



Ecology and equity in global fisheries: Modelling policy options using theoretical distributions



Crelis Ferdinand Rammelt^{a,*}, Maarten van Schie^b

^a International Development Studies, Department of Human Geography and Planning, Faculty of Geosciences, Utrecht University, Heidelberglaan 2, 3508 TC Utrecht, The Netherlands

^b Bijltespad 30B, 1018 KH Amsterdam, The Netherlands

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ABSTRACT

Global fisheries present a typical case of political ecology or environmental injustice, i.e. a problem of distribution of resources within ecological limits. We built a stock-flow model to visualize this challenge and its dynamics, with both an ecological and a social dimension. We incorporated theoretical distributions for non-linear variables that serve to calibrate the model as well as facilitate real-time exploration of scenarios. These scenarios represent potential policy interventions aimed at addressing ecology and equity concerns in fishing. Model results show oscillation representative of predator-prey dynamics, as well as various degrees of stabilisation, inequality in resource extraction and/or collapse. Our results support the view that the most effective policy choices directly affect the growth of physical capital for ecological stabilisation, and in the social dimension reduce inequity in political control over the accumulation of capital and allocation of resources.

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1. Introduction

Acknowledging the methodological limitations, the [Global Footprint Network \(2015\)](#) estimates it takes the Earth one year and six months to regenerate what renewable matter we use in a year. Our way of life cannot be sustained in the long-term. At the same time, roughly 20% of the world population account for 86% of the world's total consumption expenditure, while another 20% at the other end consumes less than 1.3% (UN 2007). In a context of biophysical limits, the issue of economic distribution of resources is even more consequential.

In this paper we take the fish economy as a case study for a renewable resource economy. A necessary condition for sustainability is that any temporary imbalance between the in- and outflow from the renewable stock (of fish) is compensated at some point in the future ([Daly and Farley, 2004](#)). A long-term imbalance between harvest and regeneration has already resulted in depleted fish stocks around the world. This ecological approach to sustainability should be complemented by other approaches, such as “political ecology” or “environmental justice”, which recognize that environmental problems are socially distributed ([Dodds,](#)

[1997; Hornborg, 1998](#)). Indeed, the fishing sector represents not just a source of profit, but also a source of food and employment for society. The inequality in control over and in the use of productive resources is very clear in many parts of the world; artisanal fisheries are overwhelmed by larger-scale industrial trawling. As a result of EU imposed restriction on North Sea cod fishing, for example, some European industrial fleets procured licenses to catch off the coast of Africa. Small-scale fishermen in Senegal and Mauritania have experienced a consequent reduction in their local catches ([Kaczynski & Fluharty, 2002](#)).

Operating within ecological limits implies that we cannot expect to resolve conflicts over use or environmental injustices by constantly increasing the size of the pie, but that we need to find ways of sharing it more equitably. Matters of distribution of income and of access to food, resources or technologies are often blurred. The easy way out has been to look merely at financial indicators of inequality, in other words, at who gets what as consumers in a market system. However, the dynamic of markets seems to aggravate inequities as resources are diverted away from those that lack the money to provide for their basic needs towards the preferences of groups with stronger purchasing power ([Dodds, 1997](#)). For example, fish exports from Senegal may generate foreign currency, but they also threaten the Senegalese population's food security ([Ndiaye, 2003](#)). When dealing with imbalance of payment or debt repayments, governments in the global South may be driven to forego long-term durability of their nations' resource stocks for

* Corresponding author.

E-mail addresses: c.f.rammelt@uu.nl, crelir@gmail.com (C.F. Rammelt), schiemaarten@gmail.com (M. van Schie).

short-term over-exploitation. While benefiting certain constituencies, these choices often imply a reduction in entitlements for other usually more vulnerable population segments. To address this problem within the current market system, it may be justified to increase salaries in the lower income brackets. The associated growth in production and consumption will however generate further ecological disruption. Interconnections between development and environment are inevitable.

