CASE STUDY 6.2

RISK ASSESSMENT OF THE POTENTIAL DECREASE OF CARRYING CAPACITY BY SHELLFISH FARMING

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6.2.1 Introduction

This case study considers whether the introduction of a new shellfish farm to a coastal embayment in France would reduce the overall shellfish production in the area. In several areas of France the introduction of new shellfish farming activity is suspected to have affected potential shellfish production, as well as ecosystem productivity and function. Scientists are being asked increasingly frequently to assist regulators in defining appropriate rules to manage the development of coastal aquaculture (Goulletquer and Le Moine 2002). The expansion of mussel aquaculture in Pertuis Breton is used as an example of the assessment of potential loss of productivity in aquaculture areas due to different types of interactions.

6.2.2 Hazard identification

6.2.2.1. Pertuis Breton case study

France has been at the forefront of coastal shellfish aquaculture for more than a century. The possibility of exceeding the carrying capacity of an embayment is a common concern, and examples can be found of how carrying capacity can be managed. France is one of the leading countries in Europe for shellfish production, with an annual harvest of more than 150 000 tonnes of the Pacific oyster (*Crassostrea gigas*) and 60 000 tonnes of mussels (*Mytilus edulis* and *M. galloprovincialis*) (Goulletquer and Le Moine 2002). The Pertuis Charentais ranks first among French shellfish rearing areas, with an annual production of 40 000 tonnes and 15 000 tonnes of oysters and mussels respectively, and standing stock estimated in 2001 at 125 000 tonnes of oysters and 13 000 tonnes of mussels (Figure 6.2.1). This biomass is held on 4 000 ha of leased intertidal areas and 3 000 ha of oyster ponds, which are environmentally sensitive and subject to many recent regulations. Pertuis Charentais is divided into two bays: Pertuis Breton, where most of the mussel culture takes place, and Marennes-Oléron Bay, which is occupied by the major part of the oyster cultivation.

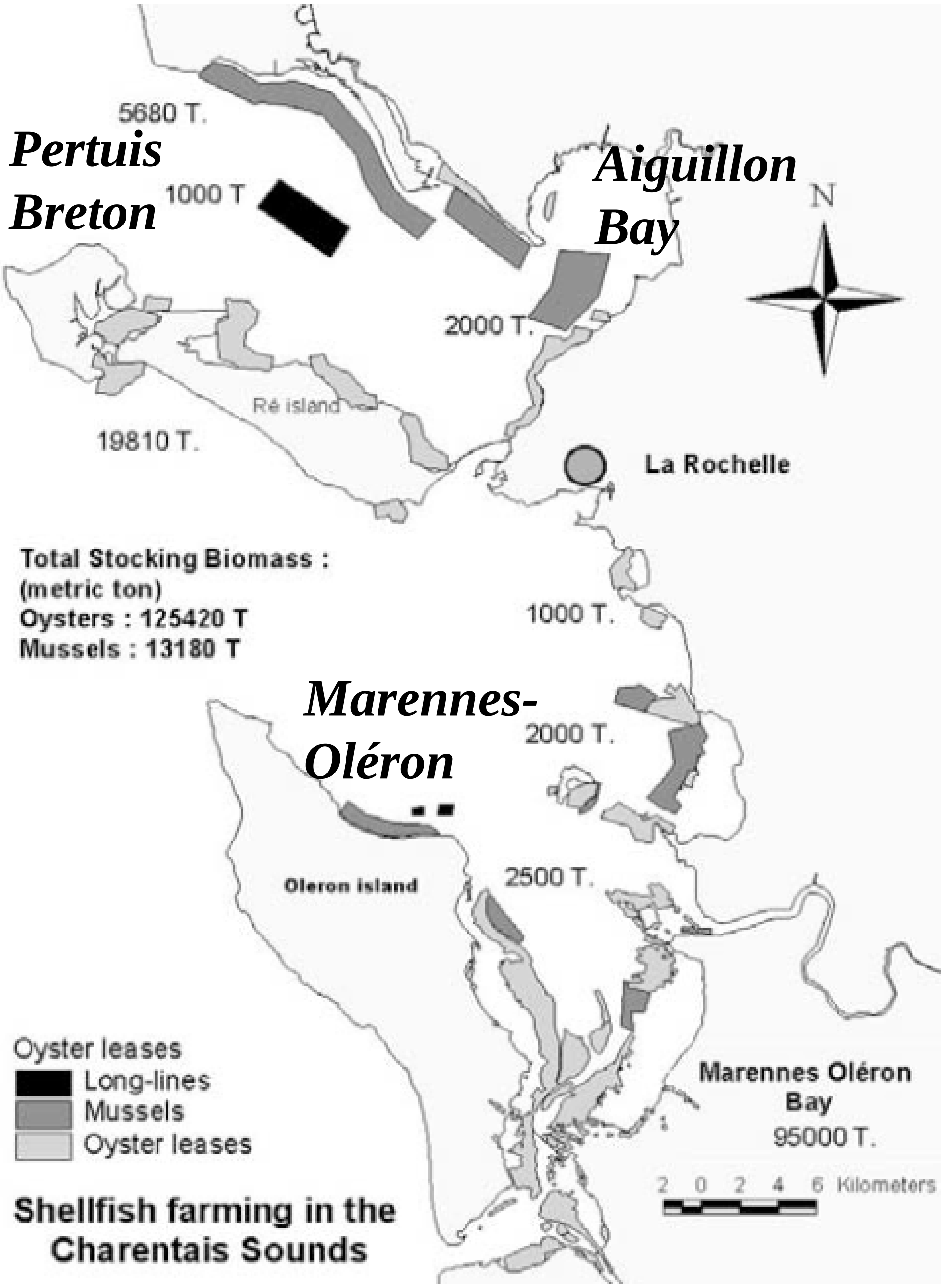
Pertuis Breton is the most important site for mussel culture in France. It is located in a macrotidal estuary of 350 km² with freshwater inputs of up to 100 $m^3.s^{-1}$ in winter, derived from two rivers (Garen *et al.* 2004). With an average depth of less than 10 m, the hydrodynamics of this water body is driven by tidal exchange and influenced by west winds. Its eastern part is covered by large intertidal mudflats accounting for one fifth of the total area. The mudflat substrate is very fine sediment that can be easily resuspended in water and generates high turbidity levels.

Blue mussels (*Mytilus edulis L.*) have been cultivated in the Pertuis Breton area since the 13th century. Mussels are traditionally grown on bouchot, which are rows of wooden poles placed perpendicularly to the shore, anchored in the sandy mud substratum beneath the surficial soft sediment layer. Mussels are collected either as seed attached on collecting ropes, or as juveniles placed in net socks, and then wound around the 2 m poles where they fatten and grow to marketable size within two years. About 337 km of bouchot are used along the Pertuis Breton shoreline.

