# A system dynamics model for marine cage aquaculture

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## Abstract

A system dynamics model is built in order to study the sustainability of marine cage aquaculture. Profitability is assumed to be influenced by the availability of dissolved oxygen in the water, which is itself influenced by the farm's effluents.

The base run suggests that as long as the farm releases organic matter in the water, the level of dissolved oxygen will tend to decrease thus increasing the fish death rate and therefore jeopardizing the aquaculture venture.

Three policy options are tested and their effects on the company sustainability are discussed:

- Any improvement in feed floatability is not likely to lead to any major change in the farm sustainability;
- The introduction of a delay between two production seasons leads to a modification in the pattern of the total profits of the company which tends to take a more linear shape;
- The cancellation of one whole season if the amount of dissolved oxygen appears to be under the threshold level of 5 mg.l$^{-1}$, leads to cancel one season every two seasons and however gives the best results concerning the long term sustainability of the company.

Keywords: system dynamics, cage aquaculture, sustainability

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# Introduction

Although the farming of aquatic plants and animals is many thousands of years old, it can be considered as a recent phenomenon. Actually, the global farmed fish and shellfish production has grown from 2 million tons in 1950 to 36 million tons in 1997 and now accounts for approximately one third of global human consumption (Kautsky, Folke et al. 2001). As regards to the overall degradation of wild fish stocks, one can quickly guess the potential positive effect a strong aquaculture sector can have on our marine resources.

However, as many commodity systems[1], aquaculture strongly rely on numerous environmental services for the assimilation of wastes, furnishing seeds, the production of feed pellets, etc. The study of this dependence to the environment is often done via the estimation of the environmental carrying capacity, i.e. "the production that can be sustained by an environment within certain defined criteria" (Beveridge 2004). Among these criteria, hypernutrification (Strain, Wildish et al. 1995; Jiang, Fang et al. 2009) and the discharge of toxic chemicals (Chou, Haya et al. 2004; Shih, Chou et al. 2009) have been particularly studied. Dynamic models have been built (Johnston, Soderquist et al. 2000; Jamu and Piedrahita 2002; Arquitt, Honggang et al. 2005) and appeared to be useful even in the case where data are scarce (Teegavarapu, Tangirala et al. 2005).

The present work is an attempt to link an economic model of a fish farming company with an environmental model of natural waste treatment and nutrient cycling. The farm is fictitious and the data is not yet site-specific.

# The aquaculture model

The model presented here simulates the activity of a fictitious commercial cage aquaculture farm in Taiwan. As for 80% of marine cages in Taiwan, the farmed fish is cobia *Rachycentron Canadum* (Liao, Huang et al. 2004). The objective of the model is to consider in a unified system, the production process of cobia, its wastes and their environmental treatment. The non respect of the environmental carrying capacity not only imposes costs on the society but also jeopardizes the aquaculture venture itself, that's why we will particularly look for the sustainability of the company. This one is strongly affected by the surrounding environmental conditions (Fig. 1).

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[1] See the "commodity project" of the Sustainability Institute (http://www.sustainer.org/) for information about commodity systems.

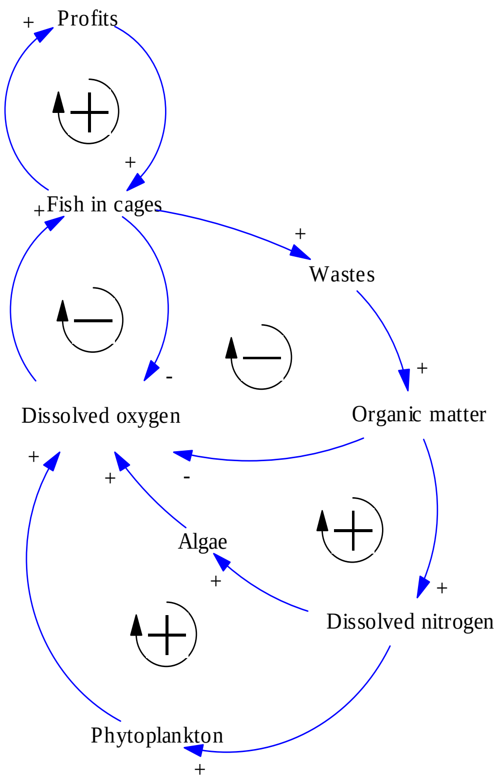

Figure 1: The aquaculture model simplified causal loop diagram

The environmental negative feedback loops are likely to become very strong when the environmental capacity is being exceeded. It will act as a brake for the potentially exponential development of the company (positive feedback loop).

The model is composed by four sectors:

1) The production sector which represents the process of fish farming,

2) The company sector which calculates the profitability of the company,

3) The biochemical sector which represents the bacterial treatment of the waste and its influence on the nitrogen loadings and the dissolved oxygen level,

4) The ecological sector which simulate the growth of phytoplankton and algae in the farm's waters.

1) <u>The fish production sector</u>:

According to Liao (Liao, Huang et al. 2004), cobia aquaculture can be divided into 7 steps: broodstock cultivation (2 years), egg incubation (30 hours), larval rearing in ponds (20 days), first phase nursery in outdoor ponds (25 days), second phase nursery in outdoor ponds (30 days), third phase nursery in outdoor ponds (75 to 105 days) and grow-out in open ocean cages (6 to 8 months).