System dynamics has already been applied for understanding the fishing economy and for assessing possible interventions (see for instance Whelan, 1994; Dew, 2001; BenDor et al., 2009; Dudley, 2008). We build on an existing model that combines ecological and economic dynamics from Meadows and Wright (2008) and that was further developed for a university classroom exercise on system dynamics (Rammelt, 2015). This basic model includes a stock of fish (a renewable natural resource) and a stock of fishing boats (capital). The ecological system boundaries limit and define the economic behaviour of the system in ways that would not become clear from linear-type economic models, and the economic model affects the ecological system in ways that would not become clear from models that focus only on ecology.

Our first contribution to these existing models is the development and application of theoretical distributions. Meadows and Wright (2008) draw graphical functions that serve to calibrate the model but do not have strong theoretical underpinnings. Based on theoretical distribution functions, we have developed a way to represent the often complex dynamics of boundary conditions into simplified mathematical formulae. Distributions form one of the building blocks of statistical analysis and we therefore consider their usage robust and justifiable in modelling the ‘ideal behaviour’ of complex relations. Moreover, these formulae can be calibrated based on empirical knowledge of a variable such as a fish population, for example. This provides increased flexibility over existing options for exploring calibrations in the form of policy scenarios, as will be elaborated below.

Our second contribution pertains to equity.¹ We have combined two (mirrored) capital substructures adapted from Meadows and Wright (2008); one capital stock belongs to industrial trawling, and one to artisanal fisheries. Both harvest fish from the same resource stock. Some clarity will emerge from exploring the long-standing discussion on inequality by looking at the physical rather than the financial economy (Kaufmann, 1987). With this in mind, Rammelt and Boes (2013) suggested applying a “dual capital structure”, which looks at changes in (1) the distribution of the ownership of the (physical) capital stock, (2) access to the services it generates, and (3) control over maintenance and investment decisions that change the composition of the stock. In other words, inequalities can be found in ownership, services and control. No system dynamics application to the fish economy has dealt explicitly with the economic issue of distribution as far as we know.

Based on this model, we explore the consequences of various policy choices to address not only (over)fishing, but also inequity. For this, we were inspired by some of the interventions in the fishing economy suggested by Whelan (1994). With system boundaries, stocks, flows and other conceptual tools, systems dynamics serves to explore how science, industry, legislation and policy can leverage more ecologically sound and equitable dynamics.

In short, our paper contributes to existing system dynamics models of renewable resource use by incorporating and experimenting with theoretical distributions, and by bringing in a dual capital stock perspective to integrate a justice perspective with existing ecological economic models. The following materials and

methods section describes the model itself and the theoretical distributions used. The results section explores the scenarios and policy interventions.

2. Materials and methods

Our basic system dynamics model builds on Meadows and Wright (2008) and is developed using STELLA Professional. Its basic elements consist of stocks,² flows³ and model parameters. These elements are linked through connections, which can provide remarkably intricate system dynamics, including reinforcing and balancing feedback loops⁴ (see basic language description in Costanza and Gottlieb, 1998; Costanza and Voinov, 2001). In our paper, modelled variables and parameters are referred to in their model-language form, e.g. as “*capital.stock*”.

2.1. Model components and system boundaries

The model shown in Fig. 1 is developed around two stock variables: *capital*, which can be thought of as a fleet of fishing vessels; and a renewable population of fish, or *resource*. The model also includes four flow variables entering or leaving the stocks. Flows of *investment* and *depreciation* respectively fill and drain capital; *regeneration* and *harvest* do this for fish populations. The *regeneration* variable is a bi-flow, which indicates that it can also be negative as will be explained later. The clouds indicate that, for this exercise, we are not interested in the origin and destination of the flows; they lie beyond the system boundaries. It should be noted that in reality, unmodelled limits or dynamics might unfold in these sources and sinks.⁵