Environmental constraints limit the potential for new sites or new culture practices. There is no more available space in the intertidal areas to set up bouchot. Long-line culture has been developed as an alternative to the traditional ‘bouchot’ method (Goulletquer and Héral 1997) of rearing mussels. In contrast, long lines can be used in the central region of the bay, where the hydrodynamics are strong and the primary production high enough to support mussel growth (Garen *et al.* 2004). For technical reasons (for example, accessibility of long-lines to boats, intensity of currents, weight of mussels and ropes), ropes must be separated by a few meters and the mussel density in long-line areas is less than in bouchot culture. As a consequence, one advantage of the long-line technique is that there are large amounts of space available for this culture technique, relative to that available for bouchot. Another advantage is in environmental conditions. Lower concentrations of inorganic particulate matter, and the continuous immersion time of mussels on longlines are more favourable to bivalve growth. Suspended culture on sub-surface long lines began in 1991 to enhance the overall production of mussels in the area and improve mussel spatfall. Two hundred and forty lines of 100 m, each carrying a 4 m mussel rope every 1.2 m, were set up in a 400 ha zone. That now accounts for about 10% of mussel production in the Pertuis Breton.

There is good reason to believe that bivalve culture could affect the carrying capacity of the environment for shellfish production. Héral (1993) established that overstocking was probably responsible for the decrease in growth of oysters in Marennes-Oéron bay. Fréchette *et al.* (2005) and Fréchette and Bacher (1998) have emphasized the role of intraspecific interactions in setting limits on mussel growth. High densities of shellfish in cultiva-

Figure 6.2.1 : Cultivation areas for oysters and mussels in Pertuis Charentais (from Goulletquer and Le Moine 2002).



tion are also likely to affect the size distribution within a culture unit (for example, rope).

These examples suggest that the introduction or extension of shellfish farming activity may result in changes at a local or ecosystem scale. There is therefore good reason for concern among farmers about the optimisation of mussel cultivation in Pertuis Breton, and a desire to locate new farming activities in a manner that will minimise the interactions with existing enterprises. A proposed expansion of farming activities in a new long-line area in the centre of Pertuis Breton is the scenario underlying this risk assessment of the interactions between and within the different farm areas. It is used to identify the underlying processes that might lead to specific types of environmental change and estimate the risk associated to them. In keeping with the definitions given by Inglis *et al*. (2000), the environmental change of concern is that of alteration (reduction) in the "Production Carrying Capacity". An analysis of "Production Carrying Capacity" aims at assessing the stocking density of bivalves at which harvests are maximised. It requires assessment of the available food supply, how it is used by shellfish and how rearing density and cultivation technique can affect food availability and shellfish growth. Below, we review some ways by which aquaculture may affect that productivity.

6.2.2.2 Effects at a local scale

In a survey of mussel growth in one site in Ireland, Karayucel and Karayucel (2000) found differences in the growth rate of mussel that was dependant on the position of the mussels within a raft. Local competition for food resources is the likely cause. Causation is not so obvious in some other studies on rafts, since food depletion arising from shellfish filter feeding depends on a range of factors – for example, current velocity, food concentration and shellfish density.

Several models of shellfish behaviour address seston depletion within the benthic boundary layer with application to bottom culture of shellfish, or to benthic bivalve populations (Campbell and Newell 1998; Newell and Shumway 1993; Roegner 1998; Verhagen 1982; Butman *et al.* 1994; Wildish and Kristmanson 1997). There is little bottom culture in France and it is not a significant production method in the area under consideration. Other studies of interest deal with cultivated species on rafts or long-lines (Rosenberg and Loo 1983; Bacher *et al.* 1997; Heasman *et al.* 1998; Pouvreau *et al.* 2000; Pilditch *et al.* 2001; Bacher *et al.* 2003). All studies stress that food depletion may limit production. However, the degree of limitation depends on the nature of the shellfish population (for example, benthic, or suspended), and on the current velocity, density and size of the stock.

Bacher *et al.* (2003) predicted food depletion as a function of hydrodynamical conditions and established a relationship between current velocity and annual growth of scallop. Strohmeier *et al.* (2005) recently measured depletion of phytoplankton within mussel long-lines in an oligotrophic Norwegian fjord. Similarly, evidence of food depletion was demonstrated by Richardson and Newell (2002) on the western shore of Canada in a study of the carrying capacity of Gorge Harbour for oyster cultivation. A reduction of phytoplankton concentrations within the oyster rafts was measured in relation to the grazing capacity of oysters. The average reduction in phytoplankton concentration was used to estimate the demand of the oyster rafts, and this information was used to estimate carrying capacity at the scale of oyster rafts. In suspended cultures, filter feeder densities range between 2 and 700 g DW m^{-3} (DW: dry tissue weight) and current velocities varies from less than 1 cms^{-1} to 35 cms^{-1}. Food depletion only appears likely to occur at spatial scales over a few kilometers when density is low or current velocity is high (Bacher *et al.* 2003; Newell and Shumway 1993).

Bacher *et al.* (2003) combined an ecophysiological model of *M. edulis* and a box model to simulate growth of mussels reared on long lines. From the model, they developed advice on the appropriate size and density of mussels for the cultivation area. Food transport in the long line area was computed using outputs from a hydrodynamical model. Simulations were carried out for different mussel densities and lease sizes to assess their effects on mussel growth. They demonstrated that actual mussel density and lease size had a minor effect on flows of particulate organic matter and phytoplankton, and would not decrease the food concentration available to other cultivated areas. If lease size and mussel density were increased, they would have a minor effect on mussel growth. Based on these simulations, a threefold increase in either mussel density or lease size would be a safe recommendation for managers willing to increase mussel production without having deleterious effect on growth.

In a very new study, Gibbs (2007) defined an indicator based on depletion of chlorophyll-a concentration in a cultivation area. He gave an example of mapping chlorophyll-a concentration and estimated the footprint of the cultivated area. Estimating the area experiencing a given percentage decrease in chlorophyll-a concentration was used as an indicator of acceptable effect.

In another study, emphasis was put on the importance for food availability of water mixing and hydrodynamics at the scale of estuaries and bays for food availability. A simplified method was used by Guyondet *et al.* (2005) to assess the risk of oyster food limitation in part of the Richibucto estuary and to evaluate the importance of water renewal. A 3D hydrodynamic model was first used to characterise the physical environment in the study area, under different forcing conditions. The corresponding water renewal times were then used in a comparison of bulk parameters defining food supply and demand by oysters and to assess the sensitivity of the depletion index method to the prescribed renewal times. Comparison of depletion indices corresponding to different oyster densities showed that this density could be increased to a certain extent without causing a major risk of food depletion.