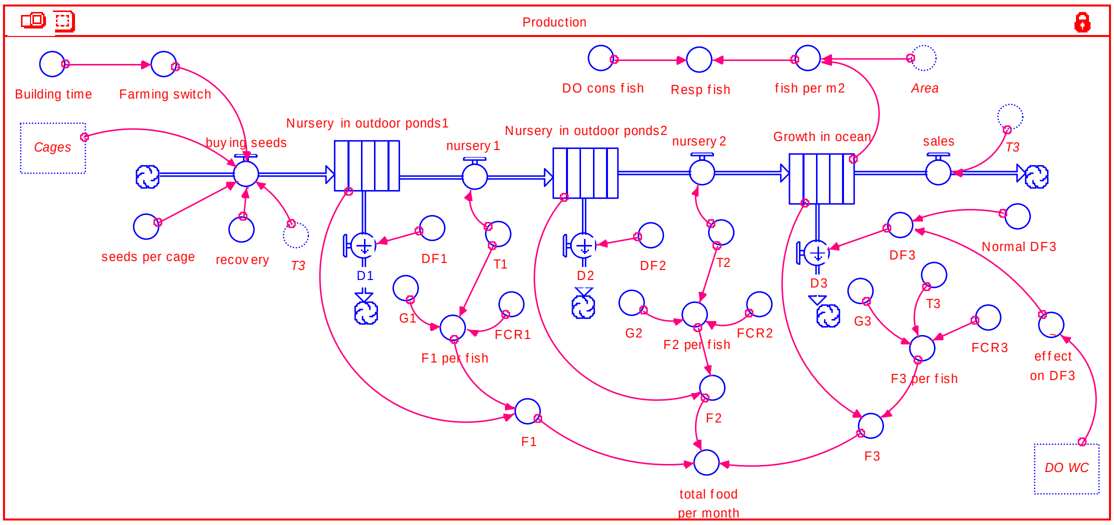

Figure 2: The fish production sector

In order to simplify, the two first phases (broodstock cultivation and egg incubation) has been removed and we consider that the company buys seeds every year. The inflow of seeds has been modeled as a pulse function of the number of available cages in the ocean: PULSE(Cages*seeds_per_cage,0,T3).

Each stage is built as a conveyor in order to simulate the delays inherent of the growth process: T1=2 months, T2=3 months and T3=7 months. Each stage is also characterized by some decreases in the fish stock: the outflows D1, D2 and D3 represent the monthly death rate and are functions of the death fractions DF1, DF2, and DF3. Based on Liao’s observations, these ones are set at: DF1=0.025; DF2=0.017. The last one is modeled as a negative function of the available dissolved oxygen and starts at Normal_DF3=0.123. A table function (effect_on_DF3) is used to represent the effect of dissolved oxygen on the death fraction.

Once the fish has journey from ponds to sea and has grown sufficiently (a weight of 8 kg is assumed here), it becomes saleable. Since aquaculture farms are ready to freeze the fish instantaneously after harvesting it and to sell it quickly all over the world, we considered that the fish was immediately sold. Consequently, harvest time and sell time are the same.

Finally, in order to loose the minimum time, the cycle starts again every 7 months that is to say when the previous harvest enters the third month of its last stage.

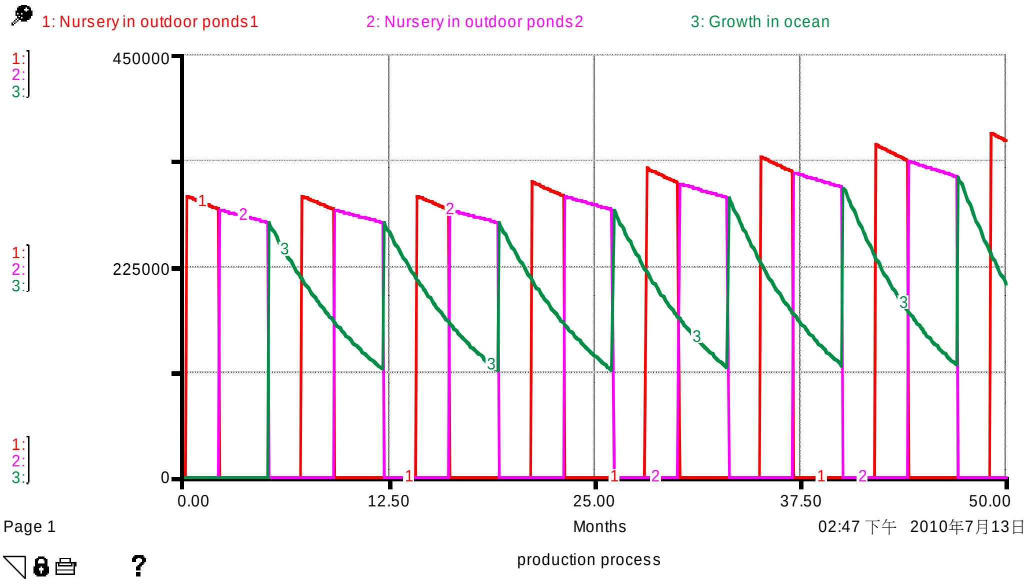

Figure 3: The fish production process (number of fishes)

The four stages are overlaid in order to prevent any waste of money or time. The stock of fish reduces along the period under the effects of the different death fractions and finally equals around the half of the initial nursery stage. As soon as harvested, the nets are filled again.

2) <u>The company sector</u>:

A 8 kg cobia can be sold 150 Taiwan dollars (TWD) per kg, which makes 1200 TWD/fish (1 TWD=0.0315 USD). The sale of fish is the only income for the company.

The main cost of an aquaculture farm is the food it has to provide to the fish (around 60% of the total costs). The quantity of food consumed by the fish during the succeeding stages (F1, F2 and F3 on Fig. 2) has been inferred from the growth rates and the Feed Conversion Ratios (FCR) provided by Kaiser (Kaiser and Holt 2005) and which gives monthly quantities of 14g/fish for the first nursery stage, 320g/fish for the second nursery stage and 1500g/fish for the growth in ocean stage (we assumed the use of only one type of food for the whole process). The second important cost is furnishing seeds. A seed is assumed to cost 16 TWD. Finally each month, the company pays its 30 employees 25000 TWD each.

The number of cages is conditioned by the profitability of the company who starts with 250 cages and ads (or subtracts) cages between two seasons as regards to the profits of the past season. The company is supposed to invest 20% of its profits at the end of each season. The conversion between profits and cages number is done thanks to the marginal cost of a cage (around 600000 TWD). A delay function (DELAY(Profits,T3)) is used to calculate the profits for each season (Fig. 4).

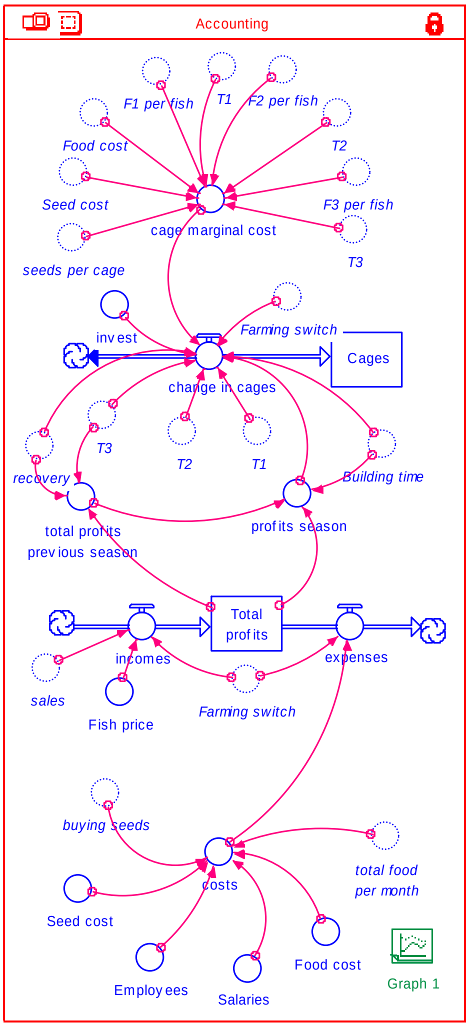

Figure 4: The company sector

### 3) The environmental sector:

Uneaten food (4%) and feces (20%) are released in the water column. It accumulates in the stock called OM_WC (Organic Matter in the Water Column). Once in the water column, the organic matter (OM) can either be decomposed (at a rate of 0.2), or sink on the seabed (at a rate of 0.8) where it accumulates in the stock called OM_SB (Organic Matter on the Seabed).