In terms of predator-prey dynamics,⁶ *capital* is the effective predator population, rather than business size or industry cash flow (money doesn't catch fish). These physical capital goods wear out over time and eventually break down, leading to value reduction. This depreciation is modelled as outflow of capital, and must be compensated for with new investments. The longer the ‘life expectancy’ of a fishing boat (assumed to form the majority of fishery capital stock), the smaller the fraction of capital that must be replaced. We assume that a ship can be in operation for 20 years before it needs to be replaced (the *capital.lifetime* constant in the diagram). This means a *depreciation* outflow of 5% per year. We further assume that the fishing industry wishes to grow its capital by 5% (the *growth.goal*). With 5% *depreciation* and 5% *growth.goal*, the *investment.rate* must be 10% of the capital stock. Each year, profit margins (the net gains to the fishing industry) determine whether or not the industry can attain this *investment.rate*. A condition is therefore included in our model: If *profits* are lower than the *investment.rate*, the industry invests whatever it can (in this case, all of its profits). External investments are not considered for this model, that is to say the fishing-economy is considered as, and insofar as

² A stock variable indicates a store or a quantity of material or information that has built up over time. In systems terminology, physical (and information) stocks are also called state variables.

³ A flow variable produces a change in the stock variable, usually an actual physical flow into or out of a stock. In systems terminology, physical (and information) flows are also called rate variables.

⁴ Feedback loops are patterns of causality that slow down or speed up the flows. In systems' language, we speak of so-called balancing or reinforcing feedback, respectively.

⁵ Sources and sinks represent systems of stocks and flows outside the boundary of the model. A source is where flows originate outside the system. A sink is where flows terminate outside the system.

⁶ When many foxes prey on rabbits, the number of rabbits declines; then because rabbits are scarce, foxes starve and their numbers dwindle, allowing the rabbit population to build up again.

¹ We associate equity with fairness in social justice and an impartial form of distribution of services and benefits. Equity is therefore not the same as equality.

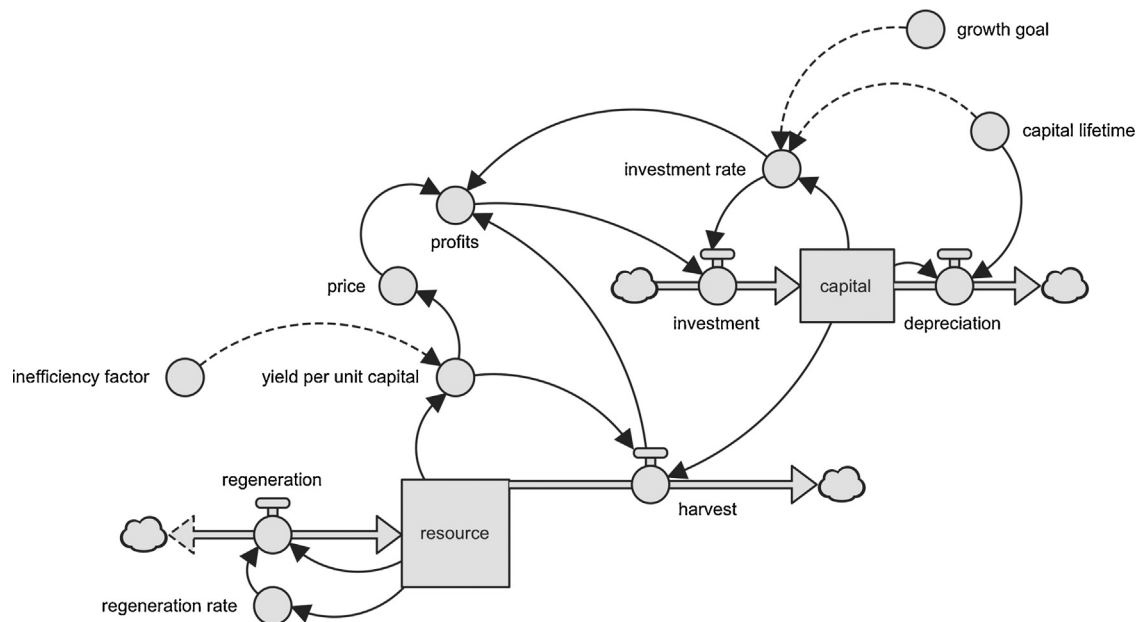


Fig. 1. System diagram of the fishing economy (adapted from Meadows and Wright, 2008).

it is, self-sustaining on the basis on an existing capital stock at the beginning of the simulations.

Natural population dynamics for the fish population are modelled as regeneration, based on the assumption that these flows are regulated by the size of the population with respect to the environment and the carrying capacity to sustain the population. This will be elaborated below.

