introduction, mussel farming takes place in net socks, or drops, into which the mussels are introduced and then hung along the headline at regular intervals (see Figure 6.1).

To design and construct appropriate long-lines for offshore sites, it is imperative to conduct calculations pertaining to the forces the system is anticipated to endure. The entire system should be designed with sufficient resilience to withstand these forces. As a result, it is highly advisable to seek guidance from a specialist with expertise in these matters to obtain the essential information and cost estimates. In situations where a custom farm design is necessary for the specific site due to the absence of a proven, demonstrated, and standardized solution, it is advisable to embrace a progressive approach. This approach involves conducting initial tests with a prototype, followed by iterative refinements and replication, before proceeding with the installation of a full-scale farm.

The following chapter sections describe the long-line system widely utilized along the western coast of the Adriatic Sea for mussel farming. Since the shoreline exhibits considerable similarity in numerous coastal areas, featuring extensive sandy regions at depths ranging from 10–20 m, "sub-floating long-line" systems have been standardized and replicated in various locations. Typically, two farm systems are installed and selected based on considerations such as water depth, site exposure, and the personal preferences of individual farmers:

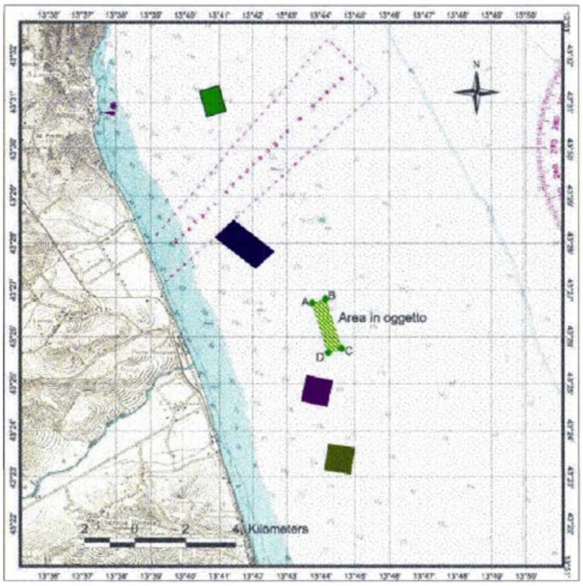
- "Sub-floating long-lines" consisting of numerous short and separated mainlines (refer to Figure 4.21c, Figure 6.3 and Figure 6.4), with each mainline typically measuring between 150–300 m.
- "Sub-floating long-lines" configured with a smaller number of longer mainlines (as shown in Figure 4.21d), where the mainline length typically span from 1 000–2 000 m, with intermediate legs fixed at intervals of 150 to 250 m.

In farm sites that are more exposed to adverse conditions such as short-period waves with a maximum height exceeding 4 m and strong currents, it is advisable to opt for the first type of long-line configuration. Short, independent units are recommended as they offer greater resistance and reliability compared to the second type.

The advantages of using short, independent headlines are as follows:

- The occurrence of an event, such as the breakage or detachment of a mooring line, does not impact the stability of nearby lines.
- Shorter lines result in lower forces exerted on the structure. For example, a 200 m headline with 180 mussel socks, each weighing approximately 30 kg, will experience less mechanical stress than a 300 m headline with 270 mussel socks of the same weight.
- In the event of a breakage, shorter lines result in a smaller loss of equipment and product.

FIGURE 6.2
**Example of an offshore long-line farm map where points A, B, C and D are the coordinates of the concession area**




In the context of extended headlines, should the main or intermediate mooring line experience breakage or detachment, the increased forces exerted on the remaining components of the culture system can potentially trigger a chain reaction leading to further rupture or detachment of other lines. This domino effect may culminate in the total loss of significant equipment and product.

Shorter lines, while offering reduced risk, come with higher associated costs and diminished capacities. This is primarily due to the unutilized spaces between the lines, which cannot be harnessed for production purposes. The resistance and cost factors are also contingent upon the materials employed and the design of the aquaculture farm. Notably, these factors hinge on the type and diameter of the ropes used, the anchoring mechanisms, and the arrangement of the buoys.

From this point onward in this chapter, all the particulars discussed pertain to a long-line farm situated in a semi-exposed location (Figure 6.2). This farm consists of 12 lines, each spanning 2 km and featuring ten independent headlines, each of approximately 180 m in length. The spacing between these lines is approximately 50 m, as depicted in Figure 6.3.

FIGURE 6.3
**Example of long-line mussel farm in the Adriatic Sea, Italy**

To provide the reader with a comprehensive understanding of the environmental conditions prevailing at the farm detailed in this chapter, the main site characteristics are outlined below:

- Water depth ranges from 13–14 m, with a minimal tidal fluctuation not exceeding half a meter.
- The seabed consists of a sandy flat terrain.
- The maximum wave height observed in this region reaches 4–5 m.
- Consistent currents flowing north to south are present, with velocities ranging from 0.1–1.0 knot, depending on the season.
- Water stratification is limited due to the pervasive influence of currents throughout the entire water column, with greater intensity observed near the seabed. Consequently, the presence of a thermocline is sporadic and predominantly occurs during summer months when there is a decrease in current strength and an increase in surface water temperature.
- The farm is situated 3.5 nm away from the coastline and 6 nm from the nearest harbour.

### 6.2.1 Long-lines

A long-line aquaculture farm comprises navigation markers delineating the boundaries stipulated in the license agreement, as well as the long-lines employed for suspended cultivation (Figure 6.4). In floating and semi-submerged long-line systems (see Figure 4.21), both navigation markers and buoys are visible from the surface, as depicted in Figure 6.5 and illustrated in Figure 6.16 and Figure 6.17. On the other hand, in the case of fully submerged long-lines, only the navigation markers remain visible.

#### *Distance between the lines*

The spacing between two parallel lines must be sufficient to facilitate the manoeuvrability of the workboat, as detailed in Section 6.2.4. Ideally, this distance should be approximately three times the length of the workboat. In cases where the topography of the seabed necessitates a narrower gap between lines, the workboat should be equipped with propellers and navigation devices designed to facilitate navigation within confined spaces.

In the farm configuration outlined in this chapter (see Figure 6.2, Figure 6.3 and Figure 6.4), the separation between the culture lines is approximately 50 m, while the total length of the workboat is 17 m.

#### *Long-line components*

As previously introduced in Section 4.4, which discusses long-line typologies and their associated components, each long-line, from the seabed to the water's surface, encompasses the following elements:

**Anchorage devices:** These are fixtures to which the mooring lines are affixed, ensuring stability and secure positioning.

**Mooring lines:** These lines are integral to maintaining tension within the aquaculture system. Buoys, positioned at various depths, contribute to this tension by keeping the mooring lines taut.

**Headlines:** These components serve as the primary support for the cultivation devices employed. They are attached to the mooring lines at the upper end, closer to the water's surface. Headlines can either operate independently or be equipped with intermediate mooring lines, also referred to as intermediate legs, depending on the specific aquaculture system design.

**Buoys:** These buoyant structures, which come in various shapes and sizes, play a pivotal role in maintaining the entire aquaculture system under tension within a single plane.

FIGURE 6.4
**Example of an offshore long-line farm layout**

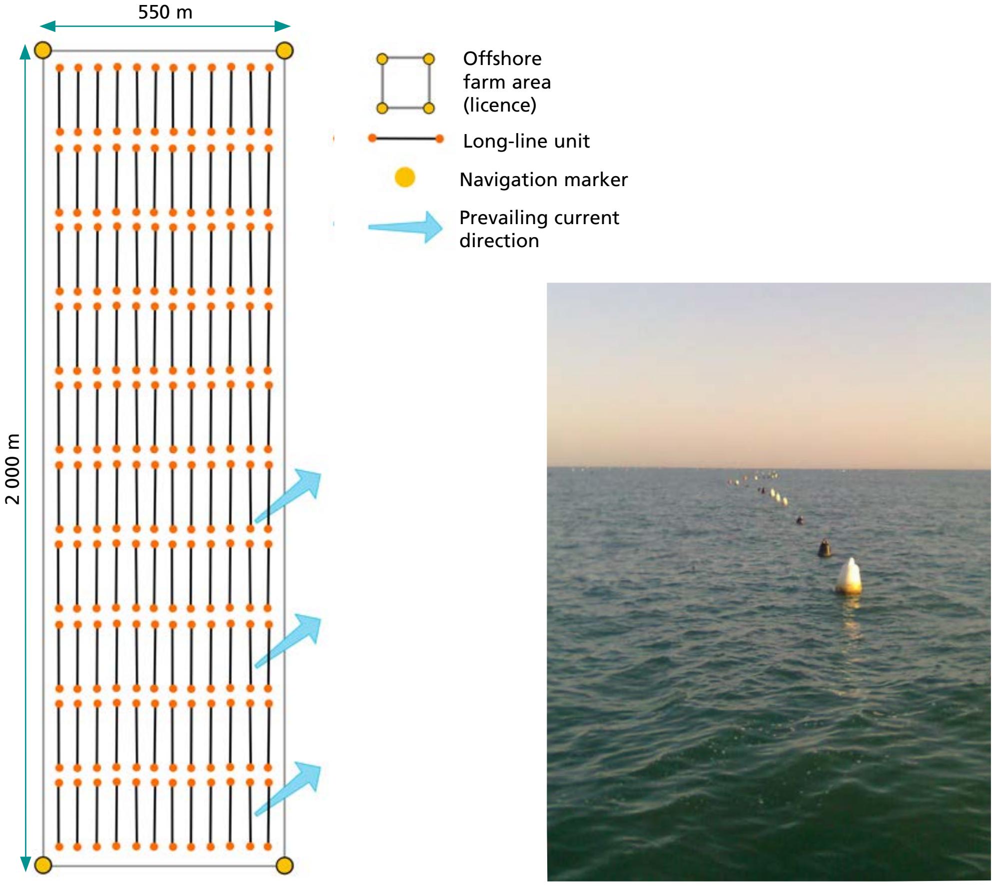



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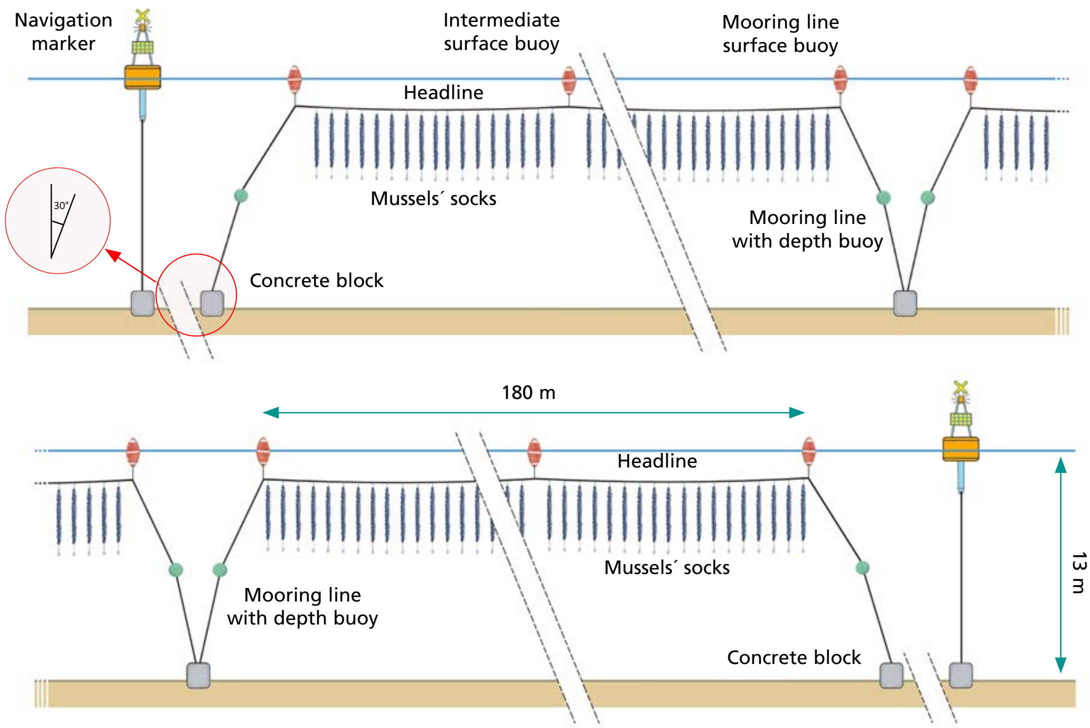
FIGURE 6.5
**Illustration of a long-line section typically in use in the Adriatic Sea, Italy**



### *Anchoring system*

The anchoring system must be meticulously engineered to enable the long-lines to withstand and endure extreme events, a critical consideration for all floating aquaculture systems. In the case of a sandy seabed, viable options for anchoring include the utilization of concrete blocks, surface anchors, or screw anchors, as illustrated in Figure 4.22 and Figure 4.23. These anchoring solutions are chosen based on their compatibility with the specific seabed conditions, ensuring the long-lines' stability and resilience even in adverse circumstances.

*Construction of the concrete blocks*

Considering the conditions mentioned and the specific characteristics of the described aquaculture farm, which features a sandy-muddy flat bottom, the anchoring solution chosen consisted of cubic reinforced concrete blocks (Figure 6.6). These blocks have approximate dimensions of 1.75 × 1.75 × 1.75 m, resulting in a volume of approximately 5.5 $m^3$ and a total weight of around 12.5 t, given that concrete typically exhibits an average density of about 2.2–2.4 $t/m^3$. Given the likely susceptibility to extreme storm events attributed to climate change, it is strongly advisable to contemplate the deployment of heavier mooring blocks.

To optimize the contact area between the block and the seabed, it is recommended that the length and width slightly surpass the height. Moreover, in scenarios with particularly soft seabed conditions, where there is a risk of blocks sinking deeply into the substrate, the height should be at least 1.5 m. This ensures that the hooks on the upper portion of the blocks remain consistently visible for inspection and maintenance purposes. Additionally, longer, lower-profile blocks are less prone to tipping over during storms.

Furthermore, in cases where the seabed exhibits a shallow incline and possesses a highly compacted nature, it is preferable to employ concave cavity blocks (see Figure 4.23). These blocks feature a partially empty lower surface, creating a suction effect, which helps mitigate the risk of slippage and ensures enhanced stability.

When fabricating reinforced blocks for aquaculture applications, it is imperative to adhere to specific precautions:

**Proportions of cement and aggregates:** Care must be taken to ensure the right proportion of cement to sand and gravel, a critical factor for the long-term durability of the blocks.

**Utilization of additives:** Additives should be incorporated into the block mix to diminish the penetration of seawater and mitigate corrosion-related processes.

**Reinforcing steel rebar:** The steel rebar, with a diameter ranging from 16–20 mm, must consistently remain at least 5 cm beneath the surface of the block. For optimal corrosion resistance, it is advisable to utilize 310/316 stainless steel rebar.

**Integration of hooks:** The hooks, crafted from the same rebar material, should be securely fastened to the internal rebar structure of the block.

**Additional hook:** It is imperative to include an extra hook in the block's design. This additional hook serves two essential purposes: assisting in sinking the block and facilitating the installation of the mooring lines.

The fabrication of these blocks can be carried out either by the farm operator or by a specialized enterprise. To minimize transportation and loading costs, it is advisable to construct the blocks near the harbour.

*Installation of the concrete blocks*

As workboats commonly employed in aquaculture operations may not be suitable, this operation often necessitates the involvement of a specialized enterprise and a dedicated vessel equipped for this specific task. Concrete blocks should be transported to the installation site via a vessel designed with adequate buoyancy and equipped with a hydraulic-powered crane or derrick for handling these substantial blocks. Alternatively, they can be towed to the site while suspended in the water using temporary buoys.

Subsequently, employing a GPS system or an equivalent technology is imperative to achieve precise positioning of the blocks. Accurate placement is paramount, as it ensures that the subsequent installation of the mooring lines can attain the requisite tension for optimal performance. This positioning work should ideally be executed during a period characterized by favourable meteorological conditions and when bottom currents are not excessively strong, safeguarding the safety and efficiency of the installation process.

FIGURE 6.6
**Long-line mooring concrete blocks**

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### *Ropes for mooring lines, headlines and buoys*

Ropes are the key components of a long-line culture systems, and as such, the careful selection of rope type and the materials from which they are constructed is of primary importance in ensuring the successful installation and operational efficacy of the aquaculture farm.

An array of rope configurations exists, including but not limited to braided, double braided, and twisted strands, each offering distinct advantages. These ropes can be manufactured from a variety of materials, such as polyester, nylon, polyethylene, polypropylene and Polysteel. Consequently, rope characteristics and prices can differ considerably.

In the selection of ropes, several critical factors need careful consideration, as they will significantly impact the operational integrity and efficiency of the farm system:

**Tensile strength when wet:** Ensuring robust tensile strength, especially when exposed to adverse weather conditions, is imperative to prevent rope breakage.

**Resistance to wear:** Ropes are subjected to considerable wear during farming operations. Therefore, choosing ropes with high resistance to wear, minimizing fraying, is essential.

**Longevity:** The longevity of ropes hinges on various factors, including the material composition, diameter, and anti-UV treatment. These aspects collectively affect the durability of the ropes.

**Elasticity:** Minimizing elasticity of the ropes is desirable to maintain stability within the aquaculture system, as excessive stretching can disrupt operations.

**Elongation over time:** Many ropes may experience lengthening after installation and necessitate periodic tensioning over several months, making this an important consideration.

**Density and flotation characteristics:** The density and flotation properties of ropes play a role in their buoyancy and how they interact with the aquatic environment. Buoyant ropes are easier to install as they remain visible on the surface.

Considering the intricacies involved in rope selection, it is highly advisable to engage with specialized rope suppliers and review technical data sheets before making a procurement decision. This ensures that the chosen ropes align with the specific needs and demands of the operation.

In the example outlined in the following section, the ropes used are as follows:

- Units of 20 m in total length of 36–40 mm diameter: double braid nylon ropes for mooring lines.
- Units of 200 m in total length of 32–36 mm diameter: Polysteel twisted 3-strand ropes for headlines (see blue rope in Figure 6.15).
- Units of 4 meters of 16–20 mm: double braid nylon ropes for buoys.

*Cutting ropes*

When it comes to cutting ropes, it is important to use methods that effectively prevent fraying. For ropes with a diameter ranging from 30–40 mm, the recommended approach involves utilizing an angle grinder. This tool generates heat during the cutting process, effectively welding the filaments and strands together. Alternatively, there are specialized heating tools designed specifically for this purpose.

For smaller diameter ropes ranging from 10–20 mm, there are two viable methods. One option is to employ dedicated heating tools designed for precision cutting. Alternatively, a simpler approach involves using a knife after creating 4–5 loops with robust adhesive tape at the intended cutting point, as shown in Figure 6.7. This technique ensures a clean and fray-resistant rope end.

FIGURE 6.7
**Cutting small diameter ropes**



*Surface buoys components and assembly process*

Surface buoys are integral components of the mooring line or will be affixed to the headline to provide buoyant support to the devices containing the farmed organisms. In preparing the buoys for deployment, the assembly process outlined below must be followed.

Concerning the farm layout described in this chapter, the specifications for each buoy at the upper extremity of the mooring lines are as follows:

- One double braid 20 mm nylon rope unit of 4 m.
- One surface 150–180 L bi-conical buoy filled with polyurethane, to be positioned at the upper segment of the mooring line.
- One unit of transparent, flexible, antifreeze PVC garden hose pipe of 0.3 m with an internal diameter not less than 20 mm, intended for reinforcing the rope at the point of attachment to the buoy.

The nylon rope is inserted into the hose section and secured with a knot, ensuring that 0.5 m of free rope remains for fastening with a thin nylon cord measuring 2–3 mm, as illustrated in Figure 6.8. Once the knot is securely fastened, the hose should remain firmly fixed in place.

The specifications for each intermediate buoy are as follows:

- One double braid 16 mm nylon rope unit of 4 m.
- One surface 120–130 L bi-conical buoy filled with air (pressure >0.8 bar/atm).

The nylon rope is threaded through the mooring eye and fastened securely with a knot. It is important to leave an additional length of approximately 0.5 m of free rope, which is used for tying a security knot, as depicted in Figure 6.9.

FIGURE 6.8
**Knot used to secure a surface buoy of a mooring line**
(views from both sides)



FIGURE 6.9
**Knot used to secure an intermediate surface buoy**
Visible the security knot to prevent the rope from becoming dislodged



### *Mooring lines*

In order to maintain the system under proper tension and within the same plane, it is imperative to maintain an angle of approximately 30 degrees between the mooring line and the vertical reference. As a result, for a water depth of 13 m, the total length of the mooring line, prepared for installation, should be approximately 15 m. Further calculation must account for the extra length of rope needed to accommodate all the knots, thereby the individual mooring unit should measure approximately 20 m.

In contrast to fish cages, which exhibit considerably higher resistance to marine currents, the utilization of bottom chains affixed to the concrete block or anchor is unnecessary.

The following sections provide a comprehensive explanation of the assembly and installation procedures for the mooring lines necessary for the farm layout outlined in this chapter. These mooring lines correspond to the sub-floating long-lines shown in Figure 4.21c, featuring a tension buoy (see Figure 4.22) and a simple concrete block (see Figure 4.22). The overall layout of the farm is further illustrated in Figure 6.3 and Figure 6.4.