Furthermore, a biflow is used to simulate the effect of currents. We supposed the surrounding waters' average content of organic matter equal to 26 $mg.l^{-1}$ and the lateral mixing time to be 1 month so that each month, the value of the biflow is equal to the difference between the value of the stock and the average value of the surroundings waters.

The decomposition of the OM generate carbon (C_WC and C_SB=OM*0.55) and nitrogen (Mineralization_WC and Mineralization_SB=C*16/106) based on the

Redfield ratio for marine organic matter (C:N:P=106:16:1) and the respiration of bacteria is calculated using the ratio $O_2$:C=138:106 (Strain, Wildish et al. 1995).

The stocks N_WC and N_SB represent the available nitrogen ($NH_3$ and $NH_4$) in the water column and above the seabed respectively. Their inflows (N_replenishment) are due to the mineralization of organic matter and their outflows (N_consumption) are due to the consumption by phytoplankton (for the water column) and algae (for the seabed). A vertical mixing time is defined to represent the vertical exchange of waters and is originally set to one month (see figure 5).

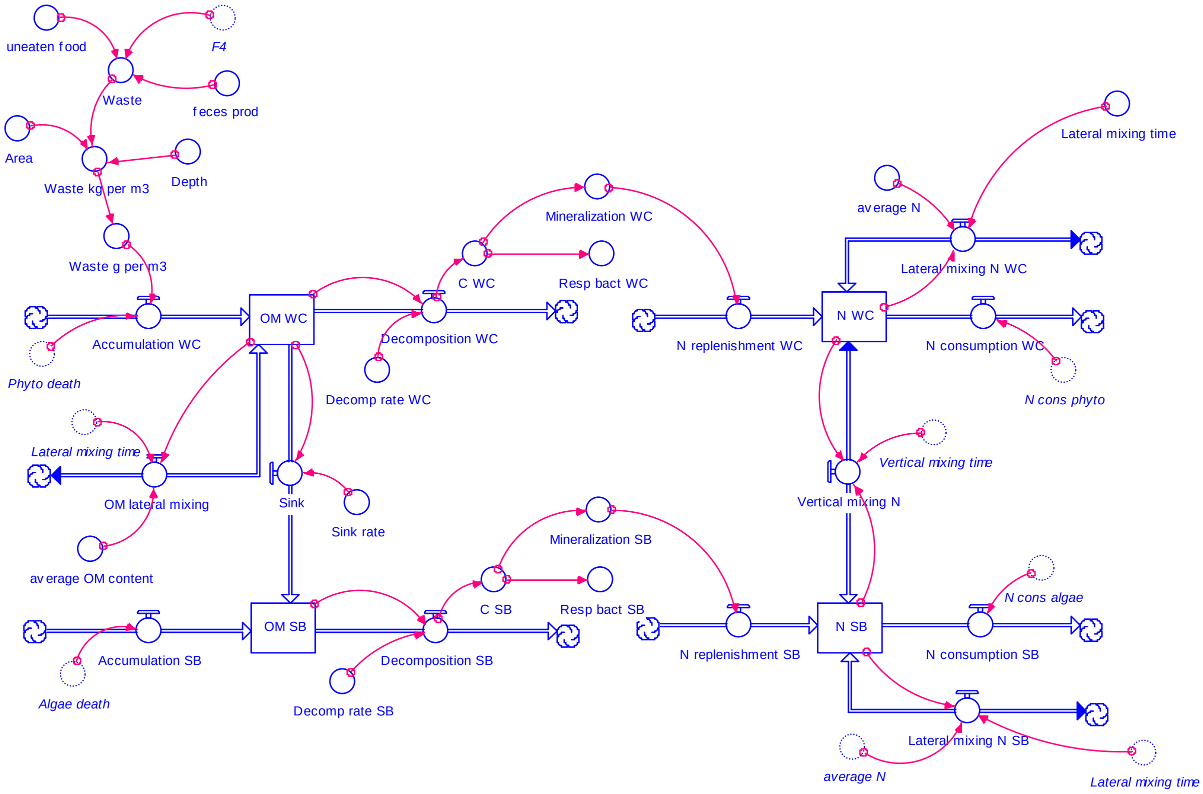

Figure 5: Nutrient dynamics

The stocks of dissolved oxygen (DO) in the water column (DO_WC) and above the seabed (DO_SB) are replenished thanks to the oxygen production of phytoplankton and algae and are drained by the respiration of phytoplankton, algae, fish and the bacteria involved in the mineralization of the organic matter. The same lateral mixing process as for nitrogen and organic matter occur and assure that the water column content tends to converge towards the DO saturation set to 7 $mg.l^{-1}$.

Finally, two outflows for supersaturated oxygen are added in order to prevent the dissolved oxygen level from exceeding the DO saturation too much. The atmosphere mixing time is set as little as possible (0,1) in order to assure the quickest adjustment (Arquitt and Johnstone 2004).