Currents patterns can be modified by cages, long-lines or rafts (Grant and Bacher 2001; Boyd and Heasman 1998; Plew *et al.* 2006; Smith *et al.* 2006) with consequent effects on carrying capacity. Aure *et al.* (2007) presented a carrying capacity model with emphasis on flow reduction as a function of farm design. The results showed that the carrying capacity of farms with a given surface area is dependent on the length of the farm,space, the distance between long-lines, seston concentration and background current speed. Reducing the length of the farm and increasing the distance between long-lines would therefore increase the carrying capacity. The authors emphasised the relationship between stocking density and food supply as a key indicator for site selection. Moving a farm to a site with higher background current speeds or seston concentrations would also affect mussel growth. In another study, Richardson and Newell (2002) measured and simulated current velocity in the vicinity of the oyster culture rafts in order to estimate the average amount of water passing through a raft. They found that flow slowed as it passed through the rafts and accelerated beneath and to either side of the rafts. The accelerated flow beneath the rafts brings phytoplankton from deeper waters to the surface in the wake of the rafts. In general, flow velocities within the aquaculture rafts were found to be about 10 times less than flow speeds measured around the periphery of the rafts. In combination with calculation of food depletion due to filtration by oysters, Richardson and Newell (2002) expressed the carrying capacity as a number of rafts which could be supported. The calculation was based on a few data and steps that could be repeated in other cases. The number of rafts was estimated by the balance between the consumption and production of phytoplankton, in a way different to that of Karayucel and Karayucel (2000), which was derived from Carver and Mallet (1990) and Incze (1980).

Survival of shellfish can also be affected by local conditions. Using self-thinning concepts, Fréchette *et al.* (2005) have emphasised the role of intraspecific interactions in growth limitation. High rearing density is likely to affect the size distribution within a culture unit - for example, rope. The density of shellfish would therefore be decreased, as would the growth (Lauzon-Guay *et al.* 2005).

6.2.2.3 Food limitation at the ecosystem scale

Smaal *et al.* (1998) stressed the importance of space and food availability for the carrying capacity of bays and estuaries. Carrying capacity estimates at the ecosystem scale require information on primary production of the system as well as the rate of water exchange with adjacent ecosystems. This contrasts with evaluation of cultivation sites and estimates of optimum densities within cultivation sites which require a much greater emphasis on information about local physical factors.

The relationship between the production and standing stock of oysters in Marennes-Oléron Bay (France) was outlined by Heral (1993), who showed that the production is below its maximum value by using an empirical model based on mortality, growth, production and stock time series. Heral (1993) found that the maximum annual production of the Marennes-Oleron Bay was around 40 000 metric tonnes fresh weight (FW) and that the production is more or less stable above 100 000 metric tonnes FW standing stock. These two values indicate the carrying capacity of the bay and it is assumed that it is governed by the food limitation. This is a restricted assessment of the carrying capacity concept (for a review *see* Kashiwai, 1995), but it is appropriate for ecosystems supporting cultured filter-feeders where typical features such as food limitation, artificial seeding, rearing time and marketable weight have to be considered in the carrying capacity assessment.

In this context, the need to understand the link between the environmental conditions and the growth of filter-feeders cannot be avoided. Dame (1993) emphasised coupling between particle transport, ecophysiology and primary production as a way to understand the relationship between the filter-feeders and their environment in coastal areas. In his scheme, food sources (phytoplankton, detritus) and trophic interactions with filter-feeders are key to the assessment of the growth of filter-feeders and effects on the environment, and motivated a great deal of ecophysiological studies. Ecophysiological studies have been developing for the last 10 years and ecophysiological models have been published recently by Van Haren and Kooijman (1993), Scholten and Smaal (1998), Grant and Bacher (1998), Casas and Bacher (2006) for *Mytilus edulis*, Powell *et al.* (1992) for *Crassostrea virginica* and Raillard *et al.* (1993), Barille *et al.* (1997), Pouvreau *et al.* (2006) for *Crassostrea gigas*. These mechanistic models generally describe and quantify physiological processes which control energy gain and loss, and result in the growth of individual shellfish. The physiological processes are driven by temperature, food concentration (particulate organic matter, phytoplankton) and total suspended matter concentration, which includes organic and inorganic particles and acts on the ability of the individual to ingest or to reject a fraction of the available food as pseudo-faeces.

Not all the available food can be used by the filter-feeders. A fraction is rejected without ingestion because of the high particle concentration in the water. Another fraction of the ingested part is not assimilated, due to short gut passage time. Tidal currents, river flows or the geographical situation of the filter-feeders may also result in a low percentage of food utilisation by the filter-feeder populations. The food sources and their dynamics are, therefore, of primary interest in carrying capacity assessment. Most of the ecosystem models focusing on food-limited growth of filter-feeders include a water transport and mixing submodel, primary production and ecophysiological submodels (Grant *et al.* 2007; Herman 1993; Raillard and Menesguen 1994; Powell *et al.* 1994; Gerritsen *et al.* 1994; Bacher *et al.* 1998; Duarte *et al.* 2003).

The other component often considered in such models deals with the population dynamics of filter-feeders. Powell *et al.* (1992, 1994) used a simple equation based on individual growth rates, mortality and recruitment to represent the temporal variation of cohorts in harvested oyster populations. Gangnery *et al.* (2004a,b) and Bacher and Gangnery (2006) estimated oyster and mussel production using two different modelling approaches to population dynamics. The above description is still valid for those species which are the concern of carrying capacity studies, since the production is the product of the individual weights after a given amount of time (rearing time) and the number of survivals.

6.2.2.4 Logic model and endpoints

From the review above, it is apparent that the most important process to be taken into account is the potential reduction in food availability arising from the filtration activity of the proposed additional shellfish population and the consequent effects of food limitation on growth and mortality at local and wider scales – for example, within farmed areas and between areas in the bay. The risk assessment therefore addresses the adequacy of the food supply and how food use by shellfish can be modified by rearing density and cultivation technique. The endpoint will be the production carrying capacity measured by a combination of indicators of individual growth rate and survival. The hazard agent is the extraction of food due to filtration activity introduced by the new farm. We will first consider how and where this introduction occurs (release assessment). The next step is to assess how farming activity can be exposed to the hazard (exposure assessment) and then to analyse the processes which may modify and alter carrying capacity at various scales (consequence assessment). The effect on carrying capacity will be characterised through the estimation of the severity and probability of the effect occurring and uncertainty associated with the predicted probability. The consequences for the proposed aquaculture extension will be estimated from the characteristics of the ecosystem, the amount of shellfish being added to the system and aquaculture technique (Figure 6.2.2). We assume that, if this type of risk is low, there will be an even lower risk of other types of effect, for example, other processes are unlikely to be significantly affected. Similarly, if the impact on mussel growth and survival within the farm is non-detectable, we assume that the effect on the surrounding environment would be negligible and reversible – for example, any effect would be expected to disappear almost immediately after the removal of the farm.