*Mooring lines components (excluding surface intermediate buoy)*

The specific components required for a single mooring line are itemized below:

**Rope:** As previously indicated, 20 m of a double braid 36–40 mm nylon rope is recommended. For optimal reliability and durability, it is important that the rope remains in one continuous single piece.

**Thimbles:** One thimble is needed, constructed from zinc-plated high-quality steel, with an estimated lifespan of approximately 4–5 years.

**Shackles:** One shackle is necessary, also made from zinc-plated high-quality steel, with a projected lifespan of around 6–7 years. The shackle should have a load capacity of 9–10 t and should be equipped with bolt, nut and pin.

**Rope clamp:** One rope clamp, composed of zinc-plated high-quality steel, is required.

**Submersible buoy:** A submersible buoy with a volume of 90–110 L (approx. 0.5–0.6 m. if spherical) is essential. This buoy should be filled with polyurethane and equipped with a central hole adapted to the diameter of the utilized rope. It is to be positioned on the mooring line approximately 5–6 m above the sea floor.

**PVC garden hose pipe:** A single unit of 1.0 m of transparent, flexible and freeze resistance PVC garden hose, with an internal diameter >40 mm. This unit is employed to reinforce the rope rings where the headline and the main buoy will be securely fastened to the mooring line.

**Surface bi-conical buoy:** Lastly, one surface bi-conical buoy with a volume of 150–180 L prepared as shown in Figure 6.8.

*Mooring lines assembly process*

1. Wrap the rope around the thimble, leaving approximately 1 meter of rope free. Use a thin nylon cord with a diameter of 2–3 mm to fasten it securely on both sides. Ensure that the fastening occurs on the narrower part of the thimble to prevent wear from contact with the shackle (Figure 6.10a).
2. Attach the free rope to the main line along 3–4 points using the same nylon cord method mentioned above. The first attachment point should be as close as possible to the thimble to prevent the rope from slipping. At the same level, position the rope clamp for added security (Figure 6.10a and Figure 6.10b).
3. After the rope clamp, tie a simple knot to prevent any movement of each element (Figure 6.10b).

FIGURE 6.10
**Extremity of the mooring line to be tied on the anchoring device**
(a) Step 1: the mooring line is securely attached to the thimble; Steps 2 and 3: the mooring line is further secured using a rope clamp, and a shackle is inserted (b)

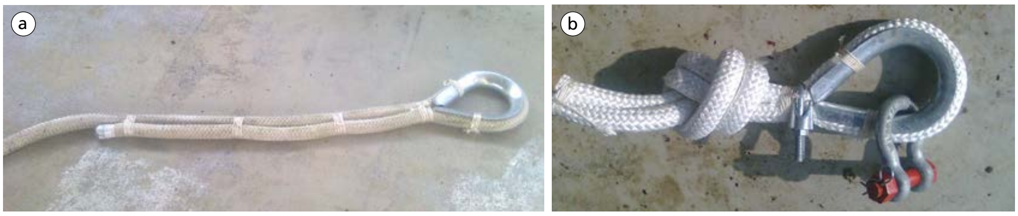




FIGURE 6.11
**The knot employed on the upper side of the submersible buoy serving to secure the position of the buoy along the mooring line**



4. Thread the rope through the central hole of the submersible buoy and make another single knot on the mooring line approximately 5–6 m from the thimble. To prevent this knot from shifting, secure it with a thin nylon cord (2–3 mm). This knot's purpose is to keep the buoy from rising, maintaining constant tension on the lower part of the mooring line to prevent contact with the concrete block or the seabed. (Figure 6.11).
5. Insert the shackle into the ring formed by the thimble. Do not tighten it yet. Place the bolt and nut in position without fully securing them. Keep the pin in a secure location until the mooring line is ready for installation on the block.
6. Insert the upper end of the rope into the 1.0 m piece of flexible garden hose, leaving 1.2 m of free rope to create the knot as illustrated in Figure 6.12. Secure it with a thin nylon cord (2–3 mm). Once the knot is tied, the hose should remain in place.
7. Place the assembled surface mooring buoy aside for future use.

*Installation of the mooring lines*

Typically, this operation necessitates the involvement of a specialized company, which encompasses the expertise of certified professional divers.

1. Preparation. The following technical components are required:
   - A first temporary double braid 20 mm nylon rope measuring 40 m in length.
   - A second temporary double braid 20 mm nylon rope measuring 2–3 m equipped with a pulley suitable for the first 20 mm rope.
   - A third temporary double braid 16 mm nylon rope measuring 2–3 m.
2. Verify that the mooring line is assembled in accordance with the instructions outlined in the assembly process (Figure 6.13).
3. Securely attach the mooring line surface buoy to the upper ring of the mooring line.
4. Fasten the first temporary rope approximately 1 m above the thimble.
5. Connect the third temporary rope to both the mooring line buoy and the boat. This will prevent the mooring line from drifting too far from the boat until the installation is complete.
6. Gradually lower the mooring line into the water, beginning from the thimble end, while ensuring that the opposite end of the initial 40 m temporary rope remains on-board.
7. During the initial (1st) dive:
   - Bring to the concrete block the second temporary 2–3 m rope equipped with a pulley and the free end of the second temporary 40 m rope (the other end is secured in proximity to the thimble).
   - Securely fasten the second temporary 2–3 m rope, along with the pulley, to the additional hook located in the middle of the concrete block (Figure 6.14).
   - Thread the second temporary 40 m rope through the pulley, and then guide the rope's end back to the boat.
   - Commence the retrieval of the second temporary 40 m rope from the boat. Initially, this can be done manually until the submersible buoy no longer descends further. Subsequently, utilize the winch to compensate for the resistance exerted by the submersible buoy, thereby completing the operation. Detection of resistance signifies that the mooring line thimble is near the concrete block hook, where it should be securely fastened.

FIGURE 6.12
**Extremity of the mooring line where the headline will be tied**
(views from both sides)

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FIGURE 6.13
**A fully assembled mooring line**

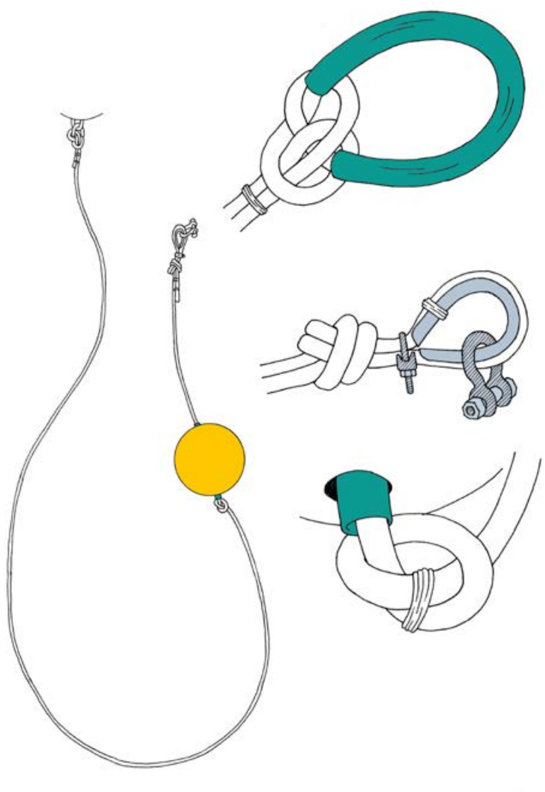

FIGURE 6.14
**Wrenches and pulleys used when installing a mooring line**

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8. During the following (2nd) dive:
   - Connect the lower end of the mooring line to the dedicated hook with the designated shackle, ensuring that the bolt and nut are securely fastened and that the pin is inserted correctly.
   - Release the first and second temporary ropes and secure them together for retrieval back to the boat.
9. From the boat, hoist the primary and secondary temporary ropes on board in preparation for the next phase of the operation.

### *Headlines*

The approximate length of the headline is determined by considering several factors, including the distance between the two anchoring devices, the total depth of the water column, the angle of inclination of the mooring lines, and the size of the headline buoys. When ordering and preparing the headlines, it is crucial to ensure that the line is sufficiently long to accommodate knots at both ends. A recommended practice is to add a few extra meters to the length to mitigate potential issues.

Deciding on the orientation of the long-lines involves a compromise between minimizing the impact of external forces, such as waves and currents, on the system and optimizing the availability of nutrients carried by water currents. To reduce the stresses the system may experience, both in terms of storm-related forces and continuous wear from prevailing currents, it is recommended that long-lines be aligned parallel to the dominant force direction. However, opting for a parallel alignment would result in the initial mussel socks benefiting from nutrient-rich water, while downstream socks would receive water that has been progressively depleted of nutrients due to filtration by the mussels cultivated in preceding socks. Moreover, maintaining a parallel configuration raises the risk of socks collision, potentially causing damage. To mitigate this, socks would need to be spaced farther apart along the headline, negatively impacting production capacity. On the other hand, positioning the lines perpendicular to the main applied forces would expose the structure to significant risks but could ensure a more uniform distribution of nutrients among all drops. As a viable compromise, positioning the lines at an angle of 30°–40° relative to the direction of the dominant applied forces can strike a balance between optimizing nutrient availability and reducing collision and damages.

Both polysteel ropes and double braid nylon ropes are commonly employed as headlines in long-line systems. Polysteel ropes, when compared for equivalent tenacity, exhibit the advantage of being lightweight (buoyant), non-absorbent to water, are UV-treated, and are less expensive. On the other hand, double braid nylon ropes offer greater flexibility, making them easier to handle for tying purposes. It is important not to confuse Polysteel ropes with polypropylene or polyethylene ropes, which are less robust and less resistant to abrasion. Headline ropes made from either of these materials will inevitably experience abrasion during lifting operations. High-quality nylon ropes can endure for more than a decade, whereas Polysteel ropes are prone to fraying sooner than that.

The subsequent section provides a detailed overview on the headlines installation process for the farm featured in this example.

FIGURE 6.15
**Temporary knot used to keep the headline in tension during positioning**
(views from both sides)

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### *Installation of the headlines*

Once the two mooring lines are ready:

1. Begin by preparing a temporary 2–3 m double braid 16–20 mm nylon rope. Securely fasten the two extremities to form a closed ring.
2. Attach one extremity of the headline to the upper ring of the first mooring line. To proceed with the next step, ensure that the deployment of the headline occurs with a tailwind, allowing the wind and current to be consistently at your back.
3. While steering the boat toward the second mooring line, extend the headline. Note that Polysteel rope will remain buoyant, while nylon rope will sink. In the latter case, for ease of installation, it is recommended to attach some small temporary buoys to help locate the position of the headline in the water. When the headline is properly tensioned, the floating rope or small buoys will be perfectly aligned with the buoys on the two mooring lines.
4. Pass the opposite extremity of the headline through the upper ring of the second mooring line.
5. Using the winch on-board, tighten the headline rope until it appears perfectly aligned.
6. While maintaining tension in the headline as described above, secure the preprepared temporary rope ring along the headline. Follow the knotting instructions illustrated in Figure 6.15. Then, wrap the other part of the ring around the boat's bitt to prevent the headline from retracting when removed from the winch.
7. Fasten the second extremity of the headline to the upper ring of the second mooring line. Once this is accomplished, untie the previously used temporary rope ring.

It is important to take into consideration that all headline ropes will experience elongation after their initial installation and will require subsequent tensioning, typically after a few months. This periodic tensioning is crucial for maintaining the desired level of tension in the headline. It is advisable not to trim any excess rope but to retain it as a precautionary measure in the event of damage or breakage.

### *Surface intermediate buoys*

As outlined in Section 4.5.1, the interaction between the shape, volume and placement of the buoys and the suspended socks will impact the yield of the farmed mussel. This issue will be thoroughly examined in the subsequent Section 6.3.2.

### *Navigation markers*

Once the designated site for farming has been established, it is vital to demarcate it with four navigation marker-buoys strategically placed at the four corners of the cultivation zone. These marker-buoys serve the critical purpose of alerting other water users to the restriction of navigation and anchoring within this area. To effectively deter interactions with the farming equipment, the markers should be positioned at least 50 m from any ropes or buoys constituting the farm's structural elements.

FIGURE 6.16
**Example of a navigation marker**
(a) The upper or exposed section with the "X" signal; and (b) the lower or submerged section fitted with a shackle


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FIGURE 6.17
**Solar-powered LED warning light fitted on a marker-buoy**

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The local navigation authority will stipulate the specific type of internationally recognized markers to be employed in compliance with both national and international laws and regulations. A standard navigation marker typically comprises a floating buoy, distinguished by either a yellow "X" and/or a yellow flashing light mounted on a vertical pole extending above the buoy (Figure 6.16 and Figure 6.17). Additionally, navigation authorities may specify the height of the yellow "X" above the water surface, the distance at which the light should be visible (typically 2–3 nm), and the colour of the emitted light. In all cases, the navigation marker must be large enough to be detected by radar systems.

As an integral aspect of the licensing process, navigation authorities will incorporate the farm area into maps and electronic navigation systems utilizing GPS coordinates to precisely delineate its geographical position. This facilitates the utilization of navigation tools such as Chart Plotters to accurately demarcate the specific zones occupied by the long-line farm.

The responsibility of determining the method by which navigation markers are anchored or moored typically falls upon the farm operator. Given their requisite distance of at least 50 m from the long-lines, these markers necessitate an independent anchoring and mooring system. The construction and installation of these anchoring and mooring mechanisms align with the procedures previously outlined in this chapter, albeit with one notable difference: the mooring line will remain in a predominantly vertical orientation.

This aspect introduces durability concerns, as all applied forces act in a single direction. To mitigate and address this issue, various strategies with varying cost implications can be employed:

- Incorporate a bottom chain into the mooring line to enhance the even distribution of forces.
- Employ comparatively smaller buoys to diminish the applied force.
- Implement a dual anchorage and mooring line setup, originating from two distinct seabed points.
- Equip the mooring line with a safety rope affixed to the nearest long-line anchoring device to prevent the navigation marker from drifting away and potentially becoming lost should the primary mooring system fail.

### 6.2.2 Farm layout

The layout of the long-line farm will be determined by the site topography. The farm depicted in Figure 6.3 serves as a typical example of a layout applicable when there is relatively ample sea space. Nevertheless, it is important to note that each site is unique and comes with its own set of constraints. Therefore, farm layouts will vary significantly to maximize cultivation space within the physical constraints of the designated area. Several key considerations must be made:

- The distance between the lines should be a minimum of three times the length of the workboat. This spacing allows for easy access to the headlines and facilitates lifting operations.
- To enhance navigation efficiency within the farm, it is preferable to employ a square farm layout over a rectangular one.
- In cases where lines are designed with lengthy headlines and intermediate legs, it is crucial to ensure that the maximum line length does not exceed 500–1 000 m. This ensures navigation space at both ends of the lines.

As emphasized in the preceding section, the design of a long-line aquaculture farm is a complex engineering endeavour. It is strongly advisable to seek consultation from a specialist to obtain comprehensive information and cost estimates. Additionally, it is important to recognize that the design of long-lines, the choice of the workboat (including propulsion and equipment), and potential onshore facilities are interdependent factors that must be considered collectively rather than in isolation.

### 6.2.3 Access to the farm - Workboat

The workboat is at the centre of the farming operation, serving as the sole means of accessing the farm. It is therefore vital that the chosen vessel is appropriately designed and sized to align with the intended production capacity and the farm's location. In addition to specific functions like headline lifting, the workboat must be versatile, as it will be required to undertake a diverse array of tasks.

The workboat design must encompass the following primary functions:

- Appropriate propulsion system and hull design to facilitate navigation between the harbour and the farm, taking into consideration factors such as distance, local meteorological conditions, required harvesting and transport capacity.
- Adequate propulsion system and hull design to facilitate manoeuvres among the long-lines within the farm.
- Properly equipped with machinery to efficiently lift the headlines from the water and carry out harvesting procedures.
- Equipped with the necessary machinery and systems for on-board farming operations.
- Sufficient deck space to accommodate the installation of required equipment and to facilitate the execution of all on-board operations.

- Suitable hull shape for accessing to the landing facilities in accordance with the water depth at the harbour.

The vessel used as an illustrative example in this section embodies the essential characteristics necessary for effective operation in offshore long-line farming. The following sections provide descriptions of the on-board equipment essential for farming operations.

### *Hull shape, deck space and propulsion system*

The workboat, described here as an exemplar (Figure 6.18), has been designed to facilitate navigation between the long-lines, ensure a stable platform for on-board personnel, and ensure swift travel, given that the farm is situated approximately 6 nm from the harbour. It boasts dimensions of 17.6 m in length and 5.22 m in width, with a gross tonnage of 8.38 t and a net tonnage of 5.7 t. These specifications are well-suited for managing approximately 12 000–15 000 m of long-lines in an offshore and exposed site.

The propulsion system for navigation consists of twin diesel inboard engines of 185 hp (1 hp = 0.75 Kw) driving two propellers, one to port and one to starboard. These two engines are used only when moving between the harbour and the farm or moving from a line to the next. The availability of two independent engines, each with

FIGURE 6.18
**A typical long-line farm workboat utilized in the Adriatic Sea, Italy**
(a) Technical illustration of the vessel; (b) a side view photograph; and (c) a hull view on the gantry

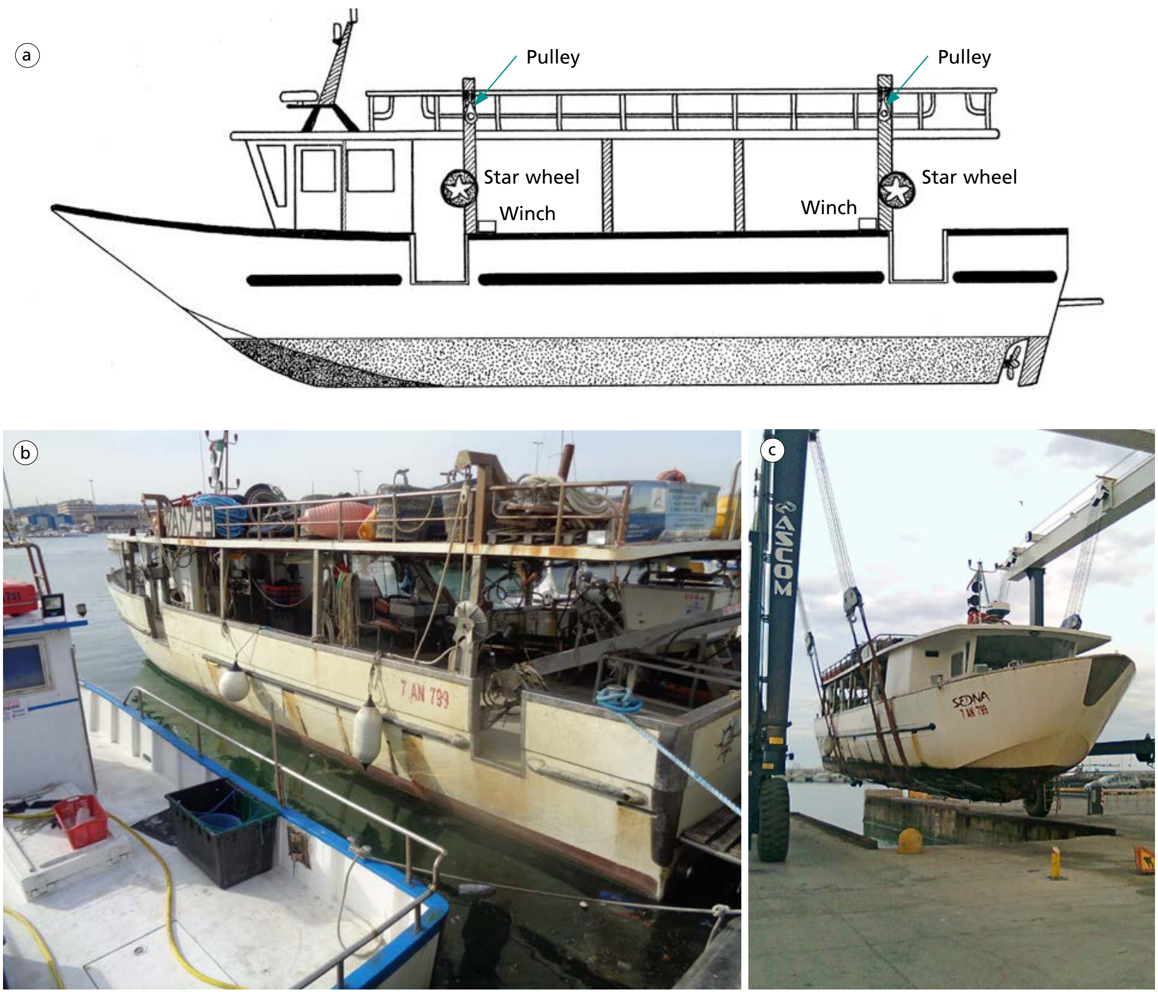

FIGURE 6.19
**Deck space on a typical long-line farm workboat used in the Adriatic Sea, Italy**

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adjustable power settings, enables precise manoeuvring and significantly aids in the headline lifting procedure, detailed in the next section below. Alongside the primary navigation engines, the vessel is equipped with a small motor located in the submerged section of the hull toward the bow, known as a "Bow thruster" used to increase the manoeuvrability of the vessel. The propeller, positioned within a circular aperture that spans from one side of the hull to the other, occupies the entire diameter of the opening. This system proves particularly valuable when countering the effects of surface currents, winds, and waves during headline retrieval manoeuvres.