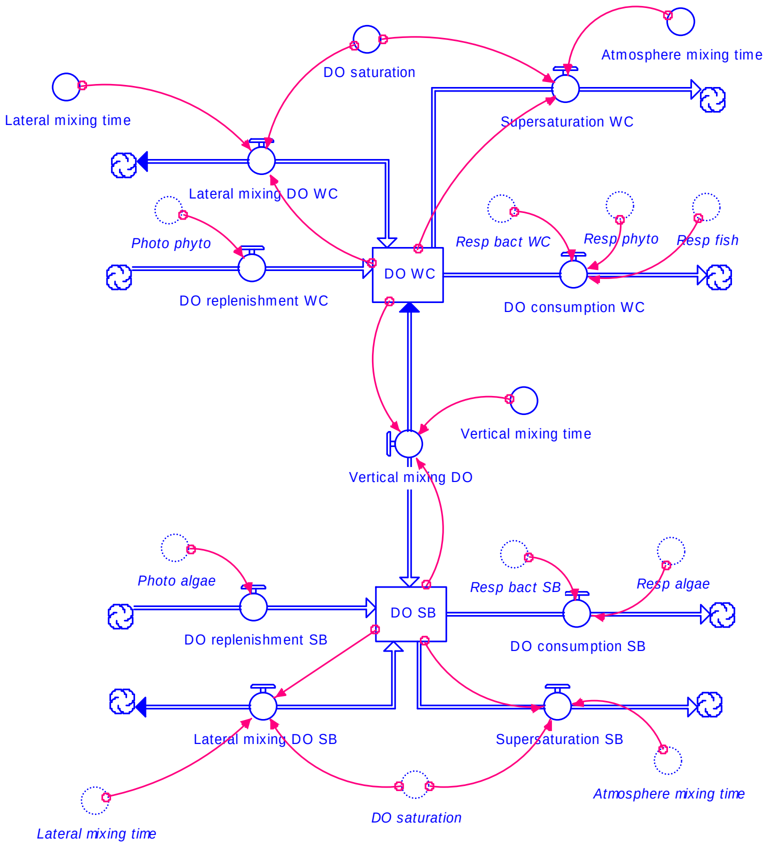

Figure 6: Dissolved Oxygen

4) <u>The ecological sector</u>:

Phytoplankton and algae growth fractions are modeled as positive functions of the availability of nitrogen and their death fractions are constrained by their respective carrying capacities (50 g.m$^{-3}$ for phytoplankton and 200 g.m$^{-3}$ for algae).

The consumptions of nitrogen are assumed to be functions of the average nitrogen content of phytoplankton and algae tissues (here set to 0.55*16/106 in order to keep the nitrogen cycle in a dynamic equilibrium).

Both phytoplankton and algae consume and produce oxygen via respiration and photosynthesis. Their net production of oxygen is assumed to be positive in order to compensate for the bacterial respiration.

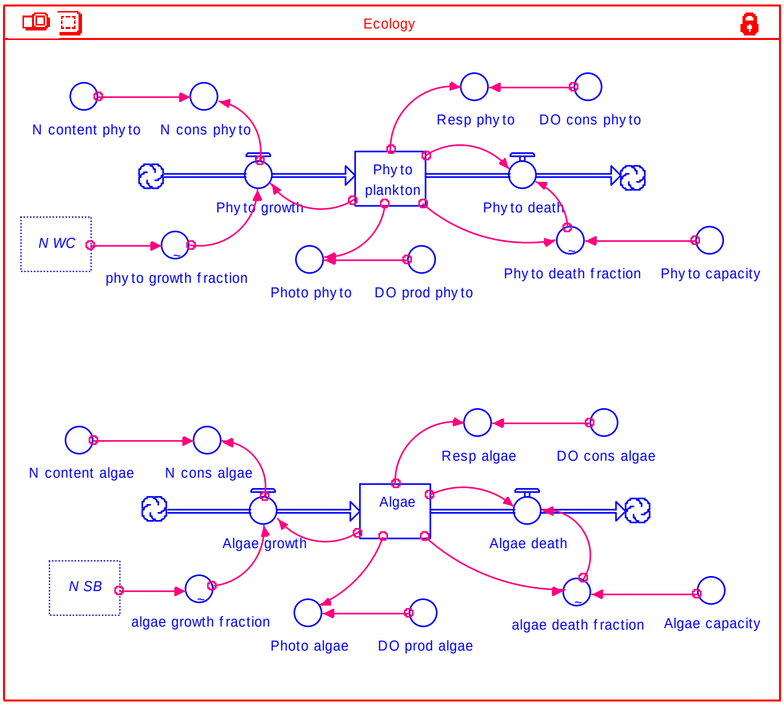

Figure 7: The ecological sector

The initial values for the environmental sector are set so that the dynamic equilibrium between organic matters, nitrogen, dissolved oxygen and biomass is already reached at the beginning of the simulation. These values are: 17.53 mg.$l^{-1}$ of organic matter, 0.58 mg.$l^{-1}$ of nitrogen and 7.14 mg.$l^{-1}$ of dissolved oxygen in the water column and 335 mg.$l^{-1}$ of organic matter, 1.12 mg.$l^{-1}$ of nitrogen and 7.05 mg.$l^{-1}$ of dissolved oxygen in the first meter above the seabed.

## Sensitivity analysis

The strength of the marine currents plays a very important role in the dispersal of organic matter. A sensitivity analysis is conducted in order to compare the effects of different vertical and lateral mixing times on the profitability of the company.

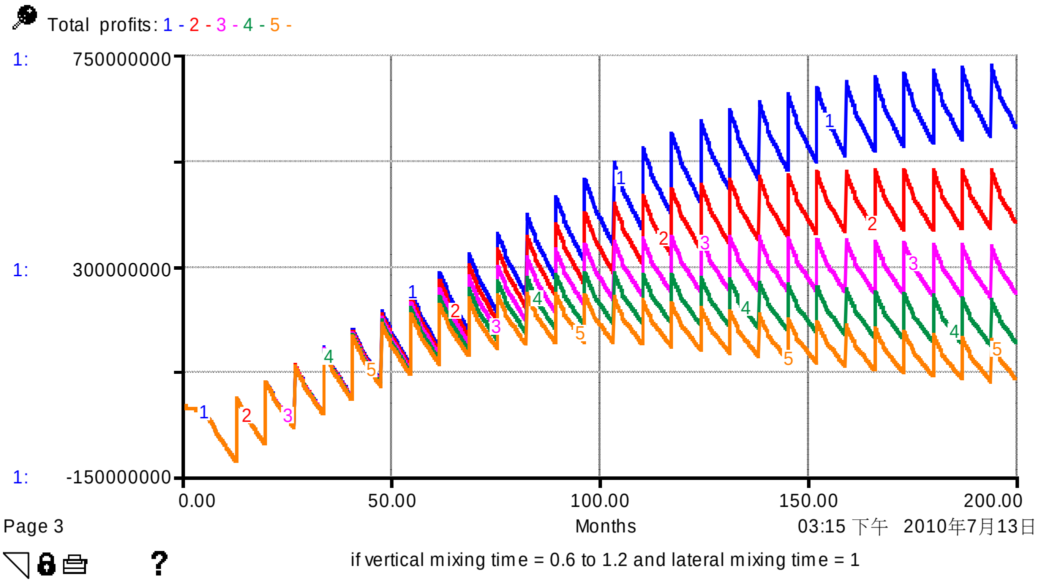

Figure 8: Total profits (TWD) for vertical mixing time = 0.6, 0.75, 0.9, 1.05 and 1.2

The faster the vertical mixing of water, the higher the concentration of dissolved oxygen and therefore, the higher the profitability of the enterprise. We can observe that whatever the speed of the vertical mixing, the total profits are likely to slow their growth soon or late.