6.2.3 Risk Assessment

6.2.3.1 Release assessment

Since the hazard agent being 'released' is the filtration pressure (extraction of food particles) arising from the bivalves, we first calculate the amount of water pumped by the mussels every day inside the long-line area. Considering the number and length of ropes (Figure 6.2.3), the number of mussels was estimated at about 240 million. If we assume that each adult mussel filters around 3 lh^{-1}, the total volume of water pumped by the actual standing stock is about 17 10^6 m^3 per day and results in a filtration time of 1.4 days. This average value will vary with environment fluctuations and mussel weight changes. Environmental parameters and mussel growth have been monitored over one year and ecophysiological experiments were conducted to assess the availability of food and its use by the mussels. Measurements of the concentrations of Total Particulate Matter (TPM), Particulate Organic Matter, and Chlorophyll-a in the long-line and the bouchot areas showed that trophic conditions in bouchot and long-line sites were different (Garen *et al.* 2004). Chlorophyll-a varied between 1 and 11 gl^{-1} with higher values being found in the bouchot areas than at the long lines, and mean values of 2.0 and 3.2 gl-1 at the two study sites. TPM was also higher in bouchot areas, and values lay between 5 and 50 mgl^{-1}. Average values were 13.1 mg l^{-1} in the long line area and 23.1 mg l^{-1} in the bouchot. Temperature varied between 5°C (December) and 22°C (August). Mussel growth showed very similar pattern in bouchot and long lines (Figure 6.2.4), but was lower in bouchot. Dry weights increased from March until September and decreased slightly thereafter. Maximum mean dry weights were 1.3 g in long lines and 0.8 g in bouchot and the final dry weights were 0.7 g and 0.4 g respectively. Shell weights increased during spring and summer and varied only slightly during the rest of the study period. Final shell weights were 4.7 g in long lines and 3 g in bouchot.

An ecophysiological model derived from Grant and Bacher (1998) was applied to calculate physiological responses to temperature, particulate organic matter, phytoplankton and total suspended matter concentration. Such processes have been studied in detail through experiments and ecophysiological models have been recently published for *M. edulis* including more or less detail of the fundamental underlying processes (Ross and Nisbet 1990; Scholten and Smaal 1998; Grant and Bacher 1998; Casas and Bacher 2006). In the model by Grant and Bacher (1998) for instance, clearance rate (l h^{-1}) of particles is a declining function of TPM. Phytoplankton and POC are both cleared at the same rate, and the proportion of the ingested mass rejected as pseudo-faeces in relation to turbidity is parameterised using a step function: no rejection at 0–5 mg l^{-1}, 20% rejection at the pseudo-faeces threshold up to 10 mg l^{-1}, 40% rejection from 10–40 mg l^{-1}, and peak rejection (85% of ingesta) beyond 40 mg l^{-1}. Phytoplankton is selected preferentially to detritus. In terms of ingestion, phytoplankton and POC are maintained as separate quantities, each with a defined absorption efficiency (AE), and absorption rates are summed to calculate total absorption. Phytoplankton AE is assumed to be 80% and the AE for detrital POC is set at 40%. In contrast to other models that use gut capacity and gut passage time to limit ingestion (Scholten and Smaal 1998), daily ingestion can not be higher than a constant value defined as the maximum daily ingestion. Net energy balance is determined as the difference between rates of assimilation and respiration, and allocated to somatic tissue and shell, which allows the computation of individual growth rate. One consequence of these calculations was that the effective amount of phytoplankton removed from the water column was about 30% of the filtered material initially estimated above.

6.2.3.2 Exposure assessment

In making assessments of carrying capacity, current velocity, primary production and filtration by cultivated shellfish can be combined to estimate food availability and individual growth (Smaal *et al.* 1998). On the local scale, food concentration, current velocity and filtra-

Figure 6.2.2 : Logical model of the risk assessment procedure, considering the process of filtration by the mussels as the hazard agent. Endpoints are mortality and growth within the new farm area in the centre of Pertuis Breton and the growth in other areas distant from this new area. Boxes refer to processes which are assessed at different steps connected with causal links shown by the arrows.

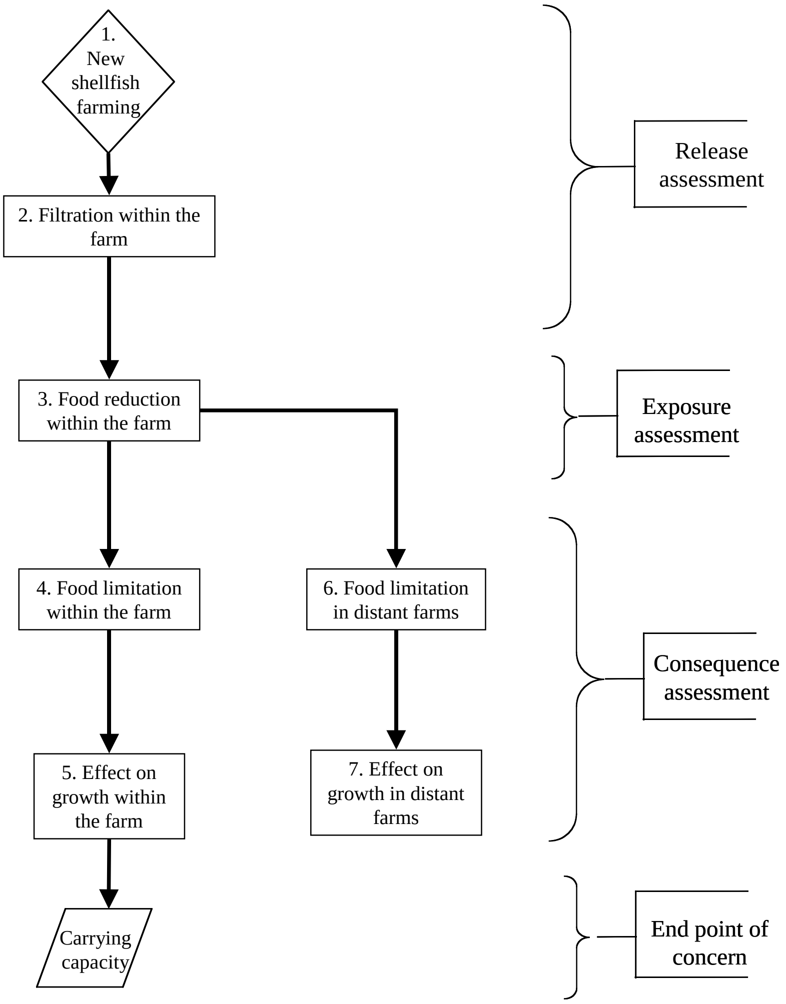
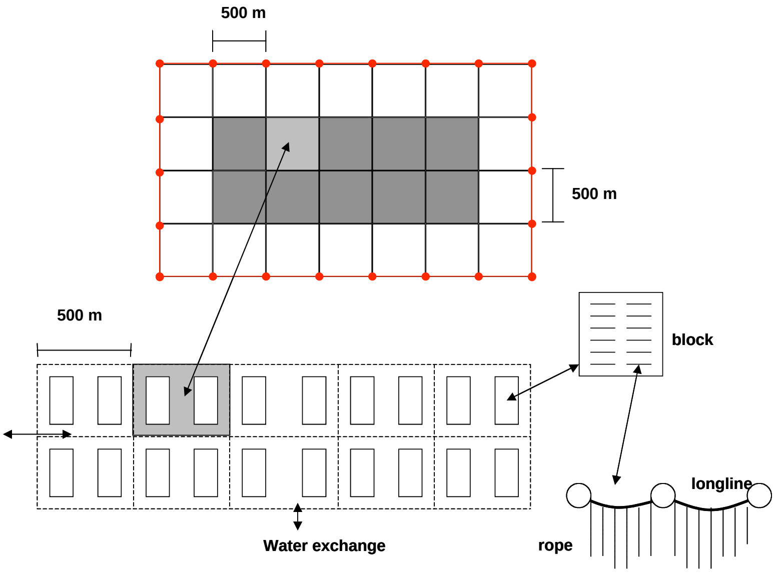