The "V" shaped hull design facilitates rapid navigation, achieving speeds of up to 9 nm/h, while keeping fuel consumption relatively economical. The vessel's width of 5.2 m ensures stability during on-board operations and provides ample deck space for equipment installation, product handling, temporary storage, and staff mobility (Figure 6.19).

It is worth emphasizing the importance of maintaining a hull draught at a depth that minimizes the potential for propellers coming into contact with the headlines.

The workboat is additionally equipped with an auxiliary diesel engine that operates a hydraulic pump, serving as the power source for all on-board machinery. This includes the two star wheels and two winches employed for elevating the headlines from the water, as well as the conveyor belts, graders, and various other machinery used in mussels handling. The auxiliary engine can be utilized either when a headline is positioned on the star wheels with the navigation engines turned off or during navigation when traveling between the harbour and the farm, and vice versa.

### *Headline lifting equipment*

Elevating the headlines and the mussel socks they support from the water, represents the fundamental operation in long-line farming. The choice of method varies depending on the farm design and the size of the workboat. Options range from manual lifting devices on smaller vessels (8–15 m in length) to mechanical lifting solutions involving cranes or winch-based equipment installed on larger workboats.

On larger and medium-sized workboats, the fundamental approach involves hoisting the headlines from the sea to a level where operators can easily inspect, remove or re-suspend the mussel socks housing the mussels. The initial step involves hoisting the headline from the water when the vessel aligns parallel to the headline. Subsequently, the headline is positioned atop apparatus known as “star wheels” or “star-rollers” which are set in motion by their hydraulic motors. Manipulating the rotation direction of the star wheels enables forward or backward movement along the headline and, as the headline is anchored to the seabed, it is the boat that adjusts its position along the headline (navigation motors are deactivated during this phase). Each star wheel is equipped with a lever that enables it to change direction and adjust its speed.

The workboat described as an example is equipped with two hydraulically powered winch-based systems designed for lifting headlines. The various components that make up this system are detailed below, while the technique for lifting headlines is elaborated in Section 6.2.4.

The system illustrated in Figure 6.20 and Figure 6.21 comprises the following elements and exhibits uniformity at both the stern and the bow:

- An anchor and its rope utilized for grasping the headline when submerged beneath the water surface.

FIGURE 6.20
**Workboat with headline placed over two star-wheels**

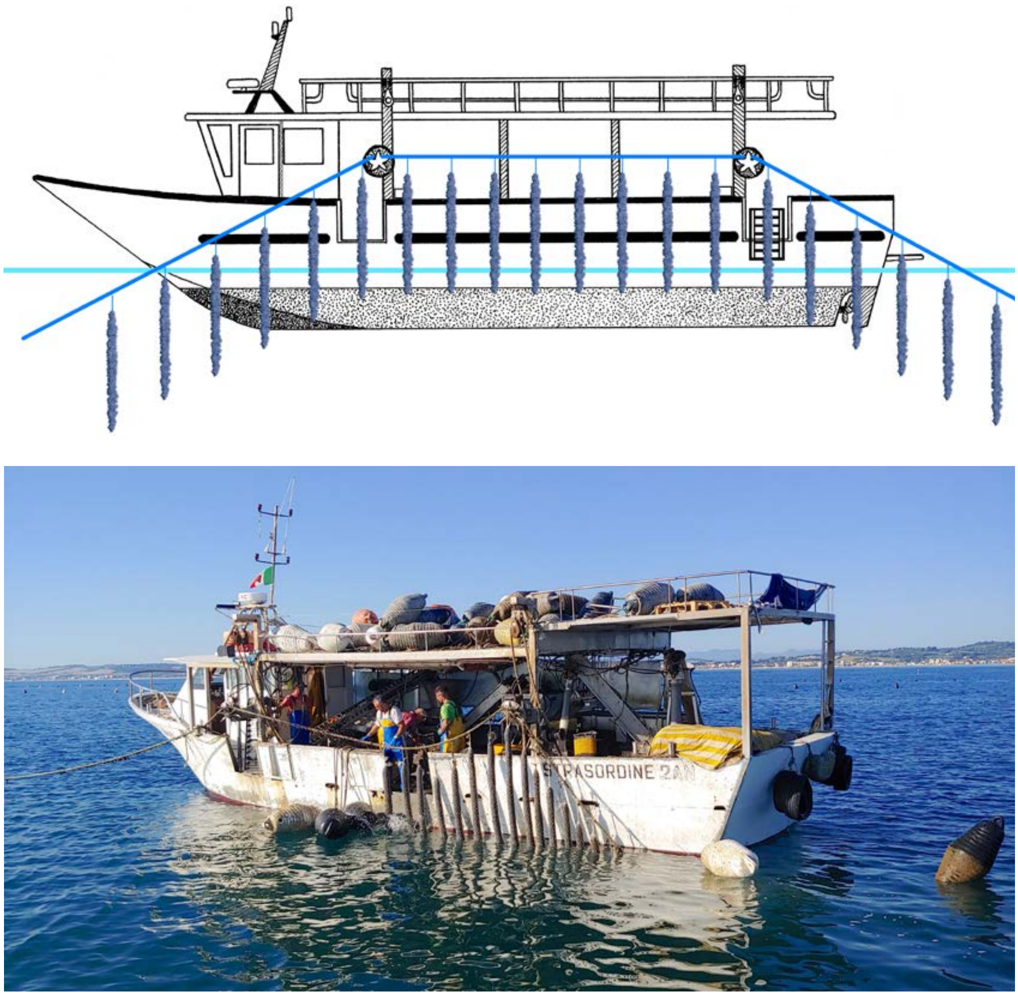
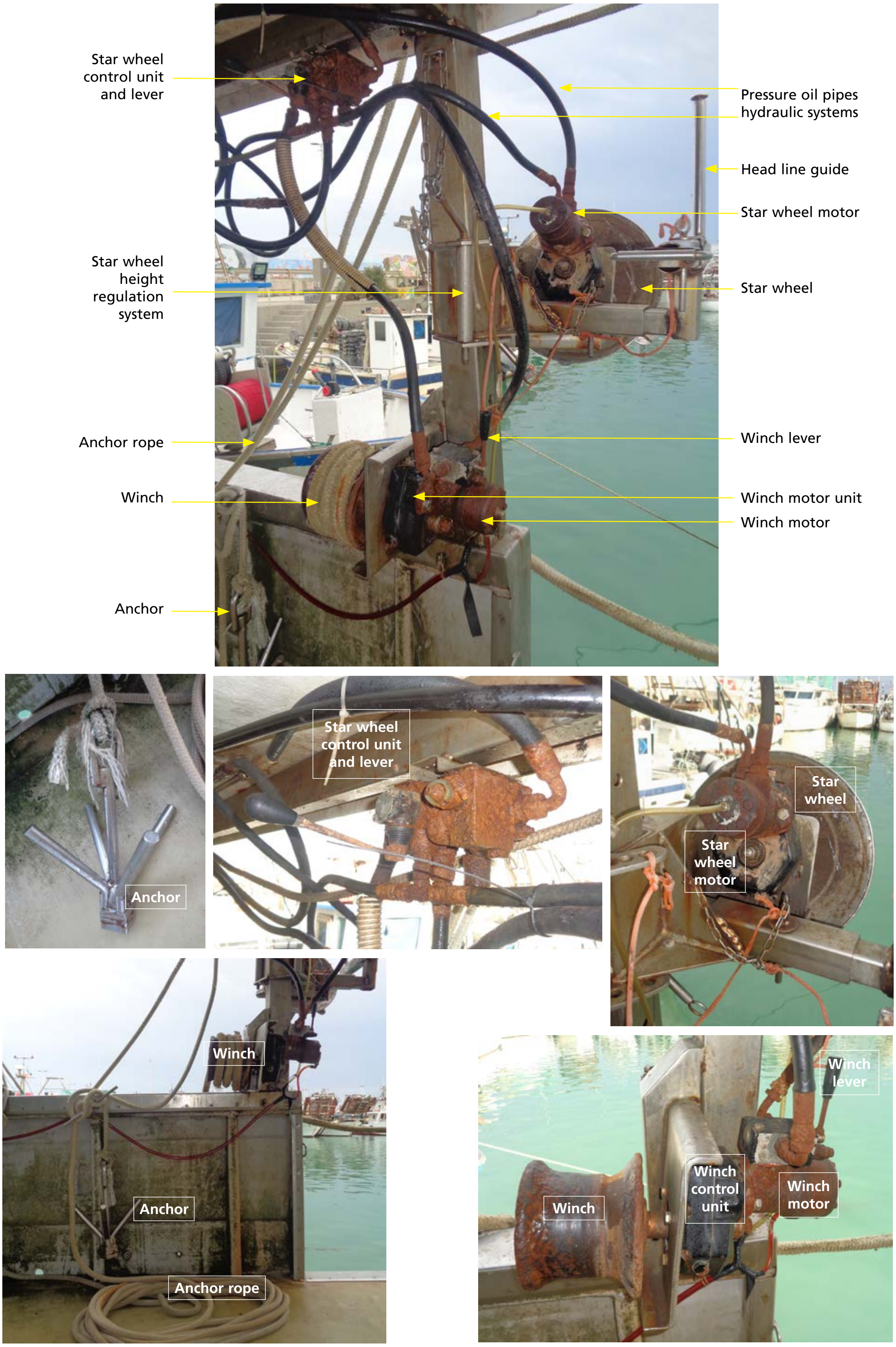


FIGURE 6.21
**Images of the headline lifting device positioned at the prow of the workboat**



- A winch for retracting the anchored headline after it has been hooked.
- A support structure with a pulley, used to elevate the anchor and headline beyond the height of the star wheels.
- A star wheel serving as a support for the headline when it is lifted out of the water.
- The anchor must possess sufficient strength and weight to quickly sink and reach the headline. However, it must not be overly heavy, as the operator needs to throw it 5–6 m away from the side of the boat. The rope should be 20 m in length, with one end attached to the anchor and the other end securely tied to the boat's gunwale to prevent loss overboard. A double-braid nylon rope is recommended for this purpose.
- Each winch is equipped with a lever that enables the adjustment of the direction of rotation and regulation of the speed.

The pulley on each hoist arm is vertically aligned with the underlying star wheel. It is important that the distance between the pulley and its corresponding star wheel exceeds the length of the anchor. This configuration is crucial to facilitate smooth operations during the insertion of the headline rope onto the star wheel.

Different designs of star wheels are available, and the selection of a model should be guided by the following criteria:

- The number of arms on the star element should range between 5 and 8.
- The shape and length of the arms must facilitate the free movement of the headline while preventing it from becoming dislodged.
- The distance from the extremity of the arm to the circular support element must be adequate to prevent entanglement or wedging of the headline ropes.
- The hinged bracket designed for affixing the star wheel to the supporting pole should provide adjustability for both the height and inclination of the roller.
- All components of the roller must exhibit a flawless, smooth surface to prevent chafing and damage to the headline ropes.

There are also different types of supports for the star wheels. While in most cases the stars face outwards as shown in Figure 6.21, Figure 6.22 and Figure 6.23a, they can also face towards the boat and the operator as in Figure 6.23b, Figure 6.23c and Figure 6.23d. Furthermore, in the example in Figure 6.23b, height adjustment is automated. In rough seas, these alternative solutions reduce the likelihood of the headline rope slipping out of the star wheels and make the operator's work easier, as there are no obstacles between their position and the headline rope with the mussel socks.

### *Pressure washer*

If land-based facilities are unavailable for equipment washing, an on-board pressure washer becomes essential. Depending on the boat design, two solutions are possible:

- The pressure washer can pump saltwater, allowing the operator to conduct cleaning tasks on the boat, during navigation, or while in the harbour. Equipment and boat deck can be cleaned while navigating between the harbour and the farm, thereby saving time.
- The pressure washer is only designed to work with freshwater when connected toa supply point in the harbour.

In the first scenario, two potential issues may arise: corrosion of the equipment due to saltwater and the risk of organisms and/or debris in the water column obstructing the water intake. If a freshwater supply point is available at the harbour, the corrosion process can be mitigated by rinsing the equipment when back from the sea. In the second scenario, there is a possibility that harbour authorities or other port users may object to the discharge of dirty water resulting from washing into the harbour.

FIGURE 6.22
**Images of the headline lifting device positioned at the stern of the workboat**


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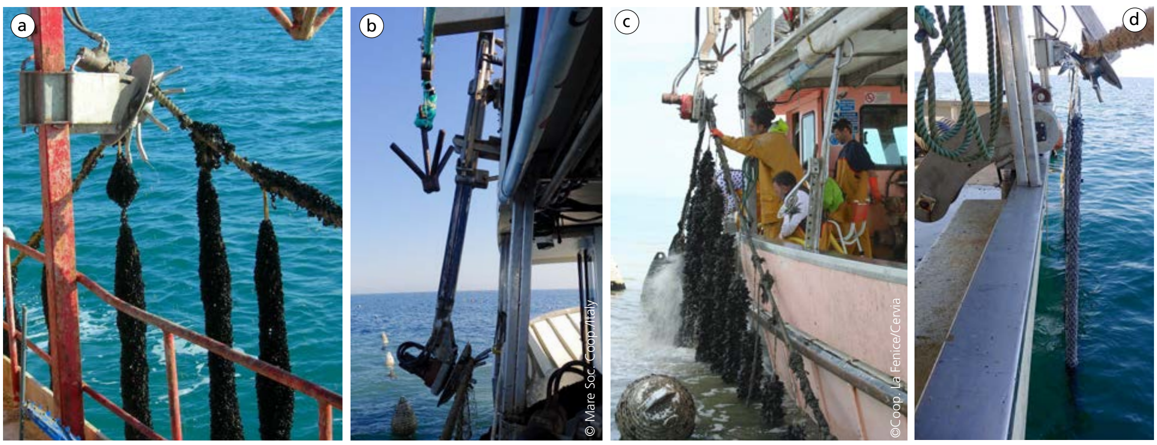
FIGURE 6.23
**Examples of different star-wheel design**
(a) Star-wheel oriented overboard; (b)(c) Star-wheel oriented inboard; and (d) Opposite star-wheels

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It should be noted that the initial investment and ongoing maintenance costs for a saltwater washer (including its filtering unit and its connection to the on-board hydraulic or electric power) will be considerably higher than those for a freshwater washer. The latter can be purchased in any hardware store with additional options such as pressure regulation.

*Other on-board basic equipment*

The workboat should be outfitted with a saltwater pumping system to ensure a continuous water supply during both operational and navigational activities. This system can be powered either by one of the main engines or by the auxiliary engine.

In addition to the essential pumping system, the boat should be equipped with chart plotters for electronic navigational aids. Integration of a VHF radio is also crucial, facilitating communication with other water users operating in the vicinity.

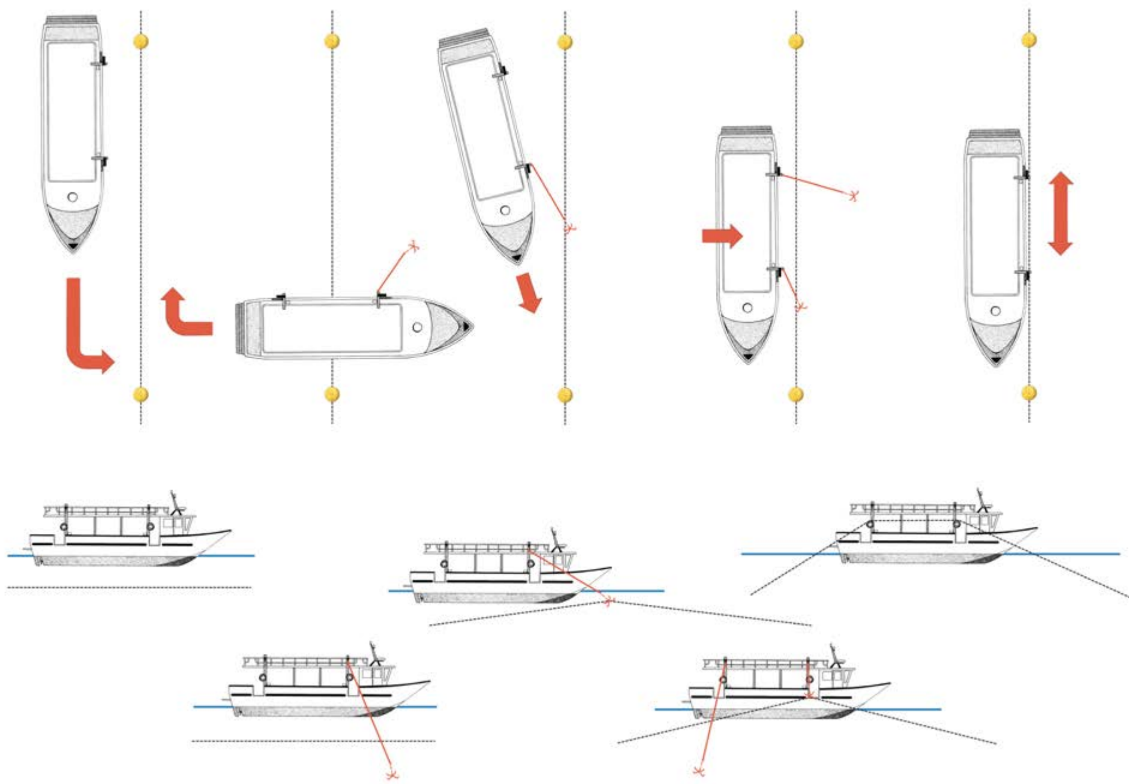
Finally, considering that certain equipment on-board may necessitate either single or three-phase electrical power, it is advisable to install a small generator capable of producing the required power output. This ensures a reliable and versatile power source to accommodate various electrical demands.

### 6.2.4 Headlines lifting technique

The headline lifting procedure illustrated in Figure 6.24, requiring a minimum of two operators, can be divided into five steps:

1) While the boat navigates parallel to the headline to be lifted, the boat captain turns the boat in the direction of the headline and positions it perpendicular to the headline, ensuring that less than half of the total length of the vessel is over the headline. It is crucial to keep the vessel's propellers as far away as possible from both the headlines and the ropes of the buoys to prevent entanglement.
2) Once the boat is in position, a second operator deploys the bow anchor overboard, giving it enough time to sink below the depth of the headline. Following this, the boat captain reverses the boat and keeps it at an angle of 20°–50° to the headline. This manoeuvre allows the anchor to hook onto the headline. When the rope is under tension, the operator winds it up on the winch and begins pulling to keep it taut.

FIGURE 6.24
**The workboat successive manoeuvres to hook and lift a headline onto the star wheels**



3) As the second operator manoeuvres the bow of the boat close to the headline by pulling the rope of the stern anchor, the captain reverses direction, moving the boat forward. Once the boat is once again parallel and in proximity to the headline, the captain places the two motors in the neutral position and shifts to the bow winch, taking over from his colleague, who now moves to the stern.
4) The second operator deploys the stern anchor over the headline, allowing it time to sink below the depth of the headline. Upon feeling tension on the rope, the operator promptly winds it up on the winch and begins pulling to maintain tension on the rope.
5) The second operator proceeds to manoeuvre the stern of the boat near the headline by pulling the rope of the stern anchor. At this point, with both anchors securing the headline suspended over their respective star wheels, the operators slowly release the winches simultaneously to facilitate the lowering of the headline onto the star wheels.

### 6.2.5 On-board equipment for mussel handling

On the workboat used as an illustrative example in this section, the whole production cycle can be carried out on-board and therefore directly in the farm without need for land-based facilities. In this way it is possible to immediately return to the sea the undersize product that is not intended for sell.

The sequence of the various operations, from seed collection to harvesting the commercial product, is described in detail in the following Section 6.3 below. These operations are:

- declumping which is a prerequisite for any subsequent processing and that consists in separating the mussels from each other and from the plastic nets of the socks;
- size grading in order to obtain homogeneous mussel batches to be returned to the sea or to be sold;
- socking the mussels below commercial size for them to be transferred in new socks where they can complete their growth.

Each operation requires the use of specialized machinery as described below.

#### *Declumping machines*

As explained in Chapter 2, mussels develop a byssus with which they attach themselves to each other and adhere to the substrate they find or that the farmer prepares for their cultivation. Consequently, before size grading and new socking, it will be necessary to separate them from each other and from the plastic net of the previous socks. The separation to obtain individual mussels is carried out with the aid of so-called "declumping machines". The different typologies are described in Section 4.5.2, while the related operations on-board are detailed in the following Section 6.3.2.

#### *Grading machines*

The growth rate of individual mussels varies, leading to a diverse range of sizes that will require size grading. This task is accomplished through the utilization of grading equipment, as detailed in Chapter 4, Section 4.5.2.

