Carrying capacity and impact of aquaculture on the environment in Chinese bays

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Context and objectives

Aquaculture in Asia has a long history of combining different species in polyculture. This embraces principles of ecological engineering within integrated farming systems, to achieve more sustainable solutions through the recycling of wastes from culture cages, culture ponds and sewage outfalls into high-value protein crops that may be removed for human consumption. In China alone, the annual output from aquaculture is more than 20 million tons, which is 30% higher than the wild catch, and represents more than 60% of total global aquaculture.

The general objective of this project was to model and define the carrying capacity for sustainable development of aquaculture in Chinese semi-enclosed bays - e.g. the maximum number or biomass of cultivated species which can be cultivated in a zone without decrease of the yield and deleterious environmental effects, taking into account constraints due to cultivation practices.

Specific objectives included:

1. To improve scientific knowledge on the interactions between aquaculture and environment in coastal areas, including the interactions between different types of aquaculture or exploitation of natural resources, with an emphasis on polyculture.
2. To establish models to predict the carrying capacity for aquaculture and its impacts resulting from different types of aquaculture in different environments.
3. To provide scientific information and recommendations that facilitate sustainable aquaculture management.

Activities

Aquaculture was studied and modelled in two bays; Jiaozhou and Sanggou, both in Shandong Province. A metadatabase was first constructed which synthesised existing data from historical records, statistics for mariculture production, available databases and spatial information both on cultivated species and hydrobiological characteristics. Data required to calibrate and ground truth the models was obtained through additional field work that involved *in situ* spatial and temporal variability in natural environmental variables, measured monthly at seven stations in each bay. Measures included stock assessment, growth rates and population dynamics of the cultivated species, as well as ecophysiological measures of interactions between those species and the environment.

Findings defined the effects of temperature, nitrogen availability and light intensity on growth of the main cultured macroalgae, the kelp *Laminaria japonica*. In addition, for each main species of cultured shellfish, which included the Chinese scallop *Chlamys farreri*, the Manila clam *Ruditapes philippinarum* and the Pacific oyster *Crassostrea gigas*, we developed separate dynamic models to replicate responsive adjustments in feeding, metabolism and growth across full natural ranges of temperature, food availability and food composition.

Models defining ecophysiological responses in each main cultured species were coupled with hydrodynamic and biogeochemical elements in common geographic grids, allowing analyses of key processes in a range of simulations at different spatial and temporal scales, according to different modelling objectives.

At the local farm scale, towards a practical tool which could be used locally by marine farmers to predict the effects of culture density upon shellfish growth at different sites, a depletion model was developed that combines each model of shellfish ecophysiology with a one-dimensional horizontal transport formulation.

At wider bay scales, two complementary strategies were employed to assess environmental carrying capacities for culture, taking into account interactions between each cultivated species, as well as between those species and their environments. Firstly, a two-dimensional coupled physical-biogeochemical model was developed for Sanggou Bay, based on a bathymetric grid of 1120 cells affording a spatial resolution of 500 m, to simulate short term responses (e.g. one year) to changes in cultivation practice. Secondly, a box model was developed using a quasi one-dimensional approach without spatial variability to assess effects of culture practice on production in the longer term. Both of these bay scale models accounted for the same processes: primary production, bivalve and kelp ecophysiology and growth, exchange with the ocean, mineralisation of detritus, particle sedimentation and resuspension, species densities, and times of seeding and harvesting.

Integrated assessments were undertaken using these tools to consider how different scenarios of multi-species culture may affect ecosystem functioning and sustainable capacities for exploitation. The scenarios considered were recommended by local fisheries managers, and the outputs considered collectively in associated workshops, as significant contributions in the development of local fisheries practice.

Training sessions and workshops took place throughout the project, both in China and Europe. This included training in database management, ecophysiology experiments, ecophysiology and ecosystem modelling.

Results and outcomes

Elements of the models defining shellfish responses are cutting edge. In particular, for the first time in such models, significant adjustments were resolved in the relative processing of living chlorophyll-rich phytoplankton organics, non-phytoplankton organics and the remaining inorganic matter during both differential retention on the gill and selective pre-ingestive rejection within pseudofaeces. A facility to simulate the energy content of non-phytoplankton organics was included. This was significant, for that energy content was very much more variable than for phytoplankton organics, and which represented less than 20% of all suspended particulate organic matter. Such resolution of the relative processing of different particle types allowed simulation of how the rates, organic compositions and energy contents of filtered, ingested and deposited matter change in response to wide differences in seawater temperature, seston availability and seston composition. Dependent relations predict rates of energy absorption, energy expenditure and excretion. By these means, resulting models were more adaptable that past models of shellfish physiology, replicating dynamic adjustments in feeding and metabolism across full ranges of relevant natural variability, and successfully simulating growth from larvae or seed to harvestable size under different temporal and spatial scenarios of culture.

Measurements and simulations of the effects of culture on hydrodynamics indicated that disregard for physical barriers associated with culture would result in a serious overestimation of the particle renewal term and thus an overestimation of carrying capacity. Coupling the models of bivalve ecophysiology and one-dimensional hydrodynamics, the resulting depletion model for use by farm managers demonstrated how shellfish density had an increasingly negative effect on growth in regions with higher water residence times or lower depths, and which could be used to establish optimal densities for aquaculture at different locations throughout the bay.

The coupled bay-scale models were used to simulate various culture scenarios, each scenario representing a whole cultivation cycle, whilst depicting differences in time of seeding and/or harvesting, according to recent changes in aquaculture practice, including different spatial distributions and/or densities of the main cultivated species. Findings established how coupled models of this kind were increasingly able to simulate the general behaviour of key ecosystem variables, both in space and time, at least within the context of this relatively simple marine system, dominated by a few species.

Main innovative findings within the content of community ecology generally included how very sensitive total production could be to changes in the composition, densities and/or distributions of dominant cultured species, where changes in local density may have effects at the bay scale.

Collective findings from different simulations using both the 2D and box models at bay-scale suggest that Sanggou Bay was already being exploited close to the environmental carrying capacity for scallop production, albeit with some potential for increased oyster production. This reflected inter-specific competition for food, with a competitive advantage for oysters compared with scallops, despite being cultivated in different areas of the bay. Given apparent limitations on harvest yield for scallops, a hypothetical analysis was requested by local managers to assess whether scallop production might be increased without changing bivalve loads, in which the total quantity of scallops and oysters remained the same as present, but when the scallops are distributed over the area currently given over for cultivation of both scallops and kelp, thereby creating areas of combined kelp and scallop culture, in which average scallop density is reduced. Predictions under this alternative management scenario suggested that harvest yields that oyster yield would be maintained, yet scallop production increased by more than three fold. This represented an increase of nearly 50% in the total combined yield of shellfish in comparison with current aquaculture scenario. The change was consistent with past observations whereby similar combinations of scallop and kelp culture had been proven successful elsewhere, and which we now understand is being trialled in Sanggou Bay.

Selected Publications and Papers

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