2.2. Linear and non-linear relationships

From the above description of the model, we can identify the following linear relationships. With a constant *capital.lifetime*, *depreciation* grows linearly with increasing *capital* (Eq. (1)). The *investment.rate* includes upkeep to maintain *capital* as well as investment to increase its size, based on a constant *growth.goal* (Eq. (2)). Gross *profit* is equal to the revenue from sales minus costs, which we associate only with the *investment.rate* (Eq. (3)). Other costs, such as labour wages, are left out of the model. Sales revenue is equal to the amount of fish harvested multiplied by the *price* paid for it on the market.

Eq. (1): Depreciation.

$$\text{depreciation} = \text{capital} / (\text{capital.lifetime}) \quad (1)$$

Eq. (2): Investment rate.

$$\text{investment.rate} = \text{capital} \cdot 1 / (\text{capital.lifetime} + \text{growth.goal}) \quad (2)$$

Eq. (3): Profit.

$$\text{profit} = \text{price} \cdot \text{harvest} - \text{investment.rate} \quad (3)$$

Other relationships in our model, namely those between *yield.per.unit.capital*, *price*, *resource* and *regeneration.rate* are non-linear. As mentioned in the introduction, we propose using theoretical distributions rather than a hand-sketched distribution. The functions are displayed graphically in Fig. 2.

2.2.1. Yield per unit of capital

Fish harvesting is not only influenced by the number of ships, but also by their individual efficiency. As the fish resource depletes it becomes increasingly difficult to harvest as fewer fish are encountered. Each boat will bring in a smaller catch. The general form

of such a relation describes return as dependent on prey amount (availability). We have modelled this relation as a cumulative distribution, i.e. a logistic function (Eq. (4)), which produces an s-curve. The basic logistic function produces a value of 0.5 at 0 and approaches its maximum of 1 and minimum of 0 at respectively 2π and -2π .

Eq. (4): Logistic function.

$$y = 1 / (y_{\max} + \exp(-2\pi(x - x_y) / \text{variance})) \quad (4)$$

We can transform this logistic function by inputting a value of the value x_y , which determines the x at which $y = \bar{y}$, and by defining the variance of the distribution. In our model the accessibility of the resource to capital is formulated in terms of the *yield.per.unit.capital*: smaller stocks mean that the same single unit of capital has a lower return because it will encounter fewer fish that can be caught. In this context x_y is an *inefficiency.factor*, set at the value of the resource stock at which half of the maximum yield is attained. The variance is how much the fish stock has to increase to achieve optimal yield. For the sake of simplicity, we have set the maximum yield at 1 and predetermined the variance to approach 0 near 0 fish stocks and to reach its maximum near 1000.

Eq. (5): Relationship between *yield.per.unit.capital*, *resource* and *inefficiency.factor*.

$$\begin{aligned} \text{yield.per.unit.capital} \\ = 1 / (1 + \exp(-2\pi(\text{resource} - \text{inefficiency.factor}) / 500)) \end{aligned} \quad (5)$$

Technology increases the capacity of the fishing industry to catch fish even at lower densities. For example, while artisanal fisheries achieve a maximum return only at full seas, high-tech fishing vessels can use bottom trawls,⁷ harvesting machines⁸ or sonar to increase their yield. These innovations lower the (fish) population at which a maximum yield is achieved. In our model, we therefore allow for adjustments of the *yield.per.unit.capital* by changing the *inefficiency.factor* of each single boat. As the curve in Fig. 2a shifts

⁷ Bottom trawling is towing a fishing net along the seafloor.

⁸ These technologies literally pump fish out of the sea.