Two options are available for grading mussels: either loading them into containers for transportation to shore-based facilities or conducting grading on the workboat itself. Undertaking this process on-board presents a dual advantage. Firstly, it eliminates the need for unnecessary transportation of mussels to shore-based facilities and back, saving time and reducing double handling. Secondly, the mussels below commercial size can be quickly returned to the water reducing possible mortality after the grading process.

On the workboat used as an illustrative example in this section grading is performed using a horizontal vibrating grader.

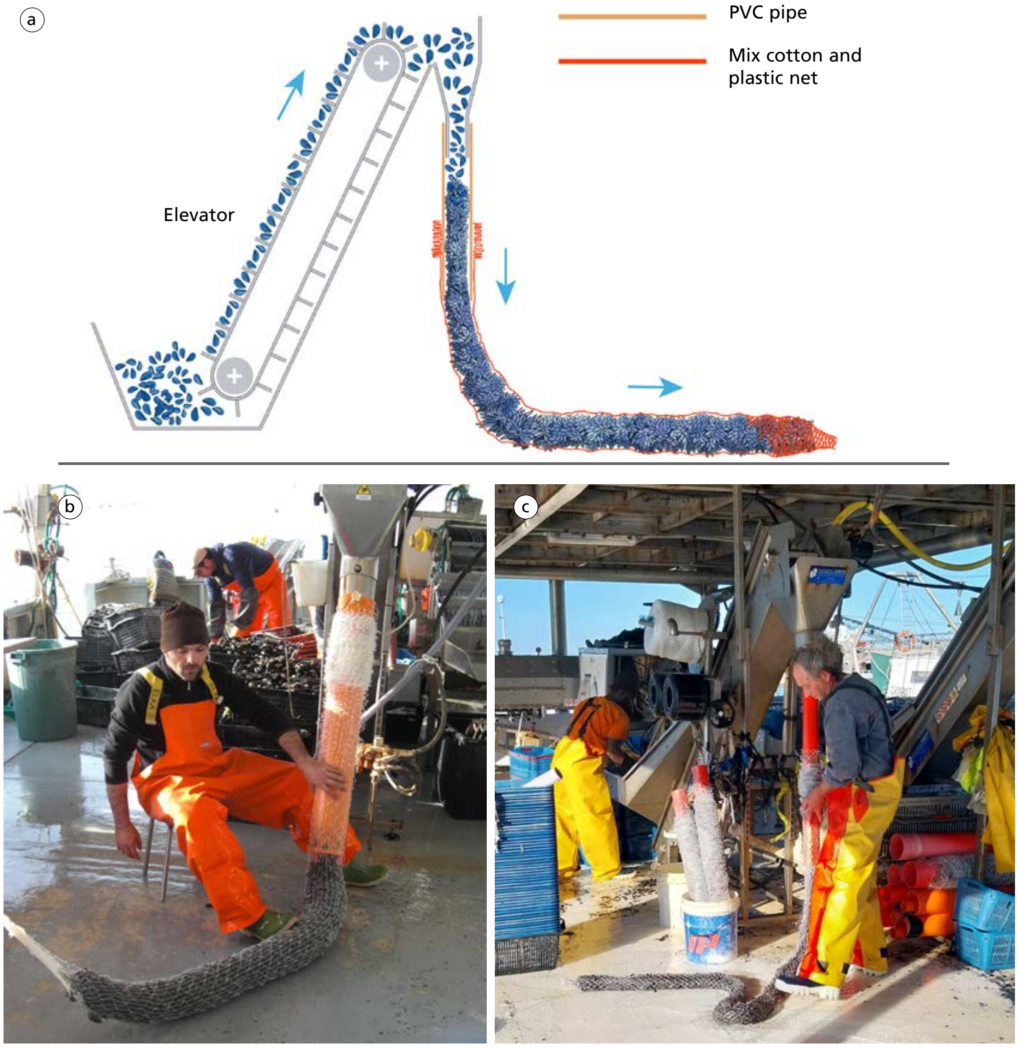
### *Socking machines*

As farming takes place in net socks, or drops, into which the mussels are introduced and then hung along the headline at regular intervals (see Figure 6.20), filling the socks with the mussels is therefore the basic operation of this production system. The mussels are introduced into the two overlapping nets, with the narrow-mesh cotton thread net on the inside and the looser-mesh polyethylene net on the outside. There are different systems to carry out this operation: by gravity, using a vertical belt that lifts the mussels, or horizontally, with a worm screw that pushes the mussels into the sock. In both cases, rigid PVC pipes where the nets are inserted are prepared in advance.

*Machine to feed the mussels into the socks from an elevator belt*

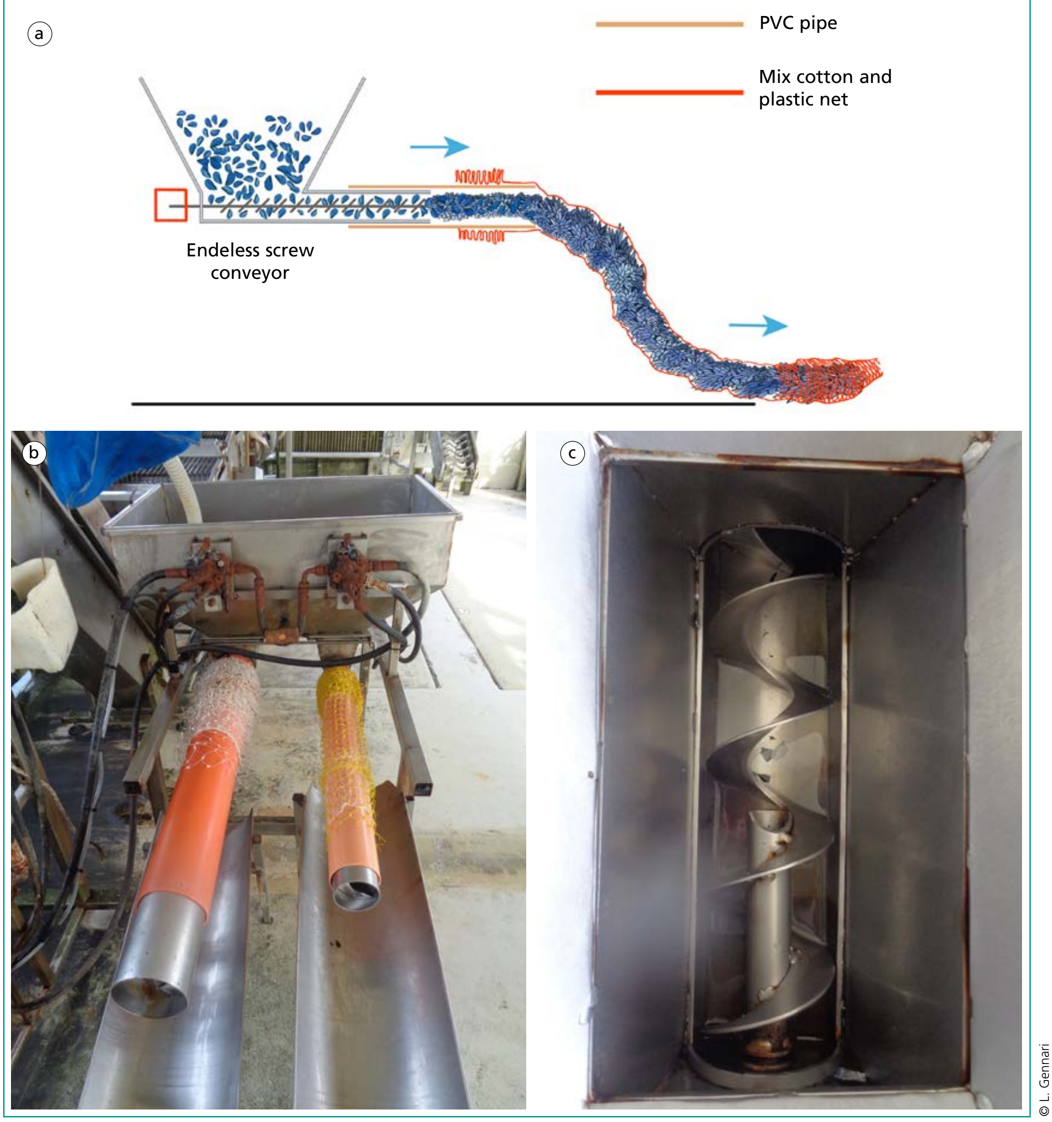
An elevator belt feeds the mussels into a hopper under which the PVC pipe with the nets is inserted. The mussels falling from the belt first fill the PVC pipe and the sock by gravity (Figure 6.25 and Figure 6.35). The operator does nothing but accompanying the progressive removal of the nets from the pipe so that the mussels are tightly packed and without empty spaces.

FIGURE 6.25
**Machine to feed the mussels into the socks from an elevator belt**
(a) Diagram showing the filling system; and (b)(c) Filling socks



*Machine to feed the mussels into the socks with screw auger conveyor*
The mussels are poured into a hopper at the bottom of which there is an endless screw which will push the mussels to fill first the pipe and then the nets (Figure 6.26). Also here the operator does nothing but accompanying the progressive removal of the nets from the pipe so that the mussels are tightly packed and without empty spaces.

FIGURE 6.26
**Machine to feed the mussels into the socks with a screw conveyor**
(a) Diagram showing the filling system; (b) Frontal view; and (c) Endless screw




*Machine to thread the nets onto the pipes used to feed the mussels into the socks*
This machine is used to sleeve cotton and plastic nets onto PVC pipes, which will subsequently be employed for filling mussel socks (Figure 6.27). The empty PVC pipe is placed vertically on its support, positioned between two rubber-coated drive wheels that are initially loosened so they do not yet contact the pipe.

The cotton net, supplied from a freely rotating roll located at the bottom of the machine, is first guided through the pipe support and then fed through the interior of the PVC pipe until it exits from the upper end. Approximately 50 cm of net should be pulled beyond the opening. Next, the plastic net, coming from a freely rotating roll positioned above the pipe, is drawn over the protruding cotton net, also for a length of roughly 50 cm.

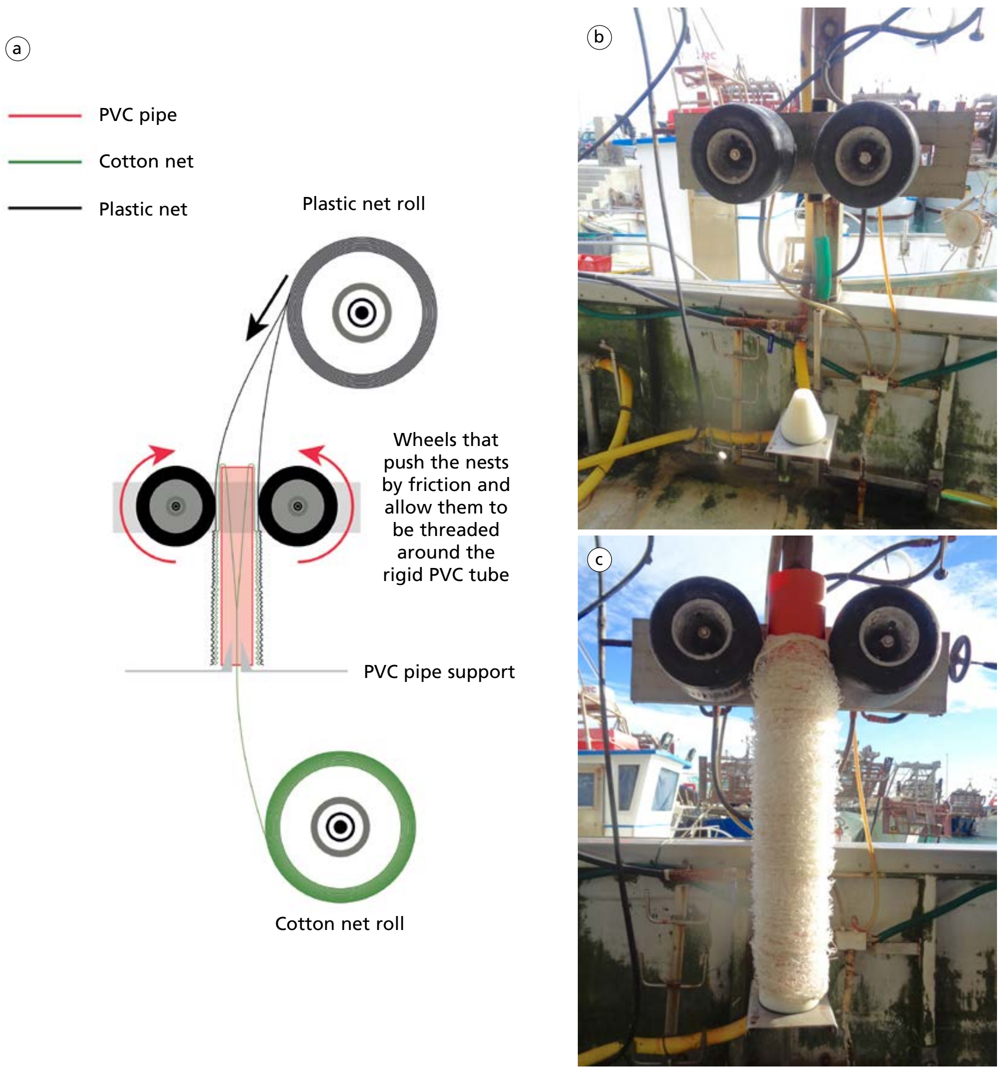
Once both nets are correctly positioned, the operator tightens the two rubber-coated drive wheels so that they make uniform contact with the nets and the PVC pipe. The wheels are then engaged, and through friction they advance both nets downward along the exterior of the pipe. The operator ensures an even distribution of the nets over the full length of the pipe, continuing until the available space is filled.

It is important that the upper edge of the PVC pipe is smooth and free of irregularities to prevent snagging or tearing of the nets during the threading process.

The PVC pipes typically range from 0.80–1.20 m in length, with diameters corresponding to those of the tubular plastic nets to be employed (see Table 6.2). These pipes are generally prepared in advance and stored beneath the workboat's roof, as illustrated in Figure 6.32.

For each mussel sock diameter, an adequate number of pre-sleeved, ready-to-use pipes must be prepared in proportion to the anticipated production volume for a day's offshore work. Each prepared pipe allows the production of approximately 20 socks, each measuring 3.0–3.5 m in length.

FIGURE 6.27
**Machine to prepare the pipes to feed the mussels into the socks**
(a) Diagram showing the preparing machine; (b) Without PVC pipe; and (c) With PVC pipe



### 6.2.6 On-board equipment layout and workboat size

All of the machines described above are powered by the hydraulic system driven by the workboat's auxiliary diesel engine. As noted at the beginning of Section 6.2.5, a key advantage of the offshore mussel-farming system presented in this chapter is that it eliminates the need for land-based facilities. Consequently, a wide range of operations must be performed directly on-board, making both the layout of the equipment and the organization of work during operations at the offshore long-line farm critically important.

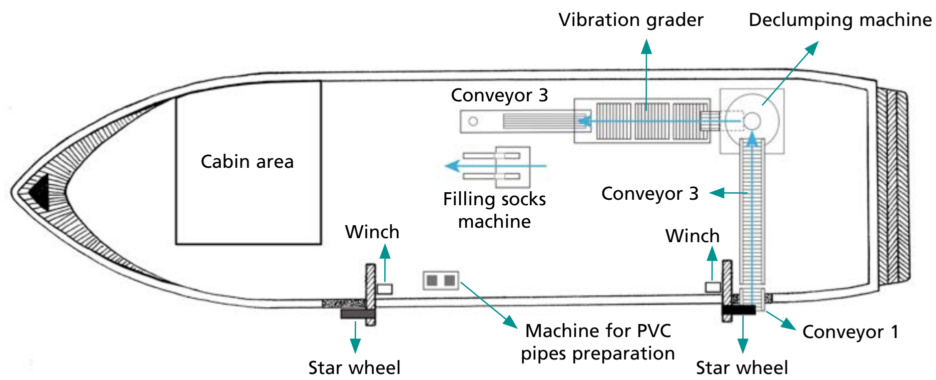
Moreover, increasing the level of automation wherever possible is essential. Automation reduces the physical demands associated with manual handling tasks, improves operator safety, and enhances the overall efficiency and profitability of offshore farming activities.

#### *Arrangement of the on-board equipment*

Deck space must be carefully organized to accommodate all on-board operations, including workflow areas, temporary storage of harvested mussels, storage of prepared socks ready for hanging, and zones dedicated to cleaning and routine maintenance. Figure 6.28 provides an example of an equipment layout on board.

This spatial arrangement, combined with decisions regarding crew size and the procedures for carrying out the operations described in Section 6.3.2, constitutes a set of critical factors that directly influence the overall efficiency and profitability of the company's offshore farming activities.

FIGURE 6.28
**Deck layout of on-board mussel-farming equipment**




#### *Landing area requirements*

The landing area must meet the following requirements:

- A docking point with electrical supply (220 and 380 volts) and a freshwater supply point.
- A product unloading zone accessible to refrigerated vehicles and to any other vehicle for loading and unloading material (net rolls, buoys, etc.). This area may be separate from the docking point and may be shared by multiple vessels. It should be equipped with appropriate handling systems such as a crane, conveyor belt, or forklift. Adequate space must be provided for vehicle circulation, parking, and operational activities.
- A nearby areas for the disposal and/or temporary storage of waste materials, including plastic nets, ropes and other equipment.

In addition, for enterprises without dedicated land-based facilities, it is advisable to have an available space, preferably covered, where buoys and spare components for the long-lines can be stored safely and protected from weather exposure.

*Boat size*

In cases comparable to the example farm described in this chapter, an offshore long-line installation with 10 000–12 000 m of available headlines, where all farm activities are performed at sea, a fully equipped workboat of 15–20 m in length and 5–6 m in beam, with a minimum crew of five, is recommended.

However, the optimal size of the vessel, the selection of on-board equipment, and the arrangement of machinery depend on multiple factors, which must be carefully evaluated:

- Production capacity of the offshore facility.
- Planned number of staff and overall work organization.
- Availability or absence of land-based facilities.
- Accessibility, equipment and special capacity of the landing area.
- Commercial strategy to be adopted (see Section 6.3.3).
- Company structure and legal framework.

With regard to the last two points, various organizational models have a direct influence on technical decisions concerning the scale of the offshore installation and the design of the workboat:

- Companies that manage production, depuration, packaging, sales and distribution autonomously.
- Companies that produce only, delivering their harvest to wholesalers who handle depuration, packaging, marketing and distribution.
- Producer organizations in which individual farms produce exclusively, while collective entities manage depuration, packaging, sales and distribution.
- Intermediate models, such as farms that operate depuration and packaging facilities and also purchase mussels from other producers.

Enterprises belonging to producer organizations, operating depuration/packaging plants, or purchasing product from other farms may choose to perform part, or all, of the mussel handling operations at their land-based facilities. In these cases, the workboat is used primarily for sock deployment and retrieval, transportation, and loading/unloading, significantly reducing on-board equipment requirements. Consequently, it is necessary to determine whether land-based facilities are essential to complement long-line operations and, if so, to define their optimal size, capacity and functional layout. The presence or absence of such facilities will strongly influence the required dimensions and technical configuration of the vessel.

These factors collectively influence the efficiency, workflow organization, and overall performance of the farming system. It is therefore essential to adapt the vessel's design to local marine conditions and operational requirements. Engaging a local, experienced boatyard is strongly recommended to ensure that the workboat is purpose-built and that reliable long-term maintenance support is available. A close, continuous collaboration between the farmer and the shipyard is crucial for achieving a practical, efficient, and well-integrated vessel design.

It is also important to consider broader sectoral trends. Market evolution increasingly drives vertical integration and the emergence of larger companies or producer groups, which improves profit margins and strengthens bargaining power with large-scale retailers. Climate change is producing notable effects as well, including a northward shift in optimal production zones, shorter production seasons, and increased handling requirements, all of which reshape the operational needs of the sector. These dynamics are contributing to a clear tendency toward the development of larger and more automated workboats.

## 6.3 FARMING PRATICES

As introduced in Section 6.2.5 which describes the machinery used to make the socks, this farming method is based on the use of overlapping tubular nets, made of cotton and plastic, into which the mussels are introduced to obtain the growth socks. Farming then consists of periodically renewing these socks before the mussels become too heavy and detach. At each transfer, in order to ensure maximum size uniformity, the mussels are graded by size before filling the new socks or selling the commercial size product. Over the months, farming therefore involves a number of transfers to new socks of increasing diameter and with mesh sizes increasing in proportion to the growth of the mussels (see Table 6.2).

Regardless of the farming strategy employed, mussel growth exhibits significant intraspecific variability, with individuals in the same cohort displaying markedly different growth rates. Consequently, periodic grading of cultivated mussels is essential to limit size heterogeneity within a batch. In the absence of grading, mussels with an average commercial length of 6 cm may vary between 3–9 cm. The primary objective of grading is to mitigate intraspecific competition, as multiple studies have demonstrated that the co-culture of mussels with disparate sizes impairs the growth of smaller individuals, which are competitively disadvantaged in accessing water flow and suspended nutrients.