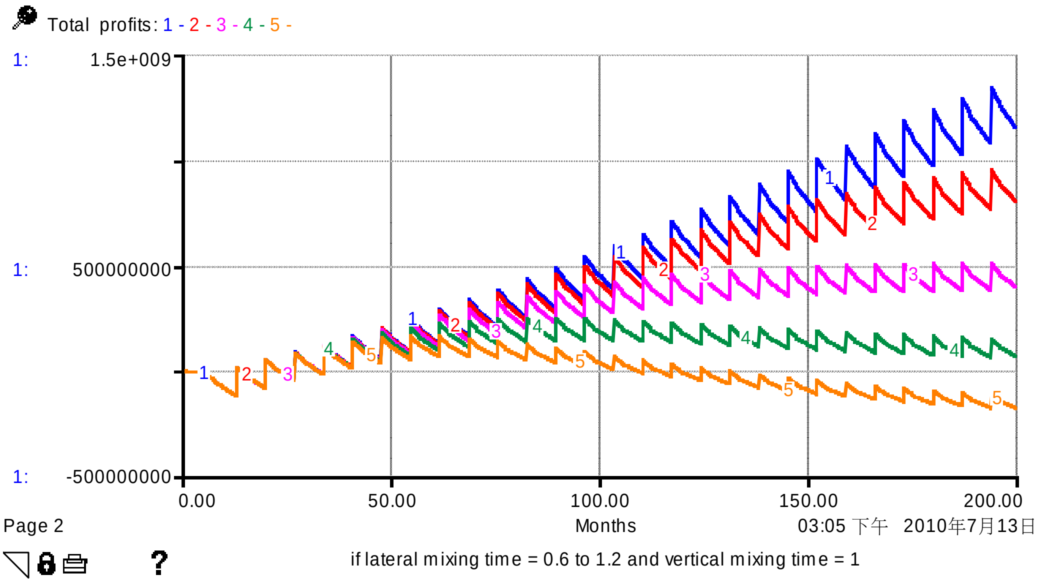

Figure 9: Total profits (TWD) for lateral mixing time = 0.6, 0.75, 0.9, 1.05 and 1.2

The effects of lateral mixing are much more likely to produce strong modifications in the behavior of our variables of interest. The total profits exhibit a positive linear growth for mixing times inferior to 0.9 month and a slowing down/collapse for slower mixing processes. Furthermore, stronger lateral current lead to higher profits than stronger vertical currents. This is due to the fact that lateral currents bring “clean” water to the farm whereas vertical currents bring water from the seabed, whose concentrations of organic matter and nitrogen are higher.

## Simulation results

The base scenario has been run using both lateral and vertical mixing times of one month.

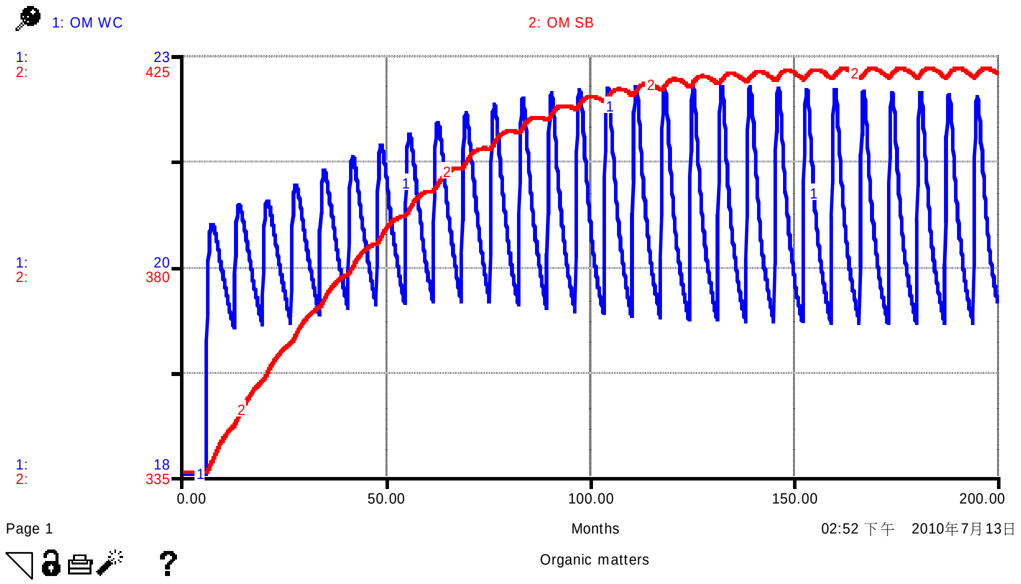

Figure 10: Organic matter (mg.$l^{-1}$)

The concentration of organic matter oscillates between 19.4 and 22.2 mg.$l^{-1}$ in the water column and rise from 335 to 422 mg.$l^{-1}$ in the first meter above the seabed.