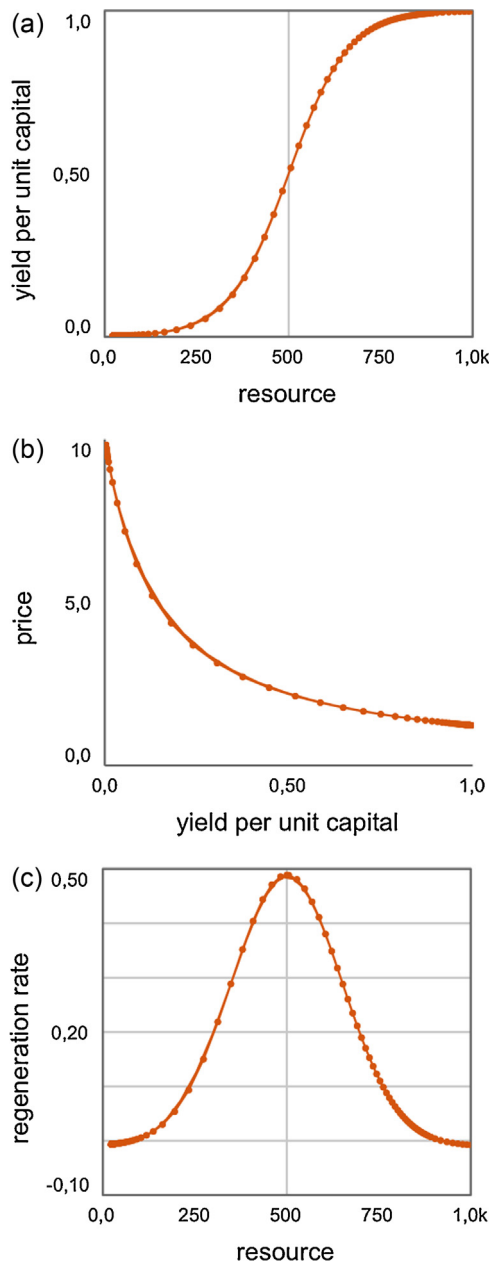


Fig. 2. (a) yield_per_unit_capital as a function of resource. (b) price as a function of yield_per_unit_capital. (c) regeneration_rate as a function of resource.

to the left, each boat's efficiency increases despite a lowering of the available fish.

2.2.2. Price

Price varies with resource accessibility. Natural resources generally become more expensive as they become scarce (price elasticity in economic terms). Scarcity is reflected in yield, and the price is low when the yield is high and decreases at a decreasing rate; the price is high when the yield is low, and increases at an increasing rate. This leads to a hyperbolic function dependent on *yield_per_unit_capital* as shown in Fig. 2b and described in Eq. (6). The price rises to 10 as the *yield_per_unit_capital* drops to 0. The value of 1.4 determines the slope, i.e., the elasticity.

Eq. (6): Relationship between *price* and *yield_per_unit_capital*.

$$\text{price} = 1 / ((0.1 + (\text{yield_per_unit_capital}) / 1.4)) \quad (6)$$

2.2.3. Regeneration rate

Environmental constraints on a population are frequently modelled through an interaction with either a resource base or a predator (based on birth and death rates). In its simplest form, the environmental constraints are modelled implicitly when the fertility rate of a population decreases as population increases, and when the mortality rate increases as population increases. In our model, environmental constraints are modelled more explicitly by considering both birth and death rates in a combined *regeneration_rate* (see Fig. 1). This is a function of the *resource* stock and allows for the direct definition of environmental constraints in the form of carrying capacity and optimal population size. The *regeneration_rate* has an explicitly defined optimal level and two clearly defined points at which the *regeneration* flow becomes negative, i.e. when either the population is too low or too high to regenerate (see explanation below).

We derive the *regeneration_rate* from a normal distribution function (Eq. (7)), which is depicted as a bell curve in Fig. 2c. The distribution is simplified and rewritten to describe the *regeneration_rate* as a function of resource in Equation (8). The first part of the distribution function ($1/(\sigma\sqrt{2\pi})$) adjusts the integral of the function to equal one. This is simplified for our purposes and is replaced with a maximum regeneration rate value of 0.5. The mean is rewritten as the optimal value of the population (500).