In newly prepared socks, all mussels are initially confined within the cotton net, which prevents escape until the individuals have produced sufficient byssal threads to attach to the outer plastic net. Within one to two weeks, the cotton net naturally disintegrates and disappears. As the mussels grow, their limited mobility allows them to optimize access to water flow and phytoplankton, gradually migrating out of the plastic tubular net. The plastic net then serves as a central support, analogous to the ropes used in the *batea* technique (Section 4.4.1).

Before harvesting, it is essential to ensure that all mussels have migrated outside the plastic net. This precaution minimizes damage during declumping. A fully developed sock ready for retrieval can contain 25–40 kg of mussels, depending on the initial net diameter. Delaying harvesting excessively introduces the risk of product loss: the cumulative weight may exceed the holding capacity of the byssal threads, causing mussels to detach from the central net and fall to the seabed. This issue is particularly pronounced during the warmest periods, when rapid growth increases individual and total sock weight, while byssal thread strength decreases (see Section 2.1.1).

The marketing period for mussels is determined primarily by two biological criteria: the majority of the product must have reached commercial size (>6–8 cm), and the meat content must be at least 18–20 percent. In the Adriatic Sea, these conditions are typically achieved between March and July–August of the second year. Peak demand, when the product is mostly sold fresh, extends from Easter (April) to the end of the summer holiday period (August) and coincides with the period of greatest product availability. For additional details on product quality criteria, see Section 2.2 of this manual.

The mussel production cycle, from the collection of seed for the initial socks to achieving commercial size, generally spans 14–20 months, covering two calendar years. The duration of the cycle depends on seasonal growth patterns and management decisions. Key factors include:

- Seed collection strategy and timing to initiate the production cycle.
- Frequency and method of separating and/or grading socks during growth.
- Target commercial size of the mussels.
- Marketing strategy, including whether the product is sold as whole socks or as declumped, packaged mussels.

The combination of these choices produces a wide range of possible production strategies. For example:

- Without initial seed grading, with frequent grading during the cycle, and the sale of declumped mussels, the production cycle typically lasts 18–20 months, with 90–95 percent of the product marketed by the end of August of the second year (Figure 6.40 and Figure 6.41). In this scenario, mussels may reach 6–7 cm, exhibit high size uniformity, and achieve relatively high market prices, although continuous sock renewal increases production costs.
- With seed grading at the start, minimal grading during the cycle, and sale in whole socks (leaving declumping, grading and packaging to the buyer), the cycle can be shortened by several months, with all entire harvest sold between April and June of the second year. Here, on-board processing is minimized, but the commercial size is smaller and size uniformity is lower, resulting in reduced production costs and lower market prices.

### 6.3.1 Strategy for seed introduction

Mussel farming in the Adriatic Sea depends entirely on natural seed recruitment, either directly on the headline ropes and buoys of the long-lines or from half-size mussel socks from the previous year. As described in Section 2.1.2, recruitment, i.e. the attachment of juvenile mussels post-metamorphosis, occurs predominantly during the winter months. By late winter to early spring, seed typically reaches 0.5–1.5 cm, the minimum size required for producing the first socks with a diameter of 60–80 mm. Consequently, seed collection is generally carried out in February–March of the first year (Figure 6.29 and Figure 6.30).

Due to climate change, the gamete release period is increasingly prolonged, with small amounts of seed being produced almost year-round. Nonetheless, the winter peak remains the primary source, ensuring sufficient seed to initiate the production cycle in spring.

#### *Seed harvesting and first socking*

At the start of the reproductive period (autumn), the majority of the previous year's mussel crop has been sold, leaving only the product harvested earlier in the year (first-year mussels), which occupies approximately one-third to one-half of the available facility space. Consequently, most headlines are empty and require inspection and cleaning by mid-September. This process involves removing any remaining pieces of stocks, cords, mussels, and attached epibionts, ensuring that the infrastructure is ready to receive the new seed. The same cleaning procedure must be performed on all buoys.

By the end of winter (February–March), the headlines become fully covered with clusters of juvenile mussels (Figure 6.29). Harvesting at this stage is carried out manually (Figure 6.30). Timely harvesting is crucial because young mussels grow fast, and if left too long, the clusters become heavy and may detach easily, leading to product loss.

To start a new production cycle, preference is given to harvesting juvenile mussels directly from headline ropes and buoys, as they are easy to collect, relatively uniform in size, and can be used immediately to produce socks without initial size grading. Freshly harvested

FIGURE 6.29
**Mussel seed naturally settled on a headline rope**

FIGURE 6.30
**Mussel seed collection from a headline rope**

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clusters are transferred to plastic crates for filling into 60–80 mm socks. For such small mussels, it is recommended to use a screw conveyor machine (see Figure 6.26). By avoiding declumping and early size grading, stress on the mussels is minimized, allowing them to maintain optimal growth rates throughout the spring. This approach enables the production of above-average size mussels for market between March and August of the second year.

Alternatively, some producers allow the seed to reach a larger size on the headlines (2.5–3 cm) before harvesting, performing initial size grading immediately. While seed declumping and grading induce stress, delaying subsequent grading can reduce the total number of sock transfers during the whole production cycle.

If seed is unavailable on-site, it must be sourced from other facilities. During transport, temperature fluctuations between origin and destination must be minimized. Upon arrival, if the environmental temperature differs significantly from the source site, an adaptation period is recommended. During this time, refrigerated or low-temperature storage should be avoided to prevent temperature shock, which can cause mortality.

Additionally, if a batch shows an abnormal proportion of dead or weak mussels, strict sanitary controls must be conducted, and transport should be suspended to prevent potential pathogen spread.

### 6.3.2 On-growing strategy

Throughout the production cycle, the sequence of operations involved in renewing the socks, from retrieving the old ones to deploying the newly filled ones into the water, remains constant and is structured as follows:

- recovery of harvest-ready socks from the sea;
- transfer to the declumper and subsequent declumping;
- size grading;
- filling of new socks;
- redeployment of the new socks into the sea.

In addition to these operations, visual inspections of headline buoyancy must be carried out while navigating within the offshore farm, with supplementary buoys added where necessary.

Regarding the workflow and the arrangement of machinery on-board, it should be noted that equipment must be positioned according to a consistent logic that ensures linear product flow. As illustrated in Figure 6.28, old socks are retrieved at the stern, while redeployment occurs at the bow. In the example shown in Figure 6.31, the process is reversed.

#### *Recovery of harvest-ready socks from the sea*

The process begins by hooking the headline, lifting it from the water, and positioning it on the star wheels, as described in Section 6.2.4. Because socks freshly retrieved from the sea can weigh up to 60–80 kg, they are too heavy to be detached from the headline and hauled aboard manually. An outboard lifting device is therefore required to support each sock during retrieval, prior to detachment from the headline rope.

FIGURE 6.31
**Lifting a sock using the conveyor overboard**

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This device is equipped with a large articulated chain that rotates upward (bottom-to-top motion), enabling progressive lifting of the sock onto the deck with minimal operator intervention. The operator's primary task is to maintain the vessel's alignment along the headline, ensuring that each sock is positioned in front of the lifting device and placed in contact with the rotating chain.

Depending on the model, the lifting device may feature a slight inclination, as illustrated in Figure 6.31, or a more pronounced, curved configuration, as shown in Figure 6.32. When not in operation or during navigation, the devices are retracted and secured on-board.

*Sock transfer and declumping*

As shown in Figure 6.32 and Figure 6.33, the outboard lifting device is typically followed by a conveyor belt that transports the mussel socks to the declumper. Because the socks are 3–4 m in length, they cannot be fed directly into the declumper. Prior to processing, each sock must be cut into segments of approximately 50 cm, after which the declumping operation proceeds automatically.

The operator's responsibilities during this phase are limited to monitoring the declumper to ensure that no blockages occur and removing any plastic net fragments for proper disposal or recycling. As a general practice, the same operator performs the sequential tasks of retrieving the socks from the sea, cutting them into segments, and supervising the declumping unit.

A similar cutting procedure is also applied to commercial-sized mussels, for which sock segments of approximately 1 m are sold directly to buyers who perform declumping and grading at their own facilities. In this case, the segments are stacked on wooden pallets at a height of 1.2–1.5 m and wrapped in plastic film to prevent displacement during handling. This method significantly improves the mussels' resistance to transport and reduces internal water loss. This topic is discussed in greater detail in Section 6.3.3, which addresses product-harvesting strategies for marketing purposes.

FIGURE 6.32
**Mussel sock on the conveyor moving toward the declumper**

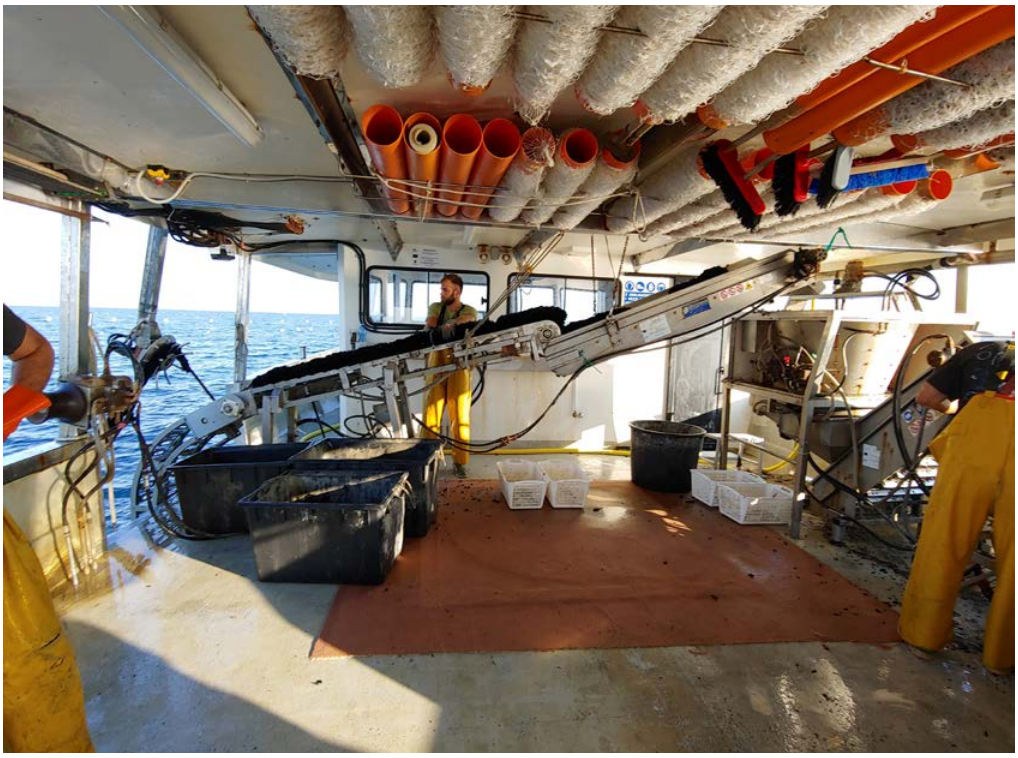




FIGURE 6.33
**Cutting a sock before introducing in the declumper**



### *Mussel size grading*

At the exit of the declumping process, a conveyor belt transports the separated mussels to the grading unit. The various types of grading machines are described in Section 4.5.2. For on-board size grading, horizontal vibrating graders with two or three

TABLE 6.1
**Average weight and count per kilogram of Mediterranean mussels by grading grid**

| Grill size (mm) | Average mussel weight (g) | Number of mussels/kg |
|---|---|---|
| 16 | 9.0–10.0 | 110–100 |
| 17 | 11.5–12.5 | 85–80 |
| 18 | 14.0–15.0 | 70–65 |
| 19 | 17.0–18.0 | 60–55 |
| 20 | 20.0–21.0 | 50 |

FIGURE 6.34
**Declumped mussel grading on-board using a horizontal vibrating grader**



grids are commonly used. A grader with two grids produces three distinct mussel size categories, while the addition of a third grid allows for four size categories.

To ensure accurate and consistent grading, it is recommended to assign one operator to each grid. In the case of a three-grid grader, two operators may be sufficient depending on operational conditions (Figure 6.34).

The size of the mussel batches leaving the grader is determined by the grid dimensions. Table 6.1 provides general guidance on the relationship between grid size and the average weight of mussels retained on each grid.

Further details on the relationship between mussel length, shell thickness, and individual weight can be found in Section 2.2.1 and Figure 2.11. It is important to note that this relationship may vary significantly depending on the production area, environmental conditions, and batch characteristics. For commercial operations, particularly when products are intended for sale, it is recommended to systematically determine either the average weight or the number of mussels per kilogram. Such measurements can also be performed on mussels temporarily returned to the sea to generate accurate data on growth rates and trends under specific environmental conditions. The information obtained from grading operations constitutes a critical stock management tool, enabling the farmer to monitor stock development, adjust production schedules, and predict yield at different stages of the production cycle.

The grading process requires preliminary declumping, which exerts mechanical and physiological stress on the mussels. Following transfer into new socks, mussels exhibit reduced growth activity, which typically resumes only after a recovery period. Consequently, the frequency of grading has a direct impact on the production cycle duration: more frequent grading can prolong the cycle. However, frequent grading also promotes improved product quality, as it results in higher meat content and the development of thicker and structurally stronger shells.

Declumping and grading further influence reproductive physiology. Outside the winter reproduction period, gamete release (sperm and eggs) is often triggered by sudden environmental changes such as fluctuations in temperature or salinity as well as variations in food availability. Declumping and grading reduces gamete emission, maintaining mussels in a condition suitable for commercial sale.

Furthermore, the grading process helps control epibiont colonization on mussel shells, including organisms such as barnacles, serpulids and ascidians. These epibionts can decrease commercial value, reducing marketable yield, and in some cases competing with mussels for phytoplankton resources (see Section 2.1.4 and Section 2.2.4). Therefore, regular declumping and grading, while facilitating accurate stock assessment, support optimal product quality and biofouling control which are critical for maintaining commercial viability throughout the production cycle.

### *Filling new socks*

Depending on mussel size, batches obtained from size grading may either be sold on the market or returned to the sea for further growth in new socks.

When preparing new mussel socks (Figure 6.25 and Figure 6.35), the operator must make several critical decisions that may directly affect product quality, mussel growth, and sock durability until the next grading. The two main factors to consider are the sock diameter and the mesh size of the plastic net.

The sock diameter is determined primarily by the requirement to provide uniform access to food (phytoplankton) and oxygen for all mussels. Excessively wide socks can create central zones with reduced water flow, limiting mussels' ability to open their shells and amplifying size variation beyond the inherent growth potential of individuals. Conversely, excessively narrow socks reduce competition for food, which may enhance growth rates, but decrease the number of mussels per linear metre, reducing overall yield.

FIGURE 6.35
**Mussel socking on-board**

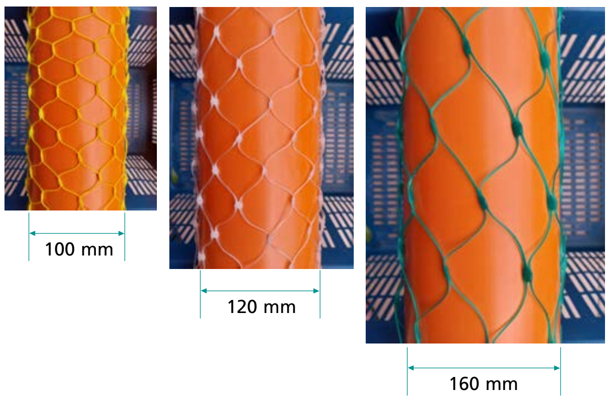
For socks of a given length and containing mussels of similar size, the diameter also defines the total number of mussels per sock and, therefore, the time required to reach the weight threshold at which the socks must be lifted from the sea to avoid losses. Smaller-diameter socks, containing fewer mussels, typically require a longer period to reach this threshold. Consequently, selecting an appropriate sock diameter allows the farmer to balance individual growth, stocking density, and the frequency of sock renewal.

The mesh size of the cotton net must be sufficient to retain newly stocked mussels until they have developed an adequate byssal attachment, ensuring cohesion among individuals and secure adhesion to the plastic net. The plastic net's mesh size must provide mechanical support that enables mussels to migrate outward and attach firmly during the growth phase.

Suppliers of mussel farming equipment generally provide sets of 6–12 tubular plastic nets with diameters ranging from 60–200 mm. The mesh number refers to the number of meshes along the sock circumference, while the mesh height corresponds to the vertical dimension of each mesh (Figures 6.36). Table 6.2 provides reference ratios between mesh number and mesh height for the most common mussel sock diameters.

The weight of plastic netting typically ranges between 15–25 g/linear metre. Most nets are made of polypropylene, although polyethylene and other materials are also used. These nets are engineered to withstand harsh marine conditions and to support the combined weight of mussels, epibionts, and water when the socks are lifted from the sea. A sock containing 30–40 kg of commercial-sized mussels can weigh up to twice as much when removed from the water. Accordingly, the nets are designed to tolerate weights of 70–80 kg without failure. They can be attached directly to the headline rope or via an intermediate thin cord.

FIGURE 6.36
**Examples of plastic neting for mussel socks**

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Plastic nets are generally supplied in rolls of 500–1 000 m, weighing 10–15 kg depending on the net type and manufacturer. Some suppliers incorporate dyes to facilitate identification.

In contrast, cotton nets exhibit elasticity, enabling a single net type to accommodate socks of different diameters. They are typically available in two diameters: one for socks 60–100 mm in diameter and another for socks 120–160 mm in diameter. Cotton nets are usually sold in 2 000 m rolls and vary in quality, with a functional lifespan of one to two weeks before they begin to disintegrate.

TABLE 6.2
**Technical specifications of plastic netting for mussel socks**

| Socks diameter (mm) | Mesh number | Mesh height (mm) |
|---|---|---|
| 60 | 12–6 | 30–45 |
| 80 | 12–6 | 40–75 |
| 100 | 10–6 | 50–85 |
| 120 | 10–6 | 60–100 |
| 140 | 10–6 | 70–105 |
| 160 | 10–6 | 80–115 |
| 180 | 10–8 | 90–100 |

### *Deployment of new socks to the sea*

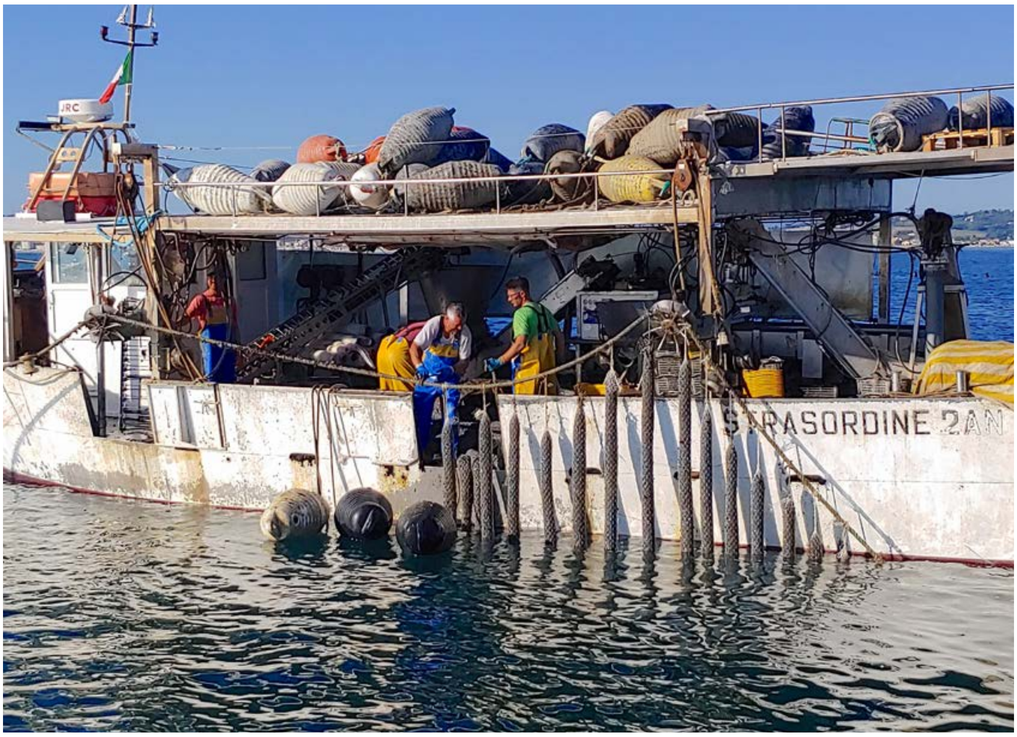
The depth of the headline and the average length of the mussel socks are determined during the farm design phase, based on site-specific factors such as water depth and prevailing currents. Additional decisions are made by the farmer during sock deployment at sea, including the selection of the destination headline, the spacing between socks, and the spacing of intermediate buoys.

Socks of identical diameter and containing mussels of the same size, i.e. batches derived from the same grading grid, must be deployed on the same headline or group of headlines (Figure 6.37). For instance, if grading produces socks of 100 mm, 120 mm, and 140 mm diameter, each size must be assigned to a separate headline group. When grading is conducted over multiple days, all socks of a given size should be placed on the same headline until the batch is complete.

