Influence of shellfish farmer rearing strategies on the carrying capacity of an ecosystem through ecological modelling

Coralie Picoche(1), Romain Le Gendre(1), Philippe Cugier(2), Aurélie Legendre(3), Frank Maheux(1), Charlotte Mary(1), Benjamin Simon(1), Sophie Parrad(1), Aline Gangnery(1)
(1)Ifremer, Laboratoire Environnement Ressources de Normandie, Port-en-Bessin, France
(2) Ifremer, Département Dynamique de l'Environnement Côtier, Brest, France
(3) Ifremer, Laboratoire Environnement Ressources de Bretagne Nord, Dinard, France
Presenter contact details : coralie.picoche@ifremer.fr, Phone +33 231 51 56 21

Summary
Mussel farming sustains a wide range of economic activities in Normandy. The farm number and density have constantly increased since the 1970's but mussel growth and quality have decreased in the last years. A 4000 km² aquaculture area has been identified on the west coast of Normandy where carrying capacity might be exceeded. This area is described by a hydrobiogeochemical model (ECOMARS 3D), supported by a large field dataset covering different spatial and temporal scales. ECOMARS 3D is coupled to an ecophysiological, individual-based model (*Mytilus edulis* DEB model), which allows a fine assessment of physiological responses to environmental variations. Coupling meteorological observations, watershed nutrient inputs and satellite data, simulations highlight the complexity and diversity of ecosystem functioning. In particular, interactions between abiotic and biotic factors drive food distribution within and between farm structures, which finally impact mussel growth. Population dynamics, described as inputs and outputs of new populations, are directed by human decisions. Rearing strategies are described by the timing and effort of seeding and harvest, which have previously been investigated. This integrated modelling approach can be used with various scenarios and help decision makers to choose between different management strategies.

Introduction
In the past five years, aquaculture has increased its share in seafood production by 20%, offering 5.5% more employments each year (FAO, SOFIA 2012). In France, it sustains all economic sectors and among all coastal regions, Normandy has become the first shellfish producer in less than half a century. *Mytilus edulis* is the second most economically significant species after *Crassostrea gigas.* Human decisions drive mussel growth through the purchase of spat, seeding density and timing, and harvest date. The registration of 'bouchot' mussels as a traditional specialty at the European level also impacts its production by constraining the expectations on the methods and quality of the production. Meanwhile, growth and quality problems have recently been identified along the west coast of the Cotentin peninsula. They have been attributed to area overexploitation, urging farmers to decrease culture density. A comprehensive carrying capacity assessment is therefore pending. Such a study has proven complex at the ecological level and several requirements have been identified (McKindsey *et al.* 2006): models must be spatially explicit, represent temporal variations and all farming activities must be taken into account. Methods have already been developed to reach those standards. Close to the area of interest, the study of interactions between ecosystem and shellfish farms has showed the importance of all biologic compartments in a hydrobiogeochemical model (Cugier *et al.* 2010) to assess ecosystem functioning. Ecophysiological models, such as those based on the Dynamic Energy Budget (DEB) theory, can be coupled to spatial models to describe variations of mussel growth at the individual scale, as was done by Guyondet *et al.* (2010) who tested several culture scenarios to determine the carrying capacity of a lagoon. However, human interventions during the growth cycle are barely described in such a disturbed habitat while coexistence of several cohorts may influence timing and pattern of growth of the different age groups.
This contribution presents the coupling of a hydrobiogeochemical model to a DEB model to describe the rearing strategy of mussel farmers. This aims at understanding the reasons of the observed spatio-temporal variability in production and testing realistic scenarios of aquaculture with fewer impacts on the whole ecosystem while sustaining economic activities in the region.