Eq. (7): Normal distribution function.

$$1/(\sigma\sqrt{2\pi}) \cdot \exp(-(x - \mu)^2/(2\sigma^2)) \quad (7)$$

Eq. (8): Relationship between *regeneration_rate* and *resource*.

$$\begin{aligned} \text{regeneration_rate} = & 0.5 \cdot \exp(-(resource - 500)^2/(2 \times 150^2)) \\ & - 0.5 \cdot \exp(-300^2/150^2) \end{aligned} \quad (8)$$

In Eq. (8), the extra parameter that is subtracted defines the range between which population stocks the *regeneration_rate* is positive relative to optimal value (in our case from 500 – 300 to 500 + 300). At lower population levels regeneration is constrained by the population size, at higher population levels regeneration is constrained by the size of the environment. Put differently, when the natural habitat is overcrowded, some fish will starve due to lack of sufficient food, or they run out of places to hide from predators. As a result, the *regeneration_rate* is negative at the right-end tail of the bell curve (see Fig. 2c). In ecological terms, this maximum is the carrying capacity. On the other hand, if the fish are too scattered, some will die (fish schools provide protection, for example) and the fish are at risk of extinction. The *regeneration_rate* is therefore also negative at the left-end tail of the bell curve.⁹

2.3. Feedback mechanisms

The dynamics of the system in Fig. 1 are governed by a number of feedback loops:

- Balancing loop of depreciation: The more the capital stock grows, the more boats depreciate, the slower the growth of the capital stock.
- Balancing feedback loop of falling harvest: The more the capital stock grows, the more fish is harvested, the smaller the resource

⁹ The single normal distribution function could also be written as the product of two separate and opposing s-curves representing the distinct limiting effect of respectively population (at low populations) and environment (at high populations), which would allow for the incorporation of asymmetric distributions and of more detailed knowledge of the ecosystem.