Figure 6.2.3 : Structure of the mussel farm in the center of the Pertuis Breton.



tion rate can limit food availability (Bacher *et al.* 2003). However, all these factors depend on the characteristics of the cultivation site and the species.

In Pertuis Breton, the current velocity field was estimated using a hydrodynamic model (Struski 2005) which predicts water height and current velocity. Water height and tidal currents were simulated for for one complete spring-neap tidal cycle. Maximum current velocity was mapped from this single simulation and showed that the long lines were located in a region of strong water exchange, with maximum current velocities over 1 ms^{-1}. The current velocity was primarily dependent on the tidal coefficient, and maximum tidal currents varied between 0.5 and 1 ms^{-1}. In the long line area, the current direction lie along a northwest/southeast axis and intensive exchange of water occurs at Pertuis Breton straight (Figure 6.2.5). Particle trajectories were computed for one tidal cycle during spring tide using current velocity field derived from the hydrodynamic model. They show that particles coming from the inner part of the bay (Aiguillon bay) exit through Pertuis Breton strait in the west or through La Pallice strait in the south. Trajectories also show that tidal excursion is almost 10 km which supports the suggestion of strong water mixing in the inner part of the bay and thereby probably minimises food depletion. In contrast, in areas with less strong mixing (Bacher *et al.* 2003), particles retained by shellfish in the central part of the bay are available for mussels on bouchot for longer periods of time.

Even though the filtration rate of mussels is affected by a range of factors (for example, temperature, food concentration, individual size and physiology) and on the particular stage of the lifecycle of the bivalve, the high value calculated for the new farm suggests that the exposure must be considered at two different scales; locally within the new cultivation area, and globally by assessing the effect of long-lines on bouchot areas.

A box model was developed to account for competition for food within the long-line areas and to assess whether the farm size and mussel density would affect the carrying capacity. The model couples food transport, food consumption by the mussel population and mussel growth at the scale of a cultivation area. The approach is the same as that used by Bacher *et al.* (2003) except that we assumed that food and particulate matter concentrations were homogeneous within the cultivated area, which was represented as a single box. The transport equation is a mass balance equation that accounts for i) the exchange of water between the box and areas outside the cultivated area (Bacher 1989; Raillard et al. 1994 ; Dowd 1997) and, ii) loss of particles due to extraction by filter feeders. Food consumption by mussels was calculated using ingestion rate of mussels instead of filtration rate, since an important fraction of the filtered particles would be returned to the water column as pseudo-faeces and could be reused by mussels with the same efficiency. Growth rate was based on the eco-physiological model of Grant and Bacher (1998). Details of the equations are given in the Annex to this study.

The box model for the long lines area used standard values of water exchange, box volume and number of mussels and environmental data as boundary conditions. It was expected that increasing the number of mussels would decrease the food concentration and result in a lower individual mussel growth rates. We therefore defined a series of theoretical scenarios combining different mussel densities and sizes of leased area. Nominal lease area was multiplied by a factor L between 1 and 5. If current speed and mussel density were kept constant, this is equivalent to multiplying the cultivation area, volume and total number of mussels by L^2, while the water volume exchange rate and residence time were multiplied by L. We varied the nominal lease size and mussel density, by a factor between 1 and 10.

An exposure indicator was defined from the depletion of phytoplankton computed for the different scenarios and averaged over one year (Figure 6.2.6). It is shown that a decrease of phytoplankton within the farm area by a factor of 10 % would be obtained if the farm size or mussel density was approximately doubled.

6.2.3.3 Consequence Assessment

Using the same box model, consequences of food depletion on growth were assessed for a range of different scenarios. The standard simulation showed only a very small reduction in mussel weight, hardly visible when plotted. It was related to the large flow of POM and chlorophyll-a into the lease area compared to the low food use by the mussel population. An annual carbon budget for phytoplankton showed that filtration was equal to 0.054 $mgC\ l^{-1}\ d^{-1}$, ingestion to 0.048 $mgC\ l^{-1}\ d^{-1}$ and inflow to 1.98 $mgC\ l^{-1}\ d^{-1}$. For detritus, the same fluxes equalled 0.55, 0.38, and 19.4 $mgC\ l^{-1}\ d^{-1}$. Less than 2% of the inflow was diverted to the mussel population and the food ration was mainly composed of detritus.

Increasing the lease size or mussel density had similar effects on final mussel dry weight. The minimum final dry weight was less than 0.5 g and was obtained when the lease size was multiplied by 5 and mussel density by 10, in comparison to 0.9 g estimated for the actual density and lease size. However, the effects of lease size and mussel density increase were the same and isolines of final dry weight were symmetrical (Figure 6.2.7).

In a second series of scenarios, we investigated the effects arising from changes in the exchange coefficient alone, in order to assess the effects on mussel growth in areas with lower tidal currents, and to make conservative predictions of the effect of flux reduction on mussel growth. In these series, multiplication factor varied from 0.1 to 1, in order to mimic cases with different current velocities but the same mussel density and lease size. The final dry weight decreased by 15 % in comparison to the actual field situation when water exchange was multiplied by 0.1. The decrease was less than 5 % with multiplication factors above 0.3.