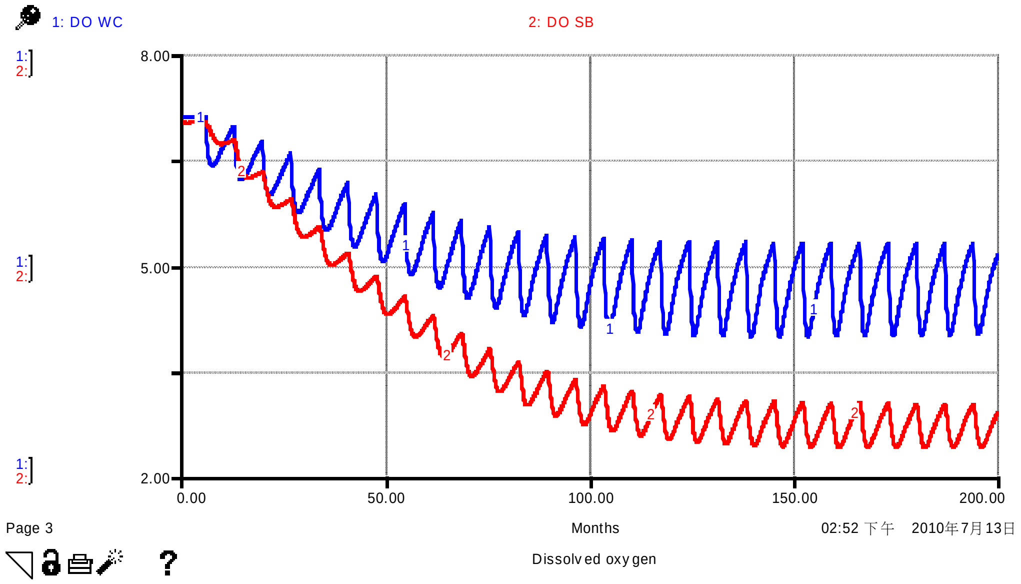

Figure 11: Dissolved oxygen (mg.$l^{-1}$)

The level of dissolved oxygen above the seabed is dramatically reduced by the increased sedimentation and mineralization due to the farm activity. It stabilizes between 2.4 and 3.1 mg.l$^{-1}$ at the end of the simulation. The upper level, somewhat higher (between 4 and 5.35 mg.l$^{-1}$) is nevertheless often under what is considered to be critical levels for cobia (Kaiser reports signs of stress under 5 mg.l$^{-1}$).

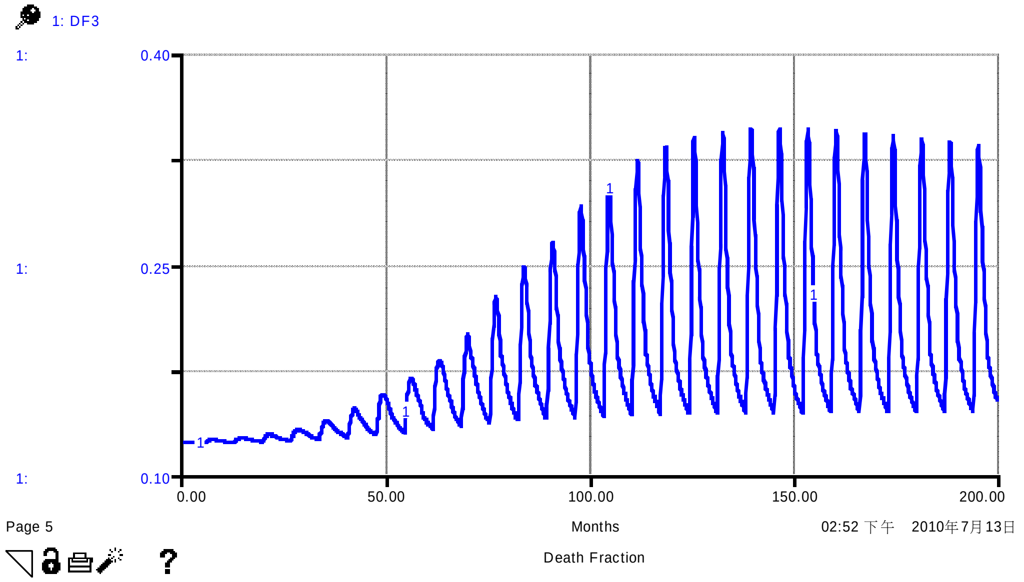

Figure 12: Fish death fraction (%)

As the dissolved oxygen varies around the threshold of 5 mg.l$^{-1}$ the fish death fraction rises and oscillates between 0.15 and 0.35 per month.

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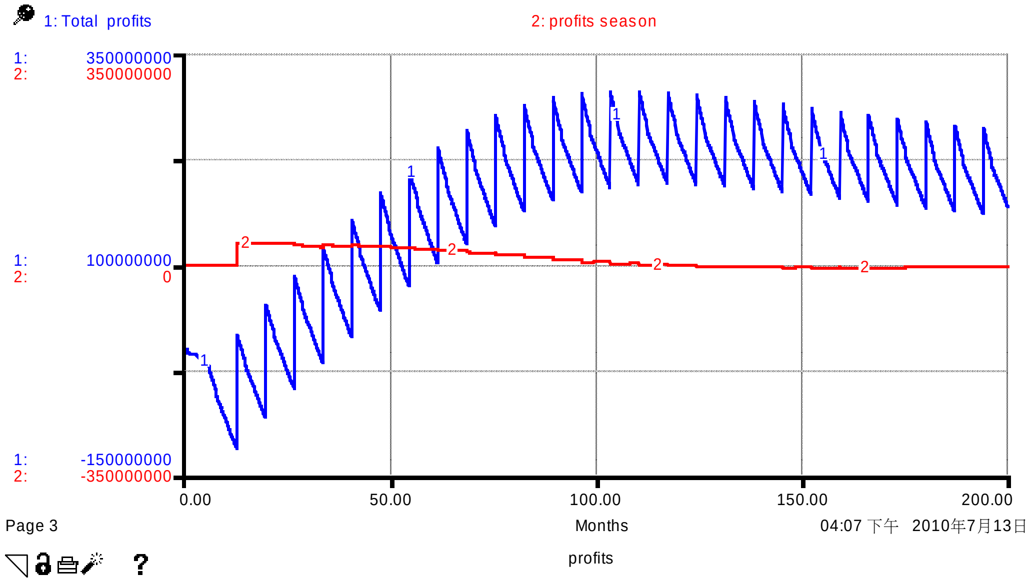

Figure 13: The company's profits (TWD)

The oscillatory pattern is of the total profits is due to the fact that costs are paid every month whereas incomes are earned every 7 months. This stock exhibits a positive linear growth on the short term (till month 90), after what it seems to stabilizes (month 90 to 150) and finally decline (month 150 to 200). We can observe that from the beginning, the seasonal profits are decreasing, reflecting the fact that the conditions have never been as good as for the first harvest. The company starts making losses on month 117 i.e. after 16 profitable seasons.

The base run suggests that as long as wastes accumulate on the seabed, the profitability of the company is likely to decrease.

## Policy analysis

1) Improvements in feed floatability

The problem of hypernutrification can be tackled in several ways. To date, the principal technological improvements towards the reduction of farm effluents have been done in the field of feed production. An amelioration of the floatability of pellets can lead to a certain reduction of wastes, delaying the company's problems as shown on figure 14.