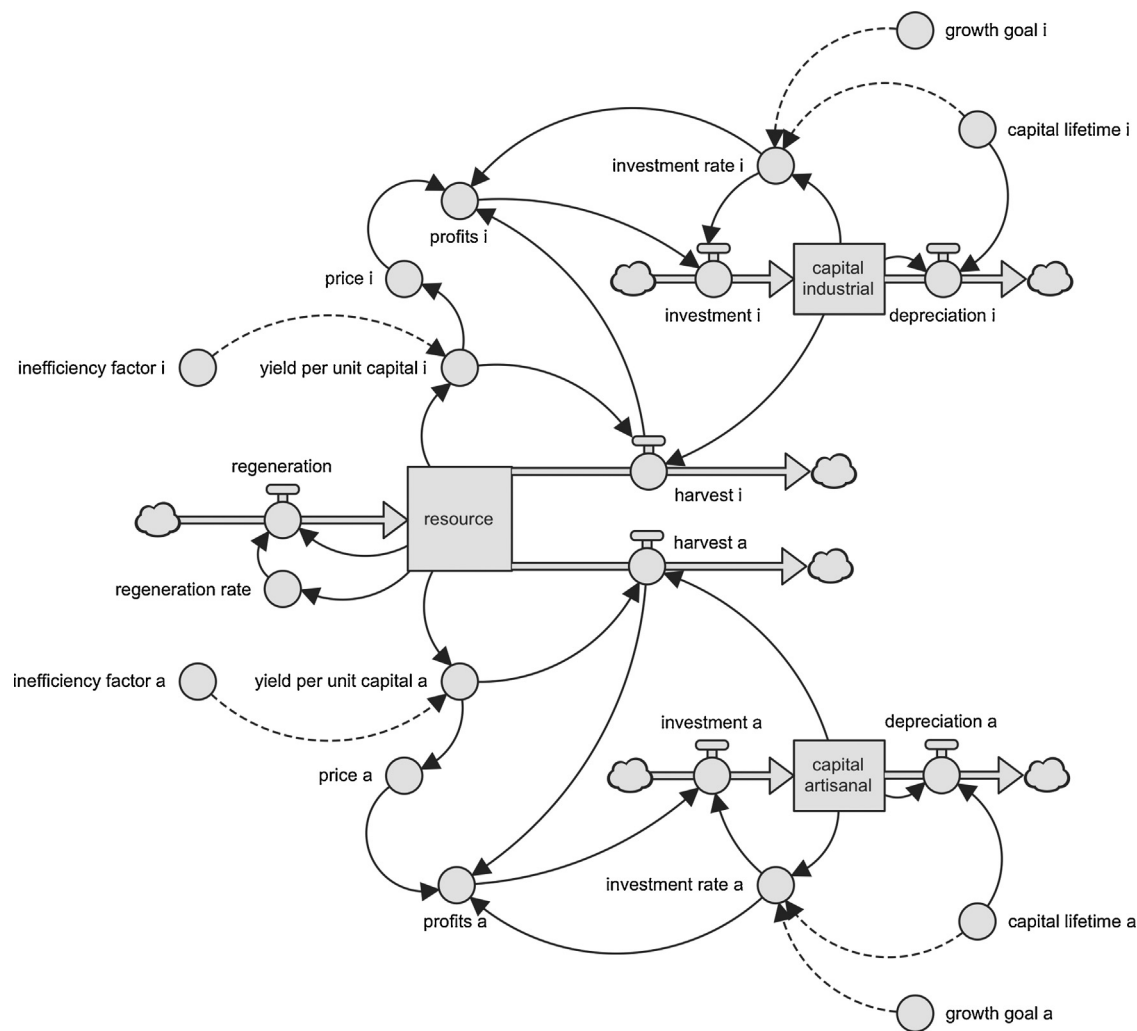


Fig. 3. System diagram of the dual fishing economy.

stock, the lower the yield per boat, the less fish is harvested, the less profits and investments, the less the capital stock grows.

- Reinforcing loop of investment: The more the capital stock grows, the bigger the investment rate, the stronger the growth of the capital stock.
- Reinforcing feedback loop of increasing harvest: More capital means more harvest, higher profits, more investment and therefore more capital.
- Reinforcing feedback loop of increasing price: More capital means more harvest, less fish, lower yields, higher prices, more profits, more investments and therefore more capital.
- Reinforcing and balancing feedback loop of regeneration: The more the fish population grows, the faster it reproduces, the bigger the inflow of newborn fish, the more the fish population grows. As mentioned, this continues up to a point where the natural habitat is overcrowded and the regeneration rate becomes negative. The feedback loop has become balancing.

For further explanations regarding these feedback mechanisms and regarding the model in Fig. 1 in general, we refer to Meadows and Wright (2008).

2.4. Dual capital fishing economy

Building on the idea of a dual capital structure briefly introduced earlier (Rammelt and Boes, 2013), we adapt our model to include

industrial fisheries (*capital industrial*) and artisanal fisheries (*capital artisanal*). We do this by mirroring two capital stock structures from Fig. 1 around one shared *resource* stock as shown in Fig. 3. This potentially leads to (unfair) competition between two fishery sectors.

2.5. Scenarios

We have run several scenarios for the purpose of highlighting the effect of policy choices on the system. We start with a situation where there is no industrial fleet. History tells us that innovation in the fishing sector has, in many cases, aggravated or accelerated ecologically unsustainable activity. Mark Kurlansky (1997) presents a vivid account of the events that led to the depletion of the North Atlantic codfish. Catches that were already declining kept on being pulled in with new and improved fishing techniques. Eventually the schools didn't return. We explore this scenario by varying the *yield_per_unit_capital* (through its *inefficiency_factor*). Investments in increasingly efficient technologies lead to oscillation and collapse scenarios. We then explore scenarios around the unequal distribution of resource extraction between two fishing sectors is based on the dual fishing economy model from Fig. 3. We start with an ecologically sustainable local artisanal fishing sector. We then introduce an industrial fishing sector and explore the impact on both sectors and on the shared resource stock.

The remaining scenarios are used to investigate different policy interventions. The policy forum on ecosystem-based fishery management (Pikitch et al., 2004) has focused mainly on solving industrial fishery problems, such as by-catch and habitat perturbation, while largely ignoring artisanal (small-scale) fisheries. These two sectors operate on different scales and therefore require different management solutions. Castilla and Defeo (2005), for example, argue for management of industrial fisheries through a reduction of fleet, ground facilities and subsidies; moratoria on new entrants into the business; and administration of catch quotas. Territorial user rights for fishers, co-management, and community quotas have been proven successful strategies for artisanal fisheries. These policies remain geared towards ecological sustainability in the respective waters of the two sectors. In reality, of course, they compete with each other.