New socks of a specific diameter may be hung on the same headline from which old socks were removed, while socks of other diameters should be temporarily stored on board until they can be allocated to their designated headlines. Effective management of headline allocation is critical to prevent mixing of sock sizes, minimize empty spaces, and reduce unnecessary handling within the farm. To support operational efficiency and long-term planning, it is recommended to maintain daily records of sock placement, enabling the farmer to plan subsequent operations on a daily, weekly, and monthly basis.

The spacing between mussel socks is determined by their diameter, the specific farm site, and prevailing seasonal conditions. Socks with larger diameters require increased spacing to prevent overcrowding, while windier periods necessitate additional separation to minimize the risk of socks colliding or tangling. During spring, seed socks with diameters of 60–80 mm can be spaced 50–60 cm apart. By the end of the production cycle, commercial socks with diameters of 140–160 mm are typically spaced 0.8–1.2 m apart. In the example farm considered in this manual, an average of 170–180 commercial-sized socks is deployed per 200 m of headline.

FIGURE 6.37
**Hanging of newly made mussel socks**



To maintain proper buoyancy of the headlines, buoys must be installed at regular intervals during sock deployment. The spacing between buoys depends on the buoy volume and the total weight of the socks, including mussels and any epibionts. When using biconical buoys, correct placement ensures that approximately 50 percent of each buoy remains submerged, while the remaining 50 percent remains above the waterline, providing both flotation and visibility for operational monitoring

### *Management of intermediate buoys*

As the mussels grow, the weight of the socks increases, causing the headlines to sit lower in the water. If not properly managed, this can reduce water circulation around the mussels, increase the risk of socks tangling, and compromise overall farm performance. Therefore, it is essential to regularly monitor the buoyancy of the buoys supporting the headlines. Buoys that are predominantly submerged indicate insufficient flotation and require reinforcement by adding additional buoys or replacing existing ones with higher-buoyancy units. Maintaining proper buoyancy ensures that the headlines remain suspended at the optimal depth and mussel socks do not come into contact with the seafloor.

### *On the way back to the harbour*

After completing a day's work at sea and performing all routine operations described above, several tasks can be carried out during the return trip to the harbour to optimize efficiency:

- Packaging or preparing mussels for sale.
- Placing nets on PVC pipes for use in the following days (Figure 6.27 and Figure 6.38).
- Cleaning recovered buoys to allow them to be stacked on the canopy or stored on land.
- Performing general on-board cleaning and maintenance.

Except during the winter–spring period, it is advisable to avoid leaving mussels on board for grading, socking, or deployment from one day to the next, in order to preserve product quality and minimize stress on the animals.

Carrying out these activities during the return trip ensures that equipment and products are properly handled, maintained, and prepared for subsequent operations, reducing downtime and supporting overall farm efficiency.

### *Optimizing work on-board*

Another consideration revolves around the deck space necessary for all handling procedures, from lifting the farmed product to its return to the sea. This allocation is essential to ensure the efficient execution of all necessary procedures. Efficient deck operations are paramount, with a preference for avoiding temporary storage of the farmed product. Such storage not only occupies valuable space but also results in time wastage. In a scenario where only three individuals are involved, all operators would initially harvest, grade and store the mussels in temporary crates. Subsequently, in a separate phase, they would fill the socks

FIGURE 6.38
**Preparing nets on PVC pipes**

and return them to the sea. On the other hand, in a 6-person team, three operators would focus on harvesting and grading the product, while the remaining three would handle the filling and re-suspension of the socks.

### 6.3.3 Harvesting strategy

As previously noted, mussels can be marketed in several forms:

- Declumped and graded mussels, either ready for sale when produced in Class A waters or ready for depuration when produced in Class B waters (see Section 2.3). In this case, mussels are typically landed in net bags with a capacity of 20–25 kg. In certain circumstances - and in compliance with applicable EU and national regulations, and with specific authorization - commercial-size mussels from Class A waters may be packed directly on board for delivery to wholesalers and retailers.
- Sock segments measuring 0.5–1.0 m, stacked on standard wooden pallets.
- Whole socks, also placed on standard wooden pallets.

In the first marketing option, declumping imposes significant physiological stress on mussels. Byssal threads may be torn, shells may crack, and many individuals - though externally intact - lose internal water content. Grading further exacerbates these effects. Consequently, mussels packaged and sold immediately after declumping and grading exhibit a reduced shelf-life.

A method to mitigate this involves grading mussels at least two weeks ahead of sale, placing them back at sea in bags, and allowing them to recover. Although this requires additional labour and netting, it enables mussels to reattach, regain water content, and restore condition, thereby maximizing shelf-life. Subsequent retrieval, declumping, and final grading become faster, easier, and far less stressful for the animals. After the final grading step, the product must be inspected to remove broken or open mussels, undersized individuals, and other waste materials prior to packaging.

In contrast, mussels sold as sock segments or whole socks have not undergone declumping or grading and therefore experience minimal handling stress and water loss during transport. For this reason, many buyers prefer to purchase mussels in this state and perform processing themselves, enabling them to offer a freshly processed product. However, this approach prevents the return of undersized mussels to the sea for further growth. As a result, socks intended for sale - either whole or in pieces - must contain only a very small proportion of undersized animals.

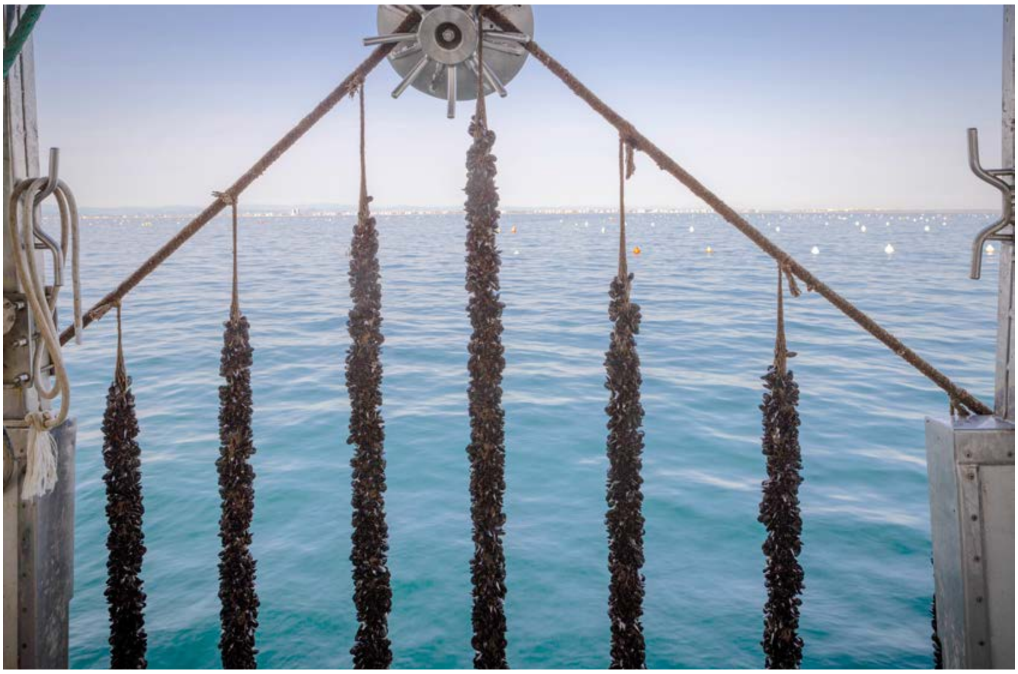
As outlined above, the marketing strategy has a significant influence on yield, production costs, and ultimately the selling price.

Regarding yield, the weight of declumped, graded, and packaged mussels typically represents about 70 percent of the weight of whole socks sold intact. This yield declines over the production season, particularly as water temperatures rise. The remaining 30 percent consists of undersized mussels, broken or open shells, epibionts, net residues and other waste. Accordingly, mussels sold as whole socks or sock segments command a lower price per kilogram than fully processed mussels.

Production costs are driven primarily by labour - namely, the number of times mussels are handled, graded, or transferred into new nets. Producing high-quality, declumped, graded, and packaged mussels can cost approximately twice as much as producing mussels sold in whole socks. Net consumption also differs markedly: plastic net use averages 0.4 m/kg for fully processed product and may be reduced by about half when mussels are marketed in whole socks.

Once prepared for sale, the product must be kept at a controlled temperature of 4–6 °C, ensuring strict maintenance of the cold chain throughout all stages of storage, processing and transportation.

FIGURE 6.39
**Mussels socks ready for harvesting**

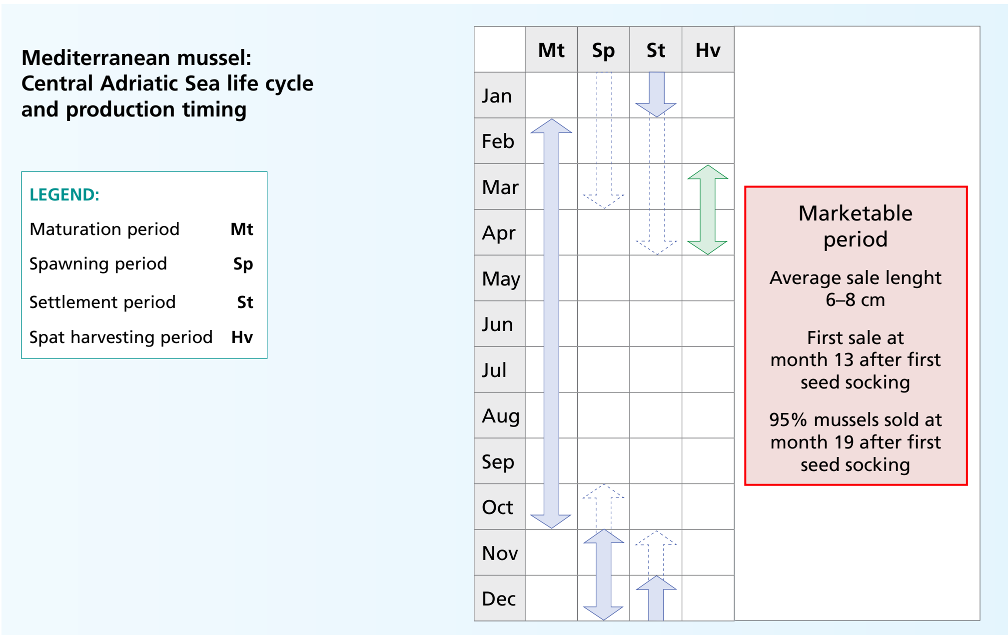




## 6.3.4 Farming calendar

The farming calendar reflects the timing of reproduction and larval settlement of Mediterranean mussels in the central Adriatic Sea, as outlined in Section 2.1 (Figure 6.40). Understanding this seasonal cycle is essential for planning all farming operations, from the collection of natural spat to socking, thinning, and harvesting. Variations in water temperature, food availability, and reproductive intensity throughout the year influence growth rates, condition index, shell strength, and overall product quality. For

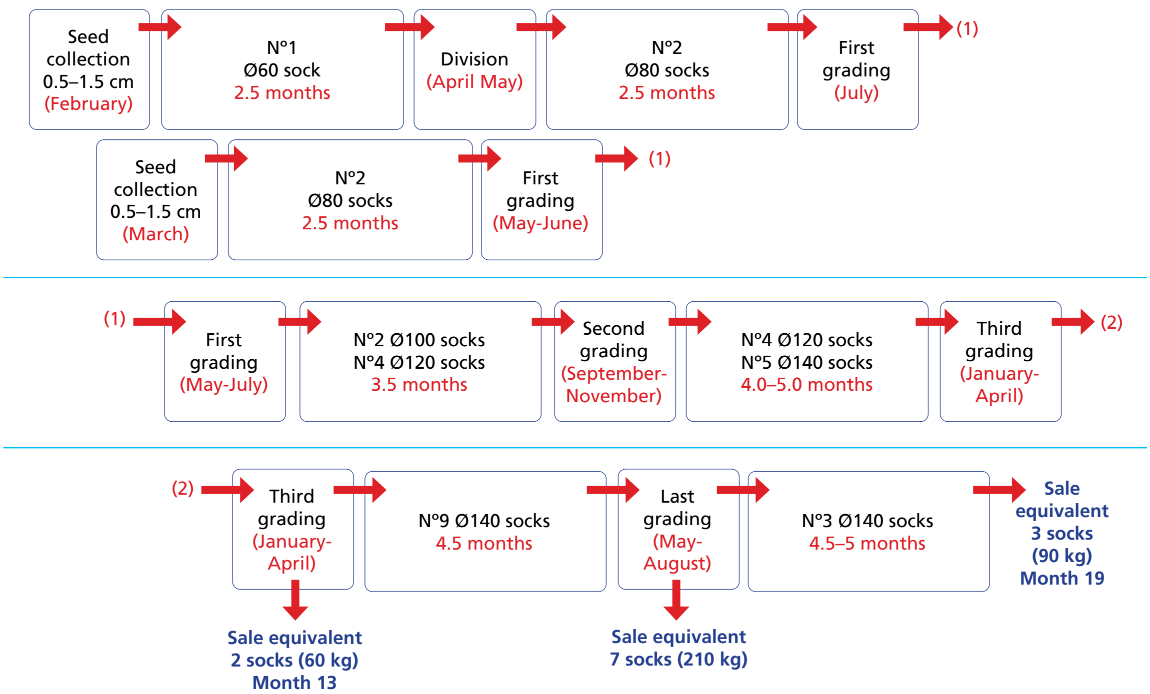
FIGURE 6.40
**Offshore Mediterranean mussel production cycle and farming schedule in the central Adriatic Sea**



this reason, each phase of the production process must be aligned with the biological rhythms of the species to maximize yield, optimize labour and resource use, and ensure consistent supply to the market.

Figure 6.41 shows an example of a production programme. Starting from one 60-mm sock and two 80-mm socks prepared in February–March of the first year, the system yields approximately 360 kg of commercial-size mussels, with harvesting and sales distributed between April (month 13) and August (month 19) of the second year. In this scenario, following one division and four size-grading operations, a total of 32 socks, each about 3.5 m in length, were produced. This required the use of roughly 130 m of netting, corresponding to about 2.5 kg of polypropylene. This example illustrates both the material inputs and the operational steps needed to reach commercial yield over a typical 18–19-month production cycle.

FIGURE 6.41
**Illustrative production schedule detailing sock sizes, processing operations, and resulting commercial yield**




## 6.3.5 Maintenance of farm equipment

Farmers must perform various routine tasks to maintain all equipment used in mussel production at the correct standard. The marine environment poses challenges to equipment longevity and safe operation. Therefore, regular checks and servicing of all farm equipment are essential. Table 6.3 below outlines some of the key items that should undergo regular inspection:

### *Workboat*

Before setting out to sea each day, it is essential to conduct thorough checks on the workboat's engines and to verify the oil levels (engine, gearbox, hydraulic), coolant level and fuel level to ensure the vessel's seaworthiness. Additionally, once the engine is running, inspect the saltwater cooling system to confirm the correct discharge flow.

Mechanical breakdowns of any propulsion unit at sea can pose serious risks to the boat crew. Therefore, it is important to adhere to regular servicing of the main engines in accordance with the manufacturer's guidelines to mitigate the risk of such incidents.

TABLE 6.3
**Farming equipment chart featuring daily, weekly, monthly and annual maintenance tasks**

| Task | Frequency |
|---|---|
| All workboat machinery | Daily – Check before use. |
| Fresh water wash-down of equipment | Daily – After each use where possible. |
| Greasing | Weekly or monthly – Particular attention should be paid to equipment that is used daily. |
| Hydraulic hose replacement | Monthly – Check for signs of wear and abrasion. |
| Hydraulic valves and fittings | Monthly – Check for signs of corrosion and ensure that the protective coverings are undamaged. |
| Anodes | Quarterly inspection – Replace anodes as necessary. |
| Workboat engine | Service intervals should align with the manufacturer's recommendations based on engine hours and usage. |
| Workboat hull | Annually – Check hull integrity, apply antifouling coating and replace anodes, as necessary. |
| Navigational markers | Full inspection annually, but farm workers should be vigilant each time they are on site. Lighting systems should be inspected every 3 months. Repairs when required. |
| Long-lines | Full inspection annually, but farm workers should be vigilant each time they are on site. Repair when required. |
| Containment devices | Repair or replace when required. |

All anodes safeguarding metallic components (such as propellers, shafts and the hull if built in steel) should undergo inspection every quarter and be replaced before reaching a state of ineffectiveness due to deterioration.

All safety, navigation and lifting equipment should be in good condition and certified by a qualified inspector if the local regulations mandate it.

The hull of the vessel is prone to corrosion and deterioration. Consistent checks are crucial to preserve hull integrity and prevent water leaks. An annual hauling of the vessel is necessary for a thorough hull inspection and the application of an antifouling coat. This protective measure safeguards the hull, mitigates biofouling, improves hydrodynamics, and reduces fuel costs. In the case of metal-hulled vessels, regular inspection and replacement of anodes affected by galvanic corrosion are essential.

### *Navigational markers inspection and repair*

Ensuring that navigational markers are functioning correctly and are in good repair is essential for the security of all sea users. When operating on the farm and weather permitting, a systematic check of all navigational markers should be conducted. Any missing markers should be promptly replaced. It is advisable to have an emergency marker ready for immediate deployment in case of marker loss. Every three months, a night inspection should be carried out on the lighting systems to verify their functionality.

Professional divers should conduct an annual inspection of mooring lines and anchoring devices. Any deteriorated parts should be replaced or repaired as needed to maintain the integrity of the system.

### *Long-lines inspection and repair*

Maintaining the integrity of the long-lines is vital to prevent product loss. While working on the farm, all operators should regularly verify that the long-lines are secure and have not moved from their original positions. Since headlines and associated buoys are typically aligned or parallel, any misalignment or incorrect positioning should be readily apparent. If an abnormality is observed, a detailed inspection will be necessary, with prompt repair of any identified damage.

The farm owner should maintain a comprehensive register that includes the following information:

- Date of installation for each anchoring device, specifying type and weight.
- Date of installation for each mooring line, including details on rope diameter and material.
- Date of installation for each headline rope, with information on rope diameter and material.
- For all the components, document the date of any inspections, intervention, and note upcoming maintenance tasks.

Professional divers should perform an annual inspection of all mooring lines and anchoring devices. Any components showing signs of wear or deterioration must be promptly repaired or replaced to ensure the continued reliability and safety of the equipment.

*Hydraulic hose replacement*

If the operator is utilizing hydraulic-powered equipment, such as star wheels, winches, cranes and derricks, regular checks should be conducted on all hydraulic hoses for signs of wear and abrasion. Hoses exposed to environmental elements, especially UV light and saltwater, are prone to deterioration over time. The rupture of a hose under pressure can pose a hazardous situation for individuals working on-board. Moreover, the discharge of hydraulic oil into the seawater can have adverse environmental effects and must be prevented at all costs.

*Hydraulic valve and fittings protection*

Many of the metallic fittings, including hose connectors and hydraulic valves, are susceptible to corrosion and should be protected from the elements. Whenever feasible, these fittings should be wrapped in corrosion prevention sealing tape or sprayed with a corrosion prevention solution to maintain their integrity.

*Grading and processing equipment*

All equipment exposed to seawater should be rinsed with freshwater, whenever feasible. Despite being constructed from stainless steel, items may still succumb to corrosion under specific conditions, albeit at a less accelerated rate and severity compared to conventional steel. Machinery with movable components, such as graders, may malfunction due to the accumulation of debris and salt deposits. Consequently, it is advisable to undertake periodic cleaning to mitigate the detrimental effects on operational efficiency.

*Greasing*

Routine lubrication of equipment components necessitating maintenance should be performed in strict accordance with the manufacturer's scheduled maintenance requirements.

### 6.3.6 Monitoring and traceability

The collection of data concerning key parameters influencing the growth and development of the mussels constitutes an important asset for farmers. This information proves instrumental in guiding operators on optimizing farm production and fostering operational efficiency. Over the course of multiple years, cumulating data from each growing season facilitates the establishment of a discernible pattern in stock management. This pattern, in turn, facilitates informed decision-making for the operator, encompassing aspects such as optimal timing for seed procurement, seed quantity required, strategic implementation of stock management practices like grading, and the anticipated harvesting timelines for distinct mussel batches.

Parameters that can be easily monitored and recorded are:

- Water temperature.
- Estimation of phytoplankton concentration using a Secchi disk.
- Date of the different operations (grading, harvesting, etc.).
- Mussel size determined through systematic sampling.
- Mussel numbers and mortalities through counting.
- Mussel meat-to-shell ratio.
- Sale prices.

From these datasets, additional key elaborations can be conducted to evaluate the following outcomes:

- Average growth rate differentials contingent upon batches, seasons, and employed farming techniques.
- Duration of the production cycle and beginning/end of commercialisation for each farmed batch.
- Final yield, expressed as harvested weight per 100 000 seed introduced.

All the data that is collected should be recorded in a stock management document so that it can be easily accessed. Data recording and management can be facilitated through custom Microsoft Excel documents or specific software packages designed for shellfish production businesses.

## 6.4 MAIN CONSTRAINTS

### 6.4.1 Environmental constraints

In contrast to intertidal and nearshore sites, which are significantly influenced by environmental factors emanating from the adjacent land, offshore sites exhibit more consistent conditions in terms of salinity, water quality and the risk of eutrophication.