Materials and methods
The study area extends from the north of Mont Saint Michel Bay to the south of Jersey Island. Shellfish farms are mainly located on 50km along the coast where the tidal range varies between 5 and 12 m and, offshore, near Chausey Island. In the former case, nutrient input and recycling are influenced by freshwater inputs from three rivers while the later is characterized by a small cyclonic gyre with slow currents. Globally, residual circulation is driven northwards alongshore. A 3D hydrobiogeochemical model (ECOMARS 3D) is used on a 200 m grid resolution to describe the area (Cugier *et al.* 2005). The NPZD model is able to describe four nutrients (ammonia, silicate, phosphate and nitrates), three plankton compartments (diatoms, dinoflagellates and nanopicoplankton) and two types of

zooplankton (according to their size range). Data from different sources are used as forcing variables. Meteorological data are supplied by Meteo France, watershed nutrient inputs are assessed by a river model, satellite data account for sedimentary processes and water turbidity. Boundary and initial conditions are provided by a larger and coarser ECOMARS 3D implementation. Hydrological variables were calibrated on satellite and surveillance network data covering nine separated sites and more than ten years. DEB simulations were calibrated on in-situ measurements, using chlorophyll a as a food proxy, and compared to a growth monitoring network dataset running for nine years over six farms. Wide spatial and temporal spans allow a better assessment of all variations. Coupling of NPZD and ecophysiological models was based on the exchange of food through supply, biodeposition and excretion. Validation relied on an independent monitoring survey (Gangnery *et al.* 2013).
Rearing strategies were estimated through a socio-economic survey conducted in 2011 and several stock evaluations, launched every five years. Along with communications with farmers, this enabled the establishment of several scenarios, focusing on the seeding location, density and timing, to estimate the impact on production and its effect on the environment.

Results and discussion

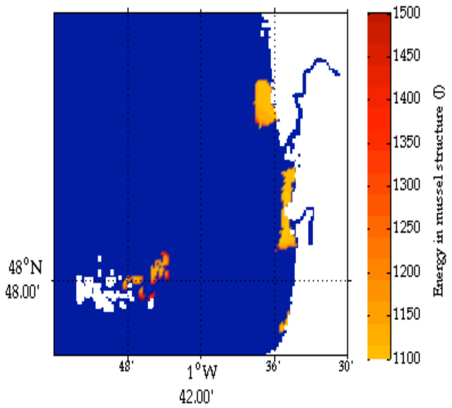

Figure 1. Variation in mussel growth along the west coast of Normandy, as the energy allocated to structure according to the DEB theory at the end of one growing season.

Preliminary results highlight the spatio-temporal variability of mussel growth. The grid is fine enough to account for intra-farm variability. The model is able to reproduce observed patterns, such as southwards and seawards gradients of mussel mass. The former phenomenon may be attributed to a 'depletion plume' observed in chlorophyll a from south to north, following residual circulation. These variations in food supply and growth were also detected by Thomas *et al. (*2011). Those results may help defining new farming areas or re-organizing existing ones. The impact on chlorophyll a might also be a first sign of an exceeded carrying capacity.

Rearing strategies were also investigated, which proved the importance of ecosystem understanding in human decisions. For instance, the same population may need between 3 and 8 months to reach a marketable size, according to seeding date and location. Ecosystem overload could be avoided by a better repartition of the effort with this knowledge.
Finally, different spatial scales also respond to variations over time, which could help predict the behaviour of the environment in a global change context.

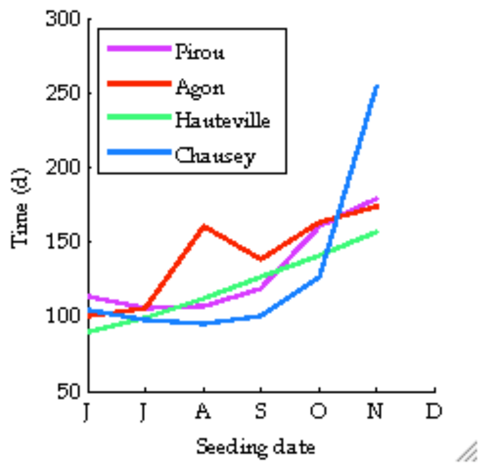

Figure 2. Time (in days) for mussels to reach a marketable size, depending on their seeding date and location (listed from north to south).

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