6.2.3.4 Logic model

The steps in the consequence assessment can be deduced from the calculations and available data

Figure 6.2.4 : Monthly progression of shell length of mussels from the 2 locations: long-line (dashed line), bouchot (plain and dotted lines). Data plotted as mean+/-S.E. (from Garen et al. 2004).

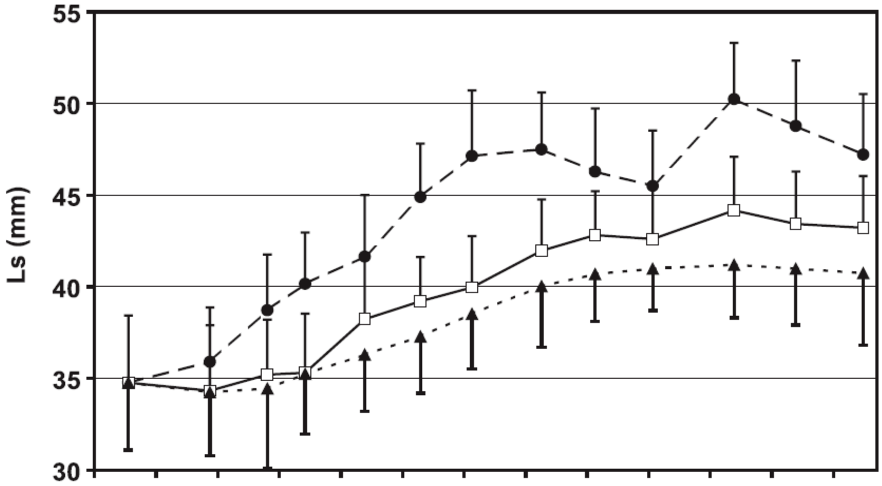
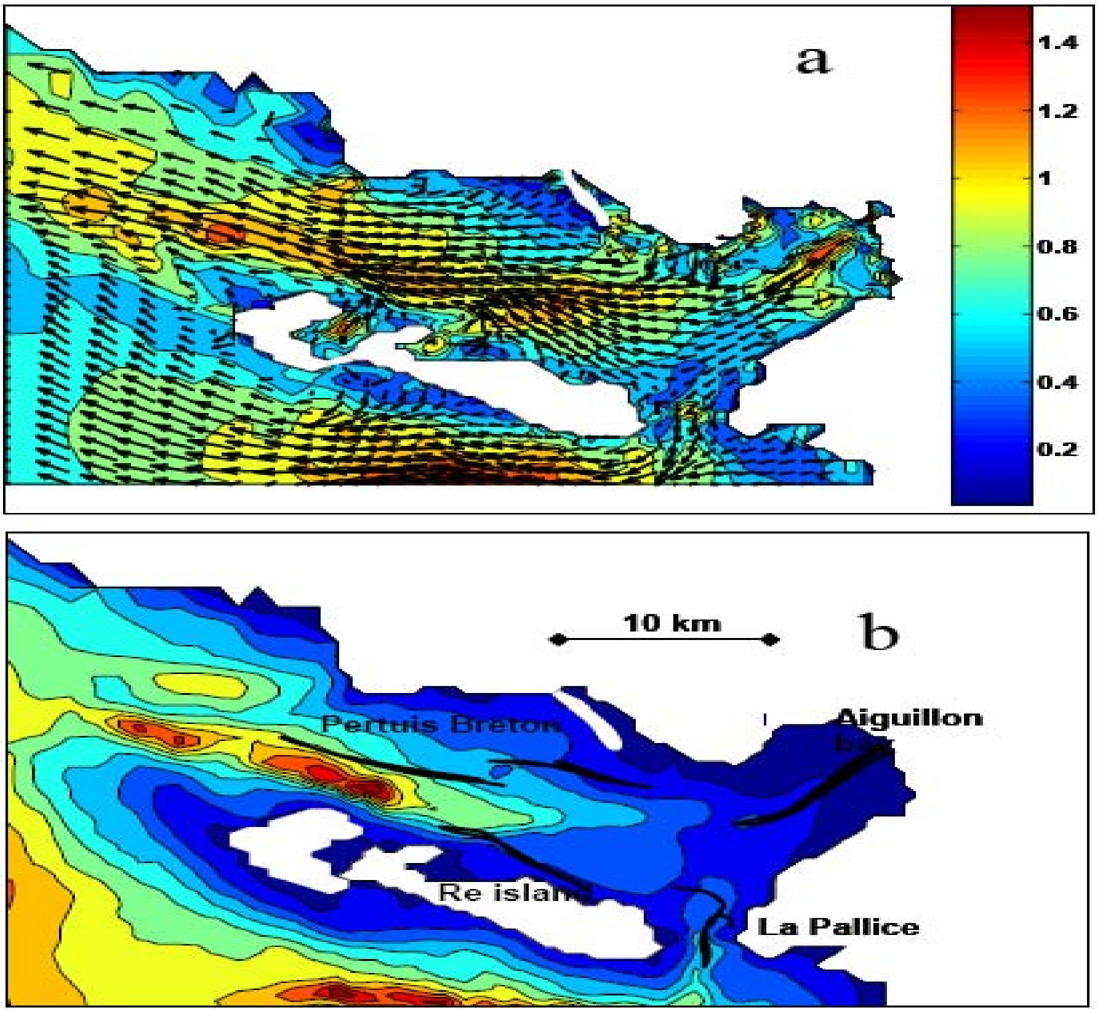


Figure 6.2.5 : Hydrodynamics simulated in Pertuis Breton: a) map of maximum current velocity (m.s-1, in colours), with arrows representing flow direction during the ebb; b) trajectories of particles.