Two primary environmental constraints are associated with offshore farming:

- Phytoplankton concentrations are typically lower offshore due to the progressive dilution of nutrient run-off from the land.
- Farm sites are significantly affected by storms, given their typical exposure in offshore locations.

Furthermore, these two constraints are worsening due to the impacts of climate change:

- Changes in precipitation patterns, marked by heightened rainfall within compressed temporal intervals, has an impact on the biological cycle of phytoplankton, altering species concentrations and dominance, and consequently the quantity and size of the available phytoplankton cells.
- The escalation in both the force and duration of storm events further amplifying the challenges posed by these constraints.

In the Mediterranean Sea area, where the rise in temperatures seams more pronounced than in other parts of the world, global warming is having an increasing negative impact on mussels:

- with lower survival of mussels during summer period;
- with lower resistance of byssus during hot period;
- with different growth patterns;
- with gamete emissions in all seasons.

For example, in the Adriatic Sea, summer temperatures reach and exceed 30–31 °C, the maximum threshold tolerated by *M. galloprovincialis*, for increasingly longer periods. Significant episodes of heat-related mortalities have already been recorded in 2024. The same phenomenon also led to a progressive reduction in the areas suitable for farming with the abandonment of the sites further South, and a reduction in the sales period with the product being completely sold by July, thus missing out on the period of high demand of the August holidays.

Finally, from the point of view of the impact of farming on the environment, mussels, like all farmed bivalves, have a well-known beneficial impact as eutrophication reduction, nitrogen and carbon absorption, and biodiversity enhancement. Long-line farms can be considered as "Other Effective Area-based Conservation Methods" as the farms where fishing is prohibited provide refuge for many species.

However, the offshore farming sector remains under scrutiny for its use of plastic nets. Although most of the nets are disposed of in accordance with the law, a small proportion are lost on the seabed following storms or due to the carelessness of some operators. To overcome this issue, but also to reduce production costs, various studies are underway to recover and recycle polypropylene or polyethylene nets, or to replace them with new biodegradable or compostable biopolymers.

### 6.4.2 Conflict for site availability and licensing

Concerning the risks associated with potential conflicts arising from other human activities, offshore locations present two salient advantages:

- **Reduced visibility from shore:** Most offshore farms are situated beyond the "visible field" from the shoreline. This spatial configuration mitigates visual impact concerns and enhances the aesthetic integration of offshore installations.
- **Lower human activity density:** Offshore locations exhibit a decreased density of human activities when compared to foreshore sites, thus minimizing the potential for interactivity conflicts.

Furthermore, the transition to offshore installations prompts governing authorities to proactively address pertinent licensing challenges. This includes the establishment of comprehensive regulatory frameworks for fully offshore sites and addressing the complexities associated with licensing mixed activities within designated zones. Examples of such intricacies involve reconciling potential cohabitation scenarios, such as wind farms coexisting with the shellfish industry, or the implementation of IMTA around fish cages. Effectively navigating these licensing challenges is imperative for the sustainable and harmonious development of diverse activities within offshore zones.

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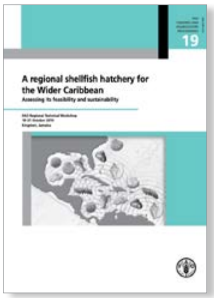


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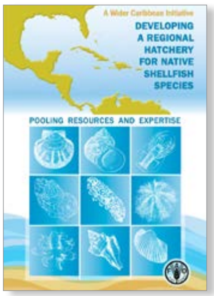


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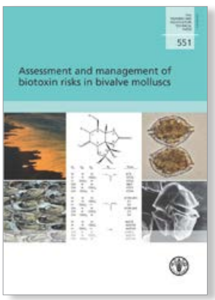


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# Glossary

| | |
|---|---|
| **Adductor muscle** | Large circular and central muscle that pulls the two valves together. |
| **Algae** | Aquatic plants that reproduce by cell division or spores. |
| **Biofouling** | Presence of organic growth on the outer surface of the mussel shell or on farming structures. |
| **Bivalve** | Mollusc having a shell made of two valves that are joined by a hinge. |
| **Diploid** | In genetics and biology, the term diploid refers to the cell containing two sets of homologous chromosomes wherein each chromosome in a set is obtained from each of the two-parent cells. |
| **D-larva** | Second free-swimming planktonic larval stage of mussels (first veliger stage). |
| **Embryo** | Early stages of development of an organism prior to larval stage. |
| **Exposure** | The risk of damages in case of exceptional events (storms, tempest or typhoon) and the deterioration of the farm components under the continuous effect of waves and winds. |
| **Fertilization** | Union of egg and sperm. |
| **Fetch** | Distance over the water that the wind has blown without hindrance in the direction of the farm site before impact with the cultivation equipment. For a given wind direction, fetch is calculated as the distance between the farm and the opposite coastline. |
| **Gamete** | Mature, haploid, functional sex cell capable of uniting with the alternate sex cell to form a zygote: sperm or egg. |
| **Gametogenesis** | Process by which eggs and sperm are produced. |
| **Gill** | Leaf-like appendage that functions in respiration and filtration of food from water. |
| **Gonads** | Primary sexual organ: testis producing sperm or ovary producing eggs. |
| **Hermaphrodite** | Organism that has both male and female sex organs at the same time or in alternate periods of their life cycle. |
| **Intertidal zone** | Area of the foreshore that is exposed to air over low tide (without seawater). |
| **Larva** | Stage of bivalves from the embryo to metamorphosis. |
| **Live weight** | Weight of the live mussel including shell, body and intra-valves water. |
| **Mantle** | Soft fold enclosing the body of a bivalve that secretes the shell. |
| **Mean tidal range** | Vertical distance between the mean high water (average high tide level) and the mean low waters (average low tide level). |
| **Meat content** | Quality criteria expressed as a percentage that reflects the weight of the meat (after draining) in relation to the total weight of the mussel before opening. |
| **Metamorphosis** | In bivalves, the period of transformation from the larval to the juvenile stage. |

| | |
|---|---|
| **Pediveliger** | Last free-swimming planktonic larval stage of mussels (forth veliger stage) characterized by the presence of a velum, an umbone and a sensitive foot needed for further settlement and attachment. |
| **pH** | Expression of the acidity or alkalinity of a solution, for instance for seawater. |
| **Pseudo-faeces** | False faeces, waste material not taken into the digestive tract. |
| **Seed recruitment** | Providing suitable substrates onto which the mussel larvae can attach themselves at the end of their planktonic stage when settlement occurs. |
| **Return time** | For extreme events (storms, tempest or typhoon), the average time between two occurrences. |
| **Salinity** | Measure of the amount of salt dissolved in water, for instance in seawater. |
| **Seed** | Young mussel with no specific definition to size. |
| **Settlement** | Behavioural process when mature bivalve larvae seek a suitable substrate for attachment. |
| **Shelf-life** | Period of time that the mussels can remain alive and suitable for human consumption once they have been removed from the water. |
| **Spat** | Newly settled or attached bivalve (also called post-larval or juvenile in bivalves). |
| **Spawning** | Release of the gametes (sperm and eggs). |
| **Subtidal zone** | Area of the shallow waters just after the "intertidal zone" before moving towards the open sea. |
| **Triploid** | Compared to diploids, triploids organisms have an additional set of chromosomes. |
| **Trochophore** | The first free-swimming planktonic larval stage of mussels. |
| **Umbo** | Beak-like projections at the dorsal part of the shell; it is the oldest part of a bivalve shell (also called the umbone). |
| **Umboned veliger** | The fourth free-swimming planktonic larval stage of mussels (third veliger stage) characterized by the presence of a velum and an umbone. |
| **Veliger** | The free-swimming planktonic larval stage of mussels (second veliger stage) characterized by the presence of a velum. |
| **Velum** | Ciliated locomotory organ of the veliger larva. |
| **Wave height** | The vertical distance between the crest (peak) and a neighbouring trough of a wave and twice the amplitude. |

# Appendices

# Appendix I – Food safety considerations for production and processing of bivalve molluscs

by
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## INTRODUCTION

Bivalve molluscs, including oysters, mussels, scallops and clams, play a crucial role in the aquatic food supply chain. Bivalve mollusc production has the benefits of not requiring substantial initial investments, not requiring the use of feeds or antibiotics, and providing employment opportunities for numerous coastal communities. In 2018, the global production of bivalve molluscs reached approximately 17.7 million tonnes mainly (about 80 percent) sourced from aquaculture. This substantial output generated an estimated first-sale value of USD 34.6 billion (FAO, 2020).

Bivalve molluscs are filter-feeding organisms, and as such possess the ability to accumulate microorganisms, chemical contaminants and toxins that may be present in the environment within which they are grown. This necessitates stringent food safety standards during their production and marketing to safeguard consumers and facilitate international trade. Regulatory frameworks established by national food safety and public health agencies, along with fisheries and aquaculture authorities, should encompass both domestic and international aspects of production and processing.

Adherence to Article 3 of the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS) under the World Trade Organization (WTO) is crucial. According to this article, Member countries are required to base their measures on international standards, guidelines, or recommendations. The Codex Alimentarius Commission (CAC) serves as the recognized international standard-setting body under the SPS agreement for food safety. This ensures that the production and trade of bivalve molluscs meet globally accepted standards, promoting consumer protection and facilitating smooth international commerce.

## INTERNATIONAL GUIDANCE

The Codex Alimentarius Commission (CAC) has developed a Standard for Live and Raw Bivalve Molluscs (FAO and WHO, 2015). Within the Codex Code of Practice (COP) for Fish and Fishery Products (FAO and WHO, 2020), there is a dedicated section on the processing of live and raw bivalve molluscs (Section 7). This section provides comprehensive guidance on the necessary steps throughout the entire food chain to produce a product which meet the requirements of the Codex Standard. The COP provides information on prerequisite programmes, sanitary surveys, the classification, and monitoring of growing areas to manage risks associated with microbiological and chemical contamination, as well as concerns related to phytoplankton and biotoxins. Moreover, specific guidelines within the CAC address particular issues, including the management of pathogenic *Vibrio* spp. (FAO and WHO, 2010), human pathogenic viruses (FAO and WHO, 2012), and methodologies for determining marine biotoxins (FAO and WHO, 2016). Application of this collective guidance helps to ensures the implementation of standards to produce live and raw bivalve molluscs, promoting food safety across the industry.

Further technical guidance to produce microbiologically safe bivalve molluscs is given in the Joint FAO-WHO Technical Guidance for the Development of the Growing Area Aspects of Bivalve Mollusc Sanitation Programmes (FAO and WHO, 2021). The guidance is intended for primary production of molluscs for consumption live or raw bivalve molluscs in estuarine or marine environments, although many of the principles may be applicable to freshwater molluscs. The FAO-WHO Technical Guidance offers in-depth scientific insights and explanations as a complement to Section 7.2 of the COP (detailed below). This guidance extends to the assessment and monitoring of areas utilized for relaying (Section 7.4 of the COP). Similar evaluation and monitoring procedures, guided by the same principles, may also be applied to areas used for conditioning and wet storage in the natural environment (Section 7.6.2). While the primary focus of the FAO-WHO Technical Guidance centres on the identification and control of microbiological hazards, it includes references to relevant Codex standards and other international guidance addressing public health risks associated with chemical hazards, phytoplankton and biotoxins. The recommendations provided in the FAO-WHO Technical Guidance are particularly broad in their applicability when common principles are pertinent to the control of multiple risks. This general applicability is evident in sections such as the Growing Area Risk Profile (Section 2), Growing Area Assessment (Section 3), Growing Area Management (Section 6), and Growing Area Review (Section 7).

## BIVALVE MOLLUSC SANITATION PROGRAMMES

The FAO-WHO Technical Guidance provides detailed scientific and technical information on the steps required to be undertaken by Responsible Authorities and other actors to establish new bivalve mollusc production areas. These are described in brief in the following sections.

### 1. Growing area risk profile (GARP)

Completion of the GARP by the Responsible Authority is the first step to determine whether, in principle, commercial bivalve mollusc production can be established in a new area. It comprises the acquisition, recording and assessment of available information and data on location of the proposed growing area, bivalve mollusc species to be harvested, intended use of the product, potential hazards requiring control, relevant epidemiological data, and the national, regional, or local capabilities and capacities to undertake assessment and monitoring (e.g. resources, laboratories, trained fisheries officers).

The GARP is typically conducted through a desk study, providing essential insights for subsequent stages of the assessment, monitoring and classification process. In specific situations, the GARP may reveal that an area is unsuitable for harvest, thereby prompting the allocation of resources to ensure that harvesting is prevented. The depth of information collected for a risk profile need only be sufficient for the Responsible Authority to make a go-no-go decision regarding the potential development of the growing area. Any surplus data can be summarized and retained for the next step, known as the growing area assessment. Additionally, the risk profiling process may highlight data gaps, prompting decisions on how to address these gaps in the subsequent growing area assessment. This iterative approach ensures that decisions are well-informed and supported by a comprehensive understanding of the risks associated with the growing area.

### 2. Growing area assessment (GAA)

The GAA builds upon information and data obtained in the GARP, through the inclusion and analysis of additional data (either existing data or new data obtained through a targeted survey – for example, of specific pathogens or faecal indicator organisms such as *Escherichia coli* or other faecal coliforms). Additionally, practical observations of the area are typically conducted through a shoreline survey.

The primary objective of the GAA is to formulate a comprehensive plan for ongoing monitoring. This plan encompasses crucial elements such as the identification of monitoring point locations, the types of samples to be collected - typically from either water or bivalve molluscs - and the specific hazards to be monitored, along with the recommended monitoring frequency. The aim is to ensure that the future monitoring programme is representative of the entire growing area, thereby enabling the effective control of any potential public health risks.

Moreover, the GAA provides valuable insights into post-harvest treatments that may be necessary before introducing the product to the market. By addressing these aspects, the GAA plays a pivotal role in safeguarding public health and establishing a robust foundation for a comprehensive and effective monitoring programme.

## 3. Growing area monitoring (GAM)

Monitoring of a growing area to provide additional evidence for the presence and concentration of faecal indicators and/or specific hazards is crucial for the classification and effective management of the growing area. Section 7.2.1 of the Codex COP envisions that monitoring can encompass water, bivalve molluscs and/or sediments. Internationally recognized Good Aquaculture Management (GAM) often relies on the determination of E. coli or faecal coliform levels, either in water or bivalve molluscs, collected consistently over time. These indicators are employed to assess the risk of faecal borne pathogens. The data generated through GAM enable predictions of the near- to mid-term sanitary quality of the growing area based on historical data. This prediction informs decisions about whether bivalve molluscs can be harvested and consumed raw directly from the growing area or if post-harvest processing is necessary. Primary monitoring, involving frequent sampling and testing, is often employed to establish an initial classification. This is followed by ongoing monitoring at less frequent intervals. Over time, individual monitoring results contribute to the determination of conditional classifications and may inform other risk management actions. While monitoring is essential for verifying the accurate classification of an area, it should be noted that monitoring programs alone cannot fully capture the risk associated with individual hazards. This limitation arises for several reasons:

- the hazard may not always be present in the potential source(s);
- even if always present, the concentration in the source(s) may vary with time (season, weather, time of day); or
- the hazard may only be present, or may only be present in high concentrations, after unexpected events.

## 4. Classification

Classification consolidates the findings from GARP, GAA, and GAM, offering a comprehensive risk categorization for a growing area. This facilitates the application of standard risk management protocols and post-harvest processing requisites, such as depuration, relaying in clean water or heat treatments. Classification establishes a unified framework of controls enforceable by regulators, aiding industry planning, and ensuring easy comprehension for purchasers. Typically subject to annual reviews, classifications may undergo adjustments, especially when extensive datasets from multi-year GAM programmes are available. Trend analyses derived from such data can inform long-term classifications or "conditional" classifications based on seasonal or other variables (e.g., rainfall). This dynamic approach may elevate sanitary status during specific periods, potentially reducing the necessity for year-round post-harvest measures and proving advantageous for the industry.

## 5. Growing area management

The Responsible Authority must possess the capacity and resources to monitor and evaluate changes that impact the status of growing areas with respect to the identified hazards and their mitigation. This entails the ability to apply criteria influencing classifications, including any conditional classifications, as well as conducting continuous surveillance activities. Additionally, the Responsible Authority should be equipped to carry out essential investigations and management actions, such as enforcing no-harvest policies during closures or increasing processing requirements. These capabilities may be shared with other regulatory bodies, as stipulated in regulations or binding agreements, such as Memoranda of Understanding.

The Responsible Authority is mandated to disclose the boundaries and classification status of each growing area, along with any criteria governing conditional classifications or the imposition of closures. Furthermore, the Authority should ensure timely communication of the effective periods of such closures or reclassifications. This information must be disseminated directly to harvesters, wholesalers and other stakeholders. Clarity in communication is crucial, including unambiguous directives that prohibit harvesting during closures and which detail any supplementary post-harvest processing requirements following a reclassification. Additionally, stakeholders should receive explicit communication when a closure is lifted, ensuring comprehensive awareness and adherence to regulatory changes.

## 6. Growing area review

This part of the sanitation programme involves a systematic and scheduled assessment, reevaluating the ongoing relevance of GARP and GAA, coupled with an analysis of monitoring data. The objective is to ascertain whether adjustments to classification status and management plans are warranted. The review process is important in identifying changes within the area that might affect the range of hazards that are of concern, and in identifying changes in the level of risk from identified hazards. A study by Hay and co-workers (Hay, B., McCoubrey, D.J. and Zammit, A., 2013) identified that the absence of a formal and structured review tended to lead responsible bodies to assume that no such changes had occurred. This assumption proved to be a pivotal factor contributing to sanitation programme shortfalls, ultimately leading to bivalve-associated viral outbreaks in Australia and New Zealand.

## BIVALVE MOLLUSCS AND MARINE BIOTOXINS

Marine biotoxins are poisonous substances that can accumulate in the tissues of some species of bivalve molluscs. Contamination usually occurs through filter-feeding on certain species of toxin-producing phytoplankton which occur naturally in marine or estuarine environments. Consumption of bivalve molluscs contaminated with these biotoxins can lead to serious illness. Section 7 of the COP for Fish and Fishery Products (FAO and WHO, 2020.) requires that Responsible Authorities control for marine biotoxins in bivalve molluscs in commercially harvested growing areas. The COP also recommends complimentary phytoplankton monitoring and observations of growing areas for signs that may indicate the presence of a toxic event (e.g. dead or dying birds, mammals or fishes). It is further indicated that monitoring programmes for toxins in bivalve mollusc flesh and phytoplankton levels in water consider seasonal variability and the presence of new or emerging toxin or toxin producing species. An FAO-WHO guidance document on management of marine biotoxins in growing areas, similar to the existing FAO-WHO Technical Guidance for the Development of the Growing Area Aspects of Bivalve Mollusc Sanitation Programmes is in preparation.

In countries or trading blocs with well-developed bivalve mollusc industries and mature regulatory frameworks, including the European Union, Republic of Korea, the

Russian Federation, the United Kingdom of Great Britain and Northern Ireland, and the United States of America, four groups of biotoxins are generally regulated in live bivalve molluscs either directly in the growing area, at the end-product stage or both. Regulated groups of biotoxins can cause:

- Paralytic shellfish poisoning (PSP) – caused by saxitoxins (STX)
- Amnesic shellfish poisoning (ASP) – caused by domoic acid (DA)
- Diarrhetic shellfish poisoning (DSP) – caused by the lipophilic toxins, okadaic acid and dinophysistoxins
- Azaspiracid shellfish poisoning (AZP) – caused by azaspiracids

In addition, the lipophilic toxins also include additional toxins such as yessotoxins and pectenotoxins, which may have regulatory limits but show little evidence of human health issues. In most countries, biotoxin testing is supplemented with phytoplankton monitoring in the growing area waters.

Direct, regular monitoring for marine biotoxins in bivalve molluscs in growing areas against legal maximum permitted limits, enables management actions such as short-term harvesting prohibitions to be put in place by the Responsible Authorities. This prevents product with a higher risk of causing human intoxication entering the food supply chain. Ongoing monitoring of certain species of phytoplankton can provide early warnings of toxic phytoplankton blooms, which allow management actions to reduce consumer risks such as modifying harvesting practices, increased growing area testing for biotoxins or enhanced end-product testing. Countries or trading blocs set out maximum permitted levels of biotoxins in national legislation.

CAC standard for Live and Raw Bivalve Molluscs (FAO and WHO, 2015) sets out maximum permitted levels in the edible parts of live bivalve molluscs:

| Name of biotoxin groups | Maximum level/kg of mollusc flesh |
|---|---|
| Saxitoxin (STX) group | ≤0.8 milligrams (2HCl) of saxitoxin equivalent |
| Okadaic acid (OA) group | ≤0.16 milligrams of okadaic equivalent |
| Domoic acid (DA) group | ≤20 milligrams domoic acid |
| Brevetoxin (BTX) group | ≤200 mouse units or equivalent |
| Azaspiracid (AZP) group | ≤0.16 milligrams |

*Source*: Elaborated by the authors.