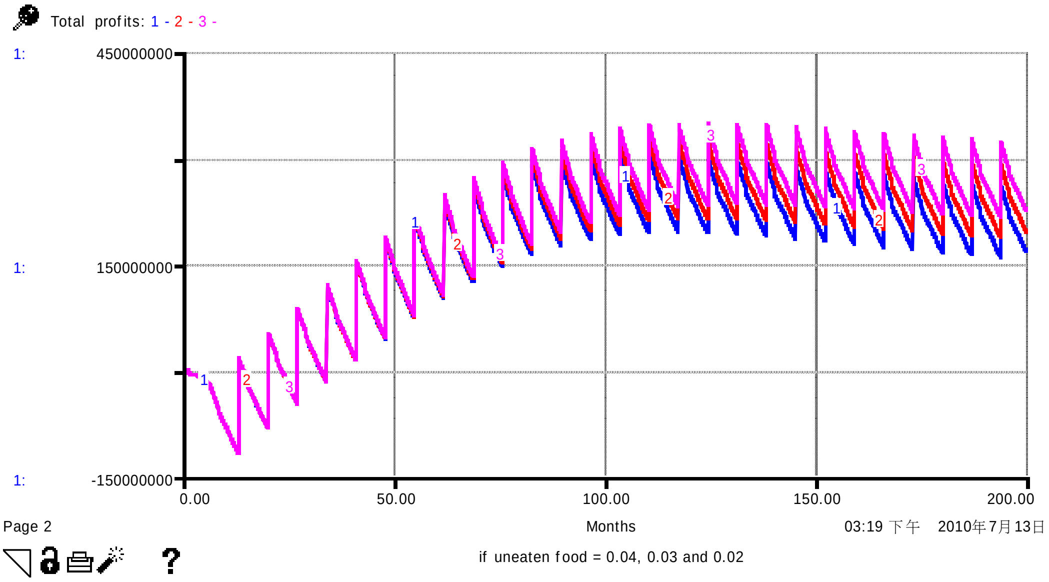

Figure 14: Company's profits (TWD) with uneaten food = 0.04, 0.03 and 0.02

As can be seen, the path toward sustainability is not likely to come from any improvement in feed floatability.

2) Exploitation of natural recovering capacity

A way to exploit the natural recovery ability of the environment is to introduce a delay between two seasons. The base run supposed that the company launches a new nursery stage two months after the beginning of the open ocean stage, so that no time is lost between two sessions.

Figures 15 and 16 show the results for the introduction of recovery times of: 0 month (base run), 2 months and 4 months.

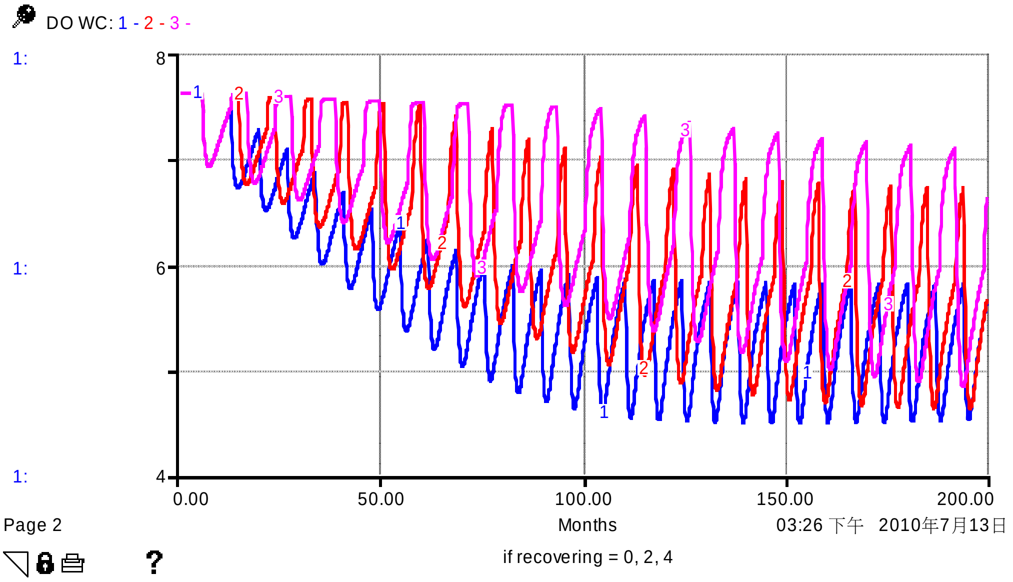

Figure 15: Water column dissolved oxygen ($mg.l^{-1}$) with recovery times between production cycles

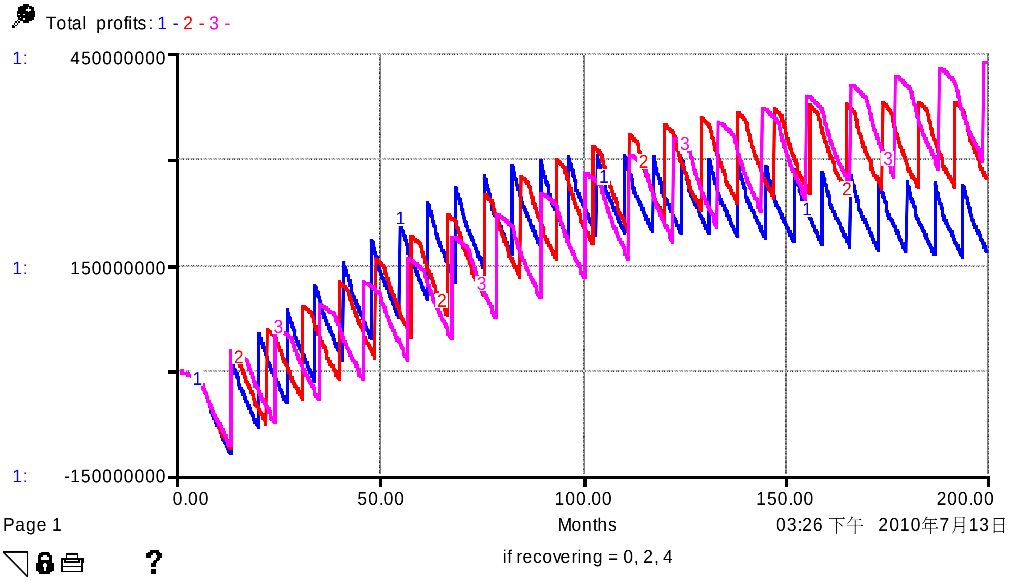

Figure 16: Profitability (TWD) with recovery times between production cycles

We can observe on figure 16 that the trend of the total profits tends to take a linear shape. The effect of the first two months are greater that the following two months because the dissolved oxygen tends to be replenished in an asymptotic way towards its saturation level (figure 15).