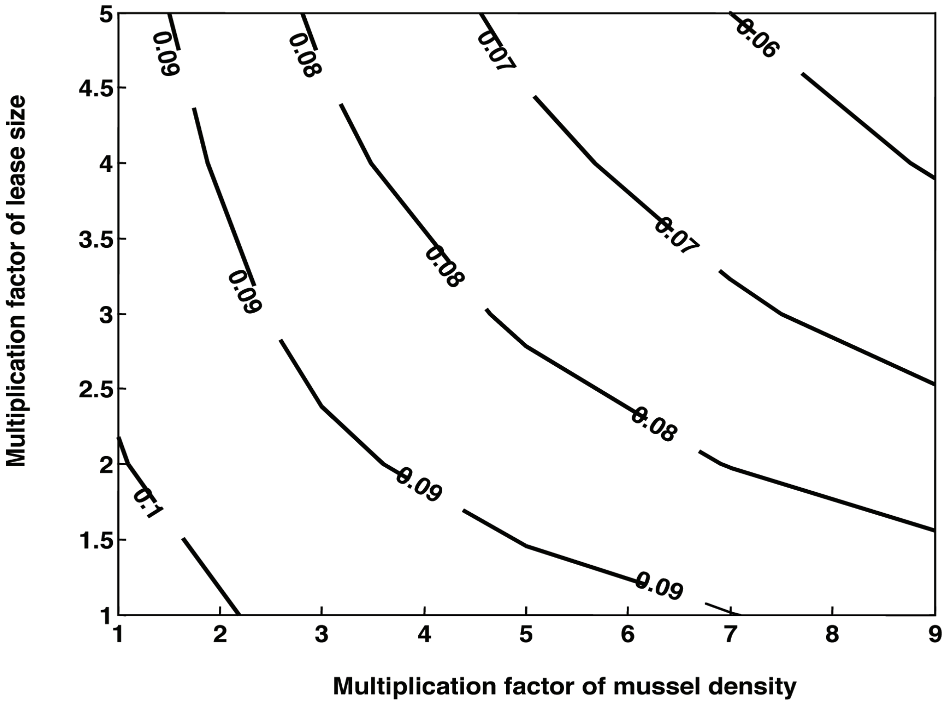


Figure 6.2.6 : Phytoplankton concentration (mg C.l^{-1}) shown by the box model with scenarios of increasing density and farm size. The actual situation corresponds to a value of 1 for both multiplicative factors.

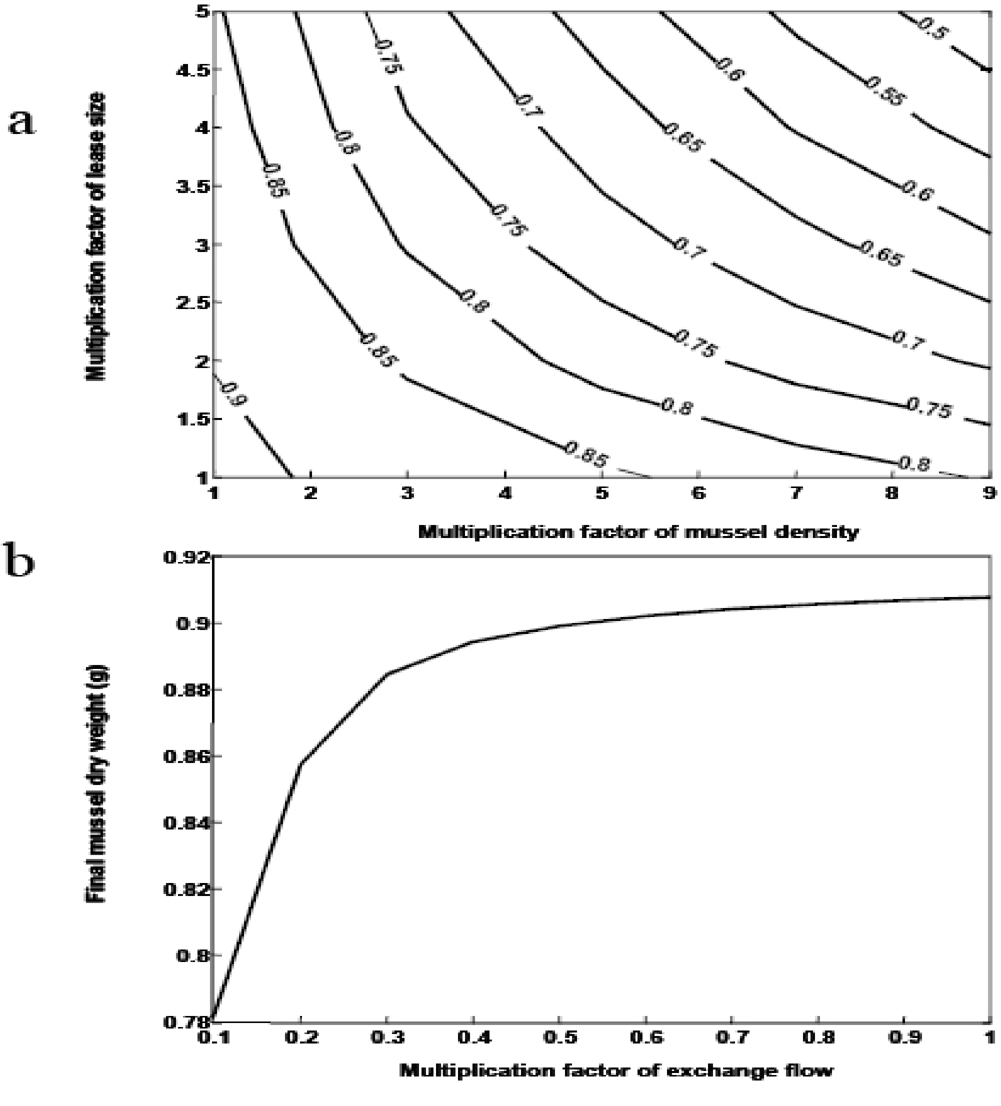


Figure 6.2.7 : Simulation of several scenarios: a) annual mussel growth as a function of density and size of the mussel farm; b) annual mussel growth as a function of water flow.