Sampling frequency within official monitoring programmes for marine biotoxins can vary both within and between countries, but should be based upon risk, with increased monitoring (sampling) undertaken during periods of the year where there is an increased likelihood of the presence of toxin producing phytoplankton. For more information consult the *Joint FAO-IOC-IAEA Guidance on Monitoring of Algal Toxins in Bivalve Molluscs*.

## ADDITIONAL CONSIDERATIONS

A complete bivalve mollusc food safety programme includes several elements in addition to those relating to Responsible Authority controls of the growing area. These are covered in Section 7 of the Codex COP (FAO and WHO, 2015) and the Codex Standard for Live and Raw Bivalve Molluscs (FAO and WHO, 2020) and include:

- Harvesting and transportation
- Relay
- Depuration
- Processing
- Lot identification
- Recall procedures
- Composition and quality
- Specified limits for contaminants and hygiene indicators
- Labelling and storage

Other requirements not related to food safety may also be required to satisfy international trade and may be relevant for consideration for production for domestic trade. One significant aspect is the monitoring and control of diseases of bivalve molluscs. Information on this aspect is available from the World Organisation for Animal Health (http://www.oie.int/), the European Union Reference Laboratory for Molluscs Diseases (http://www.eurl-mollusc.eu/) and the United States National Oceanic and Atmospheric Administration (http://www.noaa.gov/).

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**Hay, B., McCoubrey, D.J. & Zammit, A.** 2013. *Improving the management of the risk of human enteric viruses in shellfish at harvest. Case studies of oyster growing areas implicated in* Norovirus *illness events*. New South Wales Food Authority.

# Appendix II – Aquaculture production and value from 2013–2024

## GENERAL NOTES

1) Production quantities of fish, crustaceans and molluscs are expressed in live weight, that is the nominal weight of the aquatic organisms at the time of capture. The harvest of aquatic plants is given in wet weight. Data are given in tonnes, except those for whales, seals and crocodiles, which are given in numbers.

2) Several countries still report their fisheries and aquaculture production at an aggregated level - due to deficiencies in their data collection and reporting systems - which can include production for a large number of species. In these circumstances the production data presented at individual species items are as a consequence likely to be underestimated. Therefore, when examining the statistics for a particular species, it should be noted that an unknown proportion of the production for that species might have been reported by the national office under the generic, family or order name of the species, or even higher aggregated levels such as, for example, "Marine fishes nei" or "Freshwater fishes nei". Consequently, the production at species level may, in some cases, be underestimated and not reflecting the real production of the individual species.

3) Where necessary, any data published in previous releases of this dataset have been revised. Where the figures in the current release differ from those previously published, the amended data represent the most recent version. Some statistics provided to FAO by national offices, in particular those for the last year, are provisional and may be amended in future editions as better information becomes available and updates are made by national partners.

4) As for the value of aquaculture production, it refers to the farm gate value in nominal terms. Value data are normally based on prices reported by national authorities, with local currencies converted to US dollars (thousand) using standard exchange rate. Standardized indicative figures have been used in case of no provision of prices by the country.

### Symbols used

" " = Official value (no symbol associated)
" E " = (previously displayed as " F ") = FAO estimate from available sources of information;
" nei " = Not elsewhere included

### Symbols associated to value " 0 "

"M " = (previously displayed as " ... ") = Data not available; unobtainable; data not separately available but included in another category;
" " = previously displayed as " - ") = Nil or zero;
" N " = (previously displayed as " 0 ") = More than zero but less than half the unit used.

*Source*: **FAO.** 2025. FishStat: Global aquaculture production 1950-2023. [Accessed on 28 March 2025]. In: FishStatJ. Available at www.fao.org/fishery/en/statistics/software/fishstatj. 

**Aquaculture production of blue mussel (*Mytilus edulis*) from 2013–2023 (Tonnes – Live weight)**

| ASFIS species (Name) | Blue mussel | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ASFIS species (Scientific name) | *Mytilus edulis* | | | | | | | | | | |
| | Year | | | | | | | | | | |
| Country (Name) | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| France | 60 047.6 | 45 825.9 | 46 653.1 | 44 926.49 | 45 641.6 | 44 082.6 | 54 207.84 | 55 389.54 | 62 641.03 | 66 840.68 | 52 101.45 |
| Netherlands (Kingdom of the) | 37 112 | 54 100 E | 54 100 E | 53 000 E | 44 000 E | 45 500 E | 38 200 | 32 400 E | 32 850 E | 29 600 E | 32 501 |
| Germany | 5 036 | 5 280 | 10 875 | 22 264 | 16 856 | 15 864 | 22 037 | 13 490 | 14 274 | 8 631 | 18 029 |
| Ireland | 15 360 | 11 374.5 | 16 015 | 15 121 | 16 340 | 13 889 | 15 184 | 14 729 | 17 440 | 19 770 | 14 684 |
| Denmark | 810 | 1 810 | 1 229 | 2 221 | 2 414 | 4 516 | 6 597.53 | 6 317 | 8 485 | 8 548 | 6 210.5 |
| United States of America | 2 228 | 1 744 | 1 788 | 2 225 | 2 201 | 2 165 | 2 250.48 | 2 250.48 | 1 402.84 | 2 090.04 | 4 387 |
| Norway | 2 328.44 | 1 983.3 | 2 731.03 | 2 176.4 | 2 382.87 | 1 648.57 | 2 134.24 | 2 033.17 | 2 162.5 | 2 611.53 | 2 199.25 |
| Sweden | 1 702 | 1 746 | 1 525 | 2 317 | 2 014 | 1 986 | 1 977 | 2 297 | 3 457 | 2 346 | 1 684 |
| Senegal | 28 | 14 | 15.5 | 741 | 349 | 135 | 200 | 198 | 190 | 142 | 78.4 |
| Jersey | 38 | 39 | 62 | 3.6 | 62.4 | 79 | 97.4 | 97.15 | 97.15 | 90 E | 52 E |
| Argentina | 5.53 | 3.68 | 6 | 5.2 | 0.54 | 5.6 | 4 | 2 | 68.9 | 0 | 4.71 |
| United Kingdom of Great Britain and Northern Ireland | 22 480 | 20 023.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Iceland | 166 | 144 | 93 | 68 | 82.7 | 108 | 96 | 14 | 18 | 12 | 0 |
| Falkland Islands (Malvinas) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Canada | 26 119 | 25 231 | 22 725 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others | 5 | 12 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Aquaculture production value of blue mussel (*Mytilus edulis*) from 2013–2023 (USD 1 000)**

| ASFIS species (Name) | Blue mussel | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ASFIS species (Scientific name) | *Mytilus edulis* | | | | | | | | | | |
| | Year | | | | | | | | | | |
| Country (Name) | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
| France | 146 186.96 | 110 164.88 | 104 325.55 | 125 867.82 | 135 944.15 | 109 421.11 | 138 386.16 | 143 511.39 | 167 579.84 | 175 999.29 | 139 983.62 |
| Netherlands (Kingdom of the) | 96 754.54 | 87 827.45 E | 72 029.58 E | 49 279.33 E | 52 688.33 E | 60 718.78 E | 64 145.89 E | 55 510.73 E | 69 935.43 E | 56 106.43 E | 60 093.35 |
| Germany | 14 446.95 | 16 904.91 | 13 151.89 | 28 340.71 | 26 849.09 | 41 028.91 | 49 586.42 | 26 193.98 | 31 907.8 | 13 178.85 | 32 165.42 |
| United States of America | 7 798 | 9 783.84 | 10 191.6 | 10 479.75 | 10 388.72 | 9 590.95 | 10 619.94 | 5 243.61 | 6 453.06 | 13 376.24 | 22 593.05 |
| Ireland | 19 787.9 | 17 982.13 | 14 037.39 | 13 540.62 | 16 797.68 | 14 105.96 | 16 590.15 | 15 141.07 | 20 214.45 | 19 569.65 | 13 972.07 |
| Denmark | 1 146.57 | 1 773.73 | 1 132.57 | 1 563.87 | 1 681.75 | 2 524.54 | 6 024.33 | 3 785.09 | 7 827.6 | 5 411.85 | 4 777.51 |
| Norway | 1 759.71 | 1 642.87 | 3 113.66 | 2 251.54 | 3 157.31 | 3 507.15 | 2 786.69 | 1 788.99 | 2 849.26 | 1 523.05 | 3 471.35 |
| Sweden | 1 567.71 | 1 552.39 | 1 102.87 | 1 623.69 | 1 413.52 | 1 370.83 | 1 672.17 | 1 496.37 | 3 627.68 | 2 783.4 | 2 698.17 |
| Senegal | 102.05 E | 56.71 | 52.44 | 2 500.82 | 1 202.09 | 486.1 | 682.7 | 687.99 E E | 685.26 E | 455.3 | 258.5 |
| Jersey | 96.83 E | 104.6 E | 96.62 | 4.03 | 76.3 | 108.56 | 124.32 | 128.28 | 137.62 E | 114.26 E | 96.95 |
| Argentina | 20.26 | 12.3 | 16.25 | 8.81 | 1.96 | 5.98 | 20.77 | 2.27 | 92.84 | 0 | 15.9 |
| Namibia | 9.63 | 30.34 | 22.41 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Guernsey | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Falkland Islands (Malvinas) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Canada | 46 543.59 | 42 697.58 | 33 900.43 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others | 58 645.01 | 51 443.84 | 744 | 544 | 661.6 | 864 | 682.77 | 133.05 | 182.43 | 114.16 | 0 |

**Aquaculture production of Mediterranean mussel (*Mytilus galloprovincialis*) from 2013–2023 (Tonnes – Live weight)**

| **ASFIS species (Name)** | Mediterranean mussel | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ASFIS species (Scientific name)** | *Mytilus galloprovincialis* | | | | | | | | | | |
| | **Year** | | | | | | | | | | |
| **Country (Name)** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** | **2023** |
| Italy | 64 235 | 63 699.72 | 63 700 E | 63 700 E | 63 700 E | 62 035.31 | 52 500 E | 50 337.65 | 61 921.4 | 60 500 | 53 596.3 |
| Greece | 18 638.4 | 16 678.4 | 18 628.4 | 23 288.6 | 19 155.8 | 21 915.9 | 23 497.5 | 19 336.85 | 13 508.3 | 10 733.85 | 18 008.37 |
| Türkiye | 0 | 0 | 3 | 329 | 489 | 907 | 4 168 | 4 037 | 4 585 | 5 469 | 8 738 |
| South Africa | 1 116 | 1 682 | 1 758.4 | 1 960 | 2 083.52 | 2 182.13 | 3 053.46 | 2 275.58 | 3 420.88 | 3 261.52 | 2 546.92 |
| France | 14 090.6 | 11 807.1 | 1 0148.6 | 6 693.1 | 7 057.4 | 4 734.9 | 6 047.15 | 5 829.96 | 3 680.27 | 4 354.79 | 2 454.59 |
| Bulgaria | 1 826.93 | 2 520.1 | 3 113.53 | 3 477.3 | 3 159.58 | 2 531.12 | 2 928.91 | 2 140.81 | 2 573.69 | 1 419.69 | 1 096.32 |
| Croatia | 1 950 | 713.84 | 746.38 | 698.7 | 919.76 | 881.63 | 946.67 | 496.8 | 854.2 | 1 006 | 924.83 |
| Montenegro | 180 E | 178 | 189 | 179 | 197 | 228 | 223 | 229 | 186 | 193 | 244 |
| Slovenia | 327 | 422 | 573.3 | 607 | 641.4 | 579.3 | 798.3 | 383.2 | 418.5 | 520.3 | 187.72 |
| Albania | 1000 | 1200 | 495 | 1450 | 430 | 1108 | 1071 | 285 | 593 | 922 | 186 |
| Algeria | 3.8 | 31.11 | 2.76 | 99.7 | 166 | 217 | 550.47 | 113.48 | 51.91 | 50 | 50 |
| Bosnia and Herzegovina | 48 E | 40 E | 40 E | 40 E | 40 E | 40 E | 40 E | 40 E | 40 E | 40 E | 40 E |
| Morocco | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Namibia | 0 | 0 | 0 | 15 | 15 E | 2.72 | 0 | 0 | 0 | 0 | 0 |
| Ukraine | 69.7 | 70 E | 70 E | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others | 123 | 167.87 | 171.82 | 79.64 | 115 | 109 | 111 | 14 | 60 | 5 | 0 |

**Aquaculture production value of Mediterranean mussel (*Mytilus galloprovincialis*) from 2013–2023 (USD 1 000)**

| **ASFIS species (Name)** | Mediterranean mussel | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ASFIS species (Scientific name)** | *Mytilus galloprovincialis* | | | | | | | | | | |
| | **Year** | | | | | | | | | | |
| **Country (Name)** | **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** | **2023** |
| France | 58 950.36 | 66 092.23 | 55 197.93 E | 55 068.1 E | 56 201.3 E | 64 103.27 | 51 425.86 E | 50 342.4 | 65 876.4 | 63 709.44 | 101 775.3 |
| Netherlands (Kingdom of the) | 0 | 0 | 2.21 | 628.56 | 597.82 | 1 222.89 | 6 420.42 | 6 739.27 | 7843.36 | 9 226.89 | 13 133.56 |
| Germany | 9 158.98 | 8 441.92 | 7 647.33 | 9 280.16 | 8 655.98 | 9 058.59 | 9 995.84 | 7 140.58 | 5 911.42 | 6 329.83 | 12 864.2 |
| United States of America | 29 329.12 | 25 883.25 | 20 357.47 | 14 570.86 | 16 954.67 | 9 408.41 | 11 524.89 | 13 906.69 | 9 239.36 | 10 534.66 | 6 979.19 |
| Ireland | 2 672.97 | 1 107.74 | 965.31 | 919.83 | 1 267.76 | 1 363.37 | 1 420.89 | 736.86 | 1 360.52 | 1 838.69 | 2 085.98 |
| Denmark | 2 157.25 | 2 940.32 | 3 070.48 | 2871.46 | 2 749.11 | 2 306.52 | 2 883.58 | 1 920.87 | 2 458.88 | 1 587.49 | 1 787.85 |
| Norway | 2 542.92 E | 3 409.67 E | 3 031.98 E | 2 931.42 | 4 378.52 | 4 122.23 | 2 113.35 | 1 036.92 | 1 851.79 | 1 595.28 | 1 332.11 |
| Sweden | 334.69 E | 331.06 | 251.64 | 257.58 | 289.31 | 376.96 | 374.46 | 470.81 | 439.98 | 447.12 | 765.11 |
| Senegal | 217.15 | 280.31 | 318.04 | 335.94 | 384.03 | 431 | 634.51 | 306.38 | 296.99 | 476.67 | 271.99 |
| Jersey | 757.08 E | 910.12 E | 275.08 | 817.61 | 252.73 | 718.22 | 974.96 | 262.31 | 572.84 | 815.63 | 208.83 E |
| Argentina | 14.97 | 135.11 | 10.96 | 364.39 E | 598.34 E | 837.52 | 2 306.05 | 247.95 | 172.94 | 158.46 | 165.63 E |
| Namibia | 91.2 E | 80 E | 80 E | 80 E | 80 E | 80 E | 80 E | 80 E | 80 E | 80 E | 80 E |
| Guernsey | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Falkland Islands (Malvinas) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Canada | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Others | 312.48 | 463.85 | 419.6 | 162.34 | 213.08 | 177.15 | 162.66 | 22.4 | 101.99 | 12.89 | 0 |

**2022–2023 Aquaculture production and value of Blue and Mediterranean mussels from 20 top production contries (Tonnes live weight & USD 1 000)**

| **ASFIS species (Name)** | Blue mussel | | Mediterranean mussel | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **ASFIS species (Scientific name)** | *Mytilus edulis* | | *Mytilus galloprovincialis* | | | | | | |
| | **Tonnes (live weight)** | | | | **Value (USD 1 000)** | | | | **Ex-Farm price** |
| **Country (Name)** | **2022** | **2023** | **Mean** | **Share** | **2022** | **2023** | **Mean** | **Share** | **USD/kg** |
| France | 71 195 | 54 556 | 62 876 | 28.00% | 186 534 | 146 963 | 166 748 | 41.32% | 2.65 |
| Italy | 60 500 | 53 596 | 57 048 | 25.40% | 63 709 | 101 775 | 82 742 | 20.51% | 1.45 |
| Netherlands (Kingdom of the) | 29 600 | 32 501 | 31 051 | 13.83% | 56 106 | 60 093 | 58 100 | 14.40% | 1.87 |
| Germany | 8 631 | 18 029 | 13 330 | 5.94% | 13 179 | 32 165 | 22 672 | 5.62% | 1.70 |
| Greece | 10 734 | 18 008 | 14 371 | 6.40% | 6 330 | 12 864 | 9 597 | 2.38% | 0.67 |
| Ireland | 19 770 | 14 684 | 17 227 | 7.67% | 19 570 | 13 972 | 16 771 | 4.16% | 0.97 |
| Türkiye | 5 469 | 8 738 | 7 104 | 3.16% | 9 227 | 13 134 | 11 180 | 2.77% | 1.57 |
| Denmark | 8 548 | 6 211 | 7 379 | 3.29% | 5 412 | 4 778 | 5 095 | 1.26% | 0.69 |
| United States of America | 2 090 | 4 387 | 3 239 | 1.44% | 13 376 | 22 593 | 17 985 | 4.46% | 5.55 |
| South Africa | 3 262 | 2 547 | 2 904 | 1.29% | 1 595 | 1 332 | 1 464 | 0.36% | 0.50 |
| Norway | 2 612 | 2 199 | 2 405 | 1.07% | 1 523 | 3 471 | 2 497 | 0.62% | 1.04 |
| Sweden | 2 346 | 1 684 | 2 015 | 0.90% | 2 783 | 2 698 | 2 741 | 0.68% | 1.36 |
| Bulgaria | 1 420 | 1 096 | 1 258 | 0.56% | 1 587 | 1 788 | 1 688 | 0.42% | 1.34 |
| Croatia | 1 006 | 925 | 965 | 0.43% | 1 839 | 2 086 | 1 962 | 0.49% | 2.03 |
| Montenegro | 193 | 244 | 219 | 0.10% | 447 | 765 | 606 | 0.15% | 2.77 |
| Slovenia | 520 | 188 | 354 | 0.16% | 477 | 272 | 374 | 0.09% | 1.06 |
| Albania | 922 | 186 | 554 | 0.25% | 816 | 209 | 512 | 0.13% | 0.92 |
| Senegal | 142 | 78 | 110 | 0.05% | 455 | 259 | 357 | 0.09% | 3.24 |
| Jersey | 90 | 52 | 71 | 0.03% | 114 | 97 | 106 | 0.03% | 1.49 |
| Algeria | 50 | 50 | 50 | 0.02% | 158 | 166 | 162 | 0.04% | 3.24 |
| Others | 57 | 45 | 51 | 0.02% | 207 | 96 | 151 | 0.04% | 2.98 |
| **Total** | **229 156** | **220 004** | **224 580** | | **385 446** | **421 576** | **403 511** | | |

# Appendix III – **Secchi disk**

The "Secchi disk" is a tool created in 1865 by Angelo Secchi and is commonly used to measure the water transparency in both fresh and seawater bodies.

It consists of a 30 cm (12 inches) circular disk with a black and white design as illustrated in Figure A3.1. The disk is suspended on a graduated rope and is lowered slowly in the water until the point where it disappears. The measure will be the depth where the disk is no longer visible to the naked eye.

The Secchi disk can be home-made. It is important that the material the disk is heavy enough for the disk to sink rapidly and vertically when lowered into the water. Where necessary, an additional ballast can be fixed underneath. The rope graduation is usually made each 0.5 metre.

Measurement depends mainly on two factors that are the phytoplankton concentration and the turbidity due to suspended matter in the water. When operating in open sea, turbidity is usually negligible, so phytoplankton concentration is the most important factor. In eutrophic seawater, the disk will disappear 1–2 m from the water surface. In oligotrophic water, the Secchi disk can still be viewed at depths of more than 5–10 m.

FIGURE A3.1
**Secchi disk**

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# Notes and observations

This manual provides practical guidance on the cultivation of blue mussel (*Mytilus edulis*) and Mediterranean mussel (*Mytilus galloprovincialis*), with emphasis on the techniques and management practices required to establish and operate a successful mussel farming enterprise. Mussels are a highly nutritious food source and, as they require no manufactured feed or fertiliser, represent a sustainable, low-carbon form of aquaculture with significant potential to contribute to responsible global food production.
The publication presents detailed descriptions of the principal cultivation systems used worldwide, with particular focus on on-bottom culture in intertidal and subtidal environments and offshore long-line culture. It includes comprehensive listings of farm components and equipment, and provides guidance on farm design, site selection, operational planning, monitoring, and harvesting through the first production cycle. The methodologies described are applicable to a wide range of farming contexts, from small-scale, low-technology operations to large-scale, industrial aquaculture developments.
The manual is intended as a technical and operational guide for new entrants to the sector, as well as for existing producers seeking to develop their farms or adopt new cultivation approaches. Extensive use is made of technical illustrations, diagrams, tables and photographs to support the text, with additional technical information provided in the appendices.

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