Another policy option could be to cancel a season if the available dissolved oxygen level in the water column falls under a threshold level (here 5 mg.l$^{-1}$). The Farming_switch equation is changed using the following “If” function: IF(DO_WC>5)THEN(STEP(1,Building_time))ELSE(0). Results are shown on figures 17 and 18.

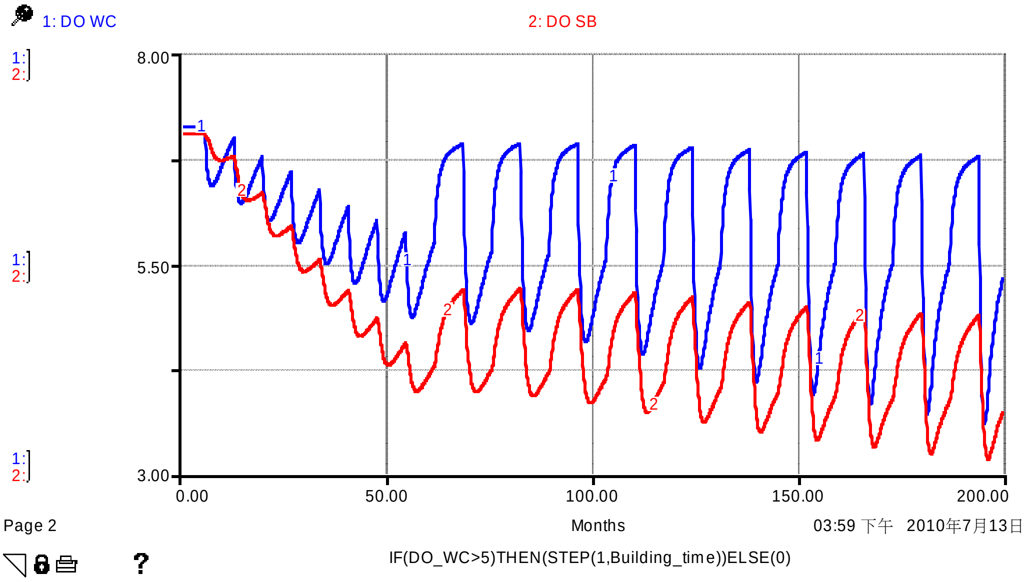

Figure 17: Water column dissolved oxygen (mg.l$^{-1}$) in the “cancel one season” scenario

The recovering capacity of the environment allows the dissolved oxygen to increase close to its saturation level. However, as soon as restarted, fish production depletes it. The production has to be cancelled one season on two.

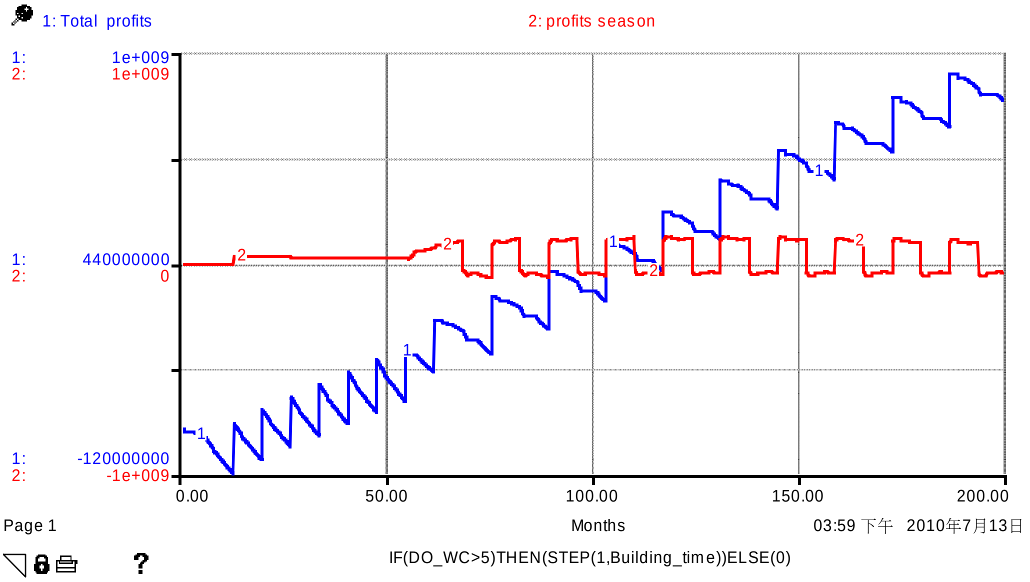

Figure 18: Profitability (TWD) in the “cancel one season” scenario

The periods where no production is launched have very high seasonal profits, around 110 millions TWD. These profits are far greater to what would have been earned during two seasons if the production hadn’t stop (around only 50 millions TWD), as suggested by the trend of the total profits (positive linear growth).

## Conclusion

Even if our model is still very rough, the first results it provides give some interesting insights. The base run showed how the negative environmental feedback is able to overcome the positive feedback of economic development when the carrying capacity is about to be reached. The growth of the total profits tends to slow down and become negative after about 10 years of activity (Fig. 13).

We saw however that this wasn’t true for lateral mixing times inferior to 0.9 month (Fig. 9). Therefore, an investment which would consist in increasing the lateral velocity of the currents (submerged or boat-based mixers) may have strong effects on the profitability of the company. The better integration and calibration of the marine currents in the model appears to be a very promising way to improve the model and we are currently working on it.

With uneaten food rates of 3 or 4%, no major change is likely to come from the feed; the principal matter that sinks and eventually accumulates being fecal matter.

The “cancel one season” scenario gives very good results because it is based on a water quality standard (threshold of 5 $mg.l^{-1}$). Moreover it generated no other cost than opportunity costs which appeared to be far lighter than the resulting benefits (Fig. 18).

The introduction of a delay between two production cycles may also be an effective solution to assure sustainable revenues, especially in the case where currents are stronger than what we considered here (in that case the linearity of the total profits would surely be evident).

Possibilities for policy analysis are numerous and we are currently considering various other alternatives to limit dissolved oxygen depletion: use of waste collectors under the cages, artificial introduction of oxygen in the water, settlement of artificial reefs on the seabed or integrated culture of fish and seaweed. The assumptions of the environmental sectors are also being discussed.

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