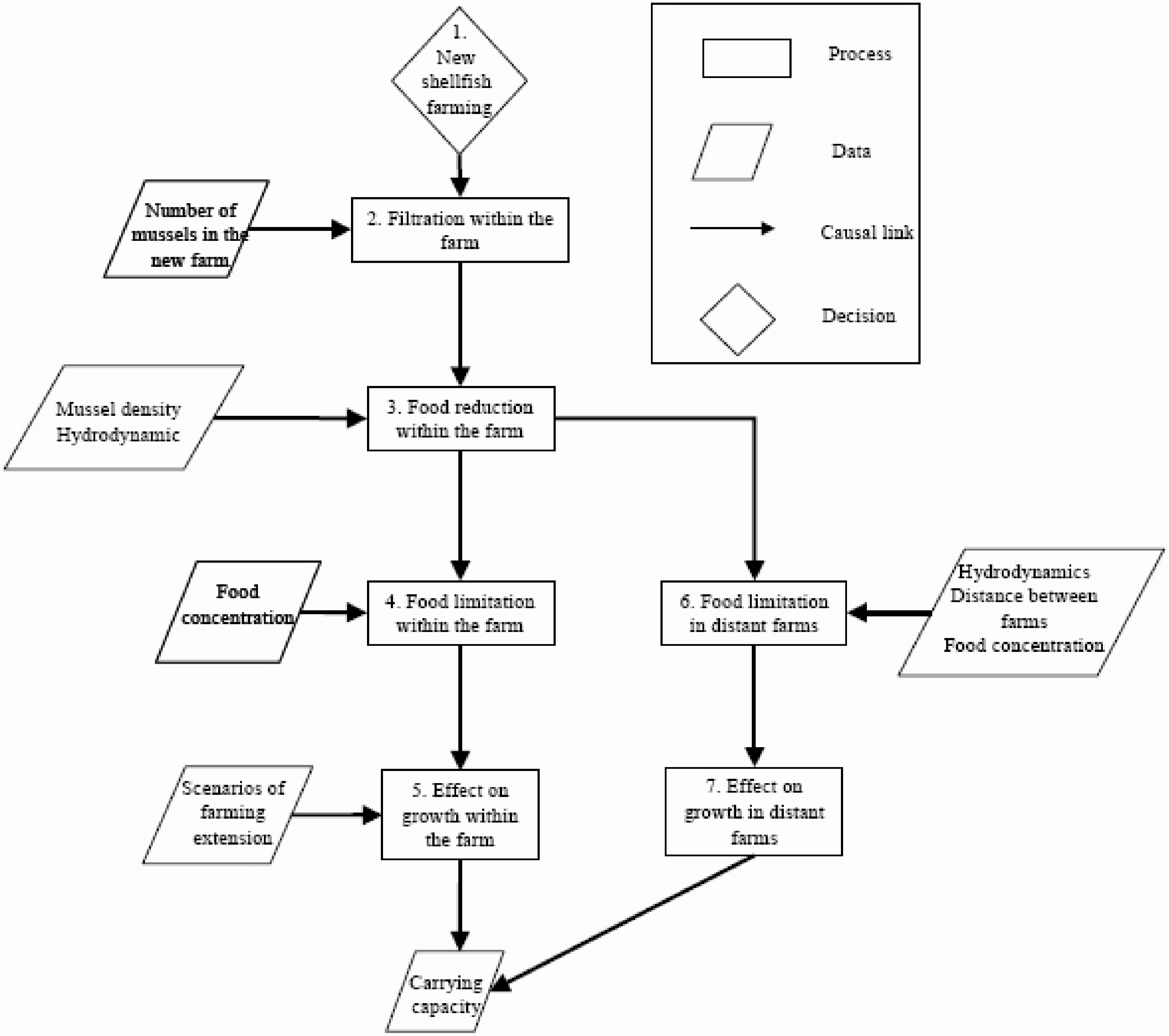


Figure 6.2.8 : Logical model of the risk assessment procedure representing the different processes (rectangles) in relation with input/output information (squeezed rectangles). Arrows represent causal links. Both local and distant effects of farm extension are considered.

according to a logic model (Figure 6.2.8). At each of these steps, probability, intensity and uncertainty of the effect can been assessed.

1. Farming will be expanded.
   Bivalves are probably the largest group of filter-feeders in the area. There are already approximately 9,000 tonnes of cultured mussels and 16,000 of cultured oysters in the Pertuis Breton area and the carrying capacity is probably partly used, which makes the addition of new areas for a 10% increase in production potentially problematic. The intensity of increase is judged to be high given the existing demands of aquaculture. The area of the bay utilised by the new production is moderate. When this new production in the Pertuis ceases, the hazard (filtering) would cease almost immediately (Low). While the area **Severity (intensity+area+duration)** is considered **Moderate**. Given the desire of industry to increase production and the lack of space for traditional production techniques, extension of shellfish farming into long line culture is likely to occur. **Probability of occurance is very High** - for the same reasons given above. **Uncertainty is Negligible**.

2. Filtration in the area of the farm is substantial.
   The estimation of total volume filtration rate in the area suggests the amount of particles present in the long-line area would be substantially decreased if filtration alone was considered. The intensity of filtration on the farm site is considered to be high. Some effect at distance from the farm is probable but it will decrease due to mixing of filtered and unfiltered water and will probably be negligible at a distance of a few kilometers, so the area affected is considered moderate. If production in the new areas ceased, the hazard (filtering) would also cease almost immediately (Low). For these reasons, **severity** is considered moderate and **probability** of occurrence is high. **Uncertainty** related to this calculation is low.

3. Food concentration will be reduced within the farm.
   The box model demonstrated that actual mussel density and lease size had a minor effect on flows of particulate organic matter and phytoplankton within the farm (arial extent is low), and that water exchange was high enough to replace the water and keep phytoplankton food available (intensity is low). The degree of depletion of phytoplankton remained low, even under the various scenarios of farm extension and increased mussel density. If production in the new areas ceased, the hazard (filtering) would also cease almost immediately (Low). **Severity** is therefore low, and **probability** of the scenario occuring is therefore high. Because of assumptions made when the model was used, **uncertainty** is medium.

4. Food availability limits mussel production in the new farm.
   Food concentration and comparison of mussel growth in two different areas indicate that differences in mussel growth may be related to differences in food concentration and other controlling factors which play an important role in ecophysiological responses (for example, particulate inorganic matter). For that reason, the intensity of interaction on the farm site is considered high. The geographical extent of this is believed to be extensive within the farm (high). As the assumption has been that, prior to installation, food availability at the farm site did not limit growth and that after removal of the farm conditions would return to that state almost immediately, post farming duration of feed limitation would be short (low). **Severity** of food limitation can be deduced from these observations as moderate, and **probability** of this occuring is high with low **uncertainty**.

5. Food supply limits growth of the new farm.
   The low degree of food depletion (step 3) implies that the standing stock of cultured mussels could be increased by farmers without consequential reductions in mussel growth. Mussel production could be increased by extending the cultivation area and/or increasing the mussel density without significantly increasing the time needed to attain marketable size or weight. Both factors would have the same tenuous effect on growth. Our results indicate that areas with lower water exchange would also be suitable for mussel production – for example, current velocity 50% lower would not result in a significant negative effect on growth and production over the extent of the site. Therefore, expansion could occur over a large area (high) relative to the present proposal and it is anticipated that there would be little if any effct of food reduction on growth (low intensity of effect). If production in the new areas ceased, the hazard (filtering) would also cease almost immediately (Low). **The severity is Moderate** – The likely degree of change is low but may extent beyond the area of the lease site and immediately downstream of it. If the production was removed, any effect on the system is unlikely to be persistent. **Probability is High** – it is highly likely that the predicted effects (lack of effect on productivity) will permit futher development on the site. **Uncertainty is Moderate** – the variability in environmental forces that have occurred are expected to be representative of the range of environmental variation in the foreseeable future, but precise prediction of that variability is elusive because of the large number of factors affecting variabilty.

6. Based on the above observations, effects, if any, of filtration at the farm site on nearby farms are likely to be negligible (intensity is low). The area affected is also likely to be negligible (geo-