We explore the following five policy interventions in relation to both ecological and distributional sustainability:

- We add a variable that represents an investment tax, which is levied on new ships and therefore reduces capital investments.
- We add a parameter to represent a fish quota that will cap the harvest outflow at a certain level.
- We add a parameter to the model that represents a tax on industry revenue.
- We add a causal link to the model which restricts capital investments as yields start to decline.
- We allow for a fixed size of the industrial fleet but restrict its growth by adjusting existing variables in the model.

By using theoretical distributions, we are able to explore these scenarios ‘real-time’ by turning the value for constants up and down and seeing the consequent changes in other variables in updated graphs. We are also able to add adjustable constants for various elements within the equations for the non-linear *yield_per_unit_capital*, *price* and *regeneration_rate* variables and relationships (see Eqs. (5), (6) and (8)).

3. Results

We wish to emphasise that the values displayed on the x and y axes of the graphs presented in this section are not intended to be in any way accurate or predictive. The emphasis should be on the differences between the industrial and artisanal sectors, and on how the dynamics change after adjusting various parameters from one scenario to the next.

3.1. Oscillations and collapse scenarios

We start with a situation where there is only artisanal fishing. A first typical scenario is one where oscillations arise. Overfishing one year occurs at the expense of catches in the following year. Balancing feedback (fewer fishing boats) temporarily brings back fish populations, but overfishing reoccurs again the next season (Fig. 4). Oscillation can often be seen in typical predator-prey systems. It is the characteristic symptom of negative feedback structures in which the information used to take action is delayed. In such cases, the action is not based on the current state of a system but on some previous state or value. Using ‘dated’ information to control the approach to a target is likely to cause the system to miss or overshoot its goal.

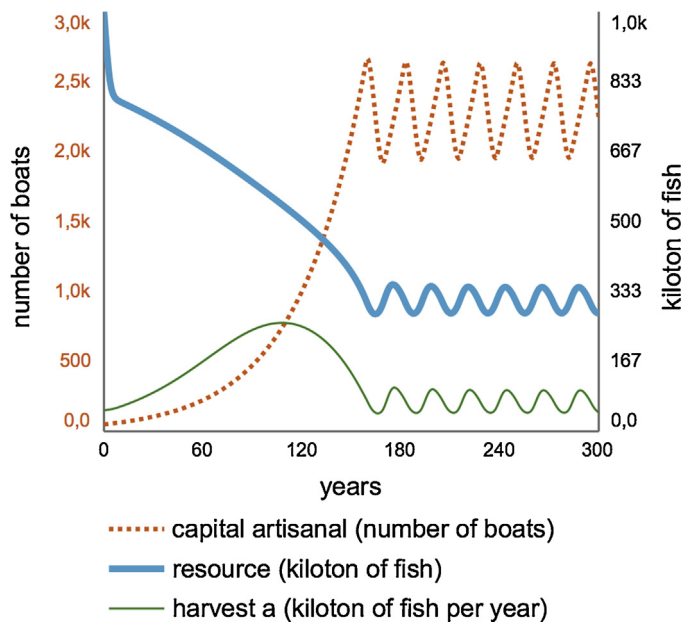


Fig. 4. Predator-prey oscillations.

We want to know if the system is likely to evolve towards stability and smaller amplitudes,¹⁰ or towards instability and larger amplitudes. The outcome will depend on a wide range of factors, but we look specifically at the productivity or efficiency of the fishing fleet. The drive for such innovations is very strong in the current economic climate. For industrial fisheries, the introduction of bottom trawls or harvesting machines maintains the yield per boat for just a bit longer despite dwindling fish populations. For artisanal fisheries, the innovations may be more ‘low-tech’, but the effect is in the same direction. We increase the efficiency of each individual fishing boat in our model by lowering the *inefficiency_factor_a*, which raises the *yield_per_unit_capital_a* variable. As we shift to higher efficiency, the oscillations get wider (Fig. 5a).

With the introduction of sonars, fishing boats are able to detect and catch the last remaining fish. Technology gets even more efficient; artisanal fishing may have become industrial. We lower the *inefficiency_factor_a* further down. The resource stock falls and the yield is too low to harvest anything, which means no profit, no investment and a collapse of the *capital_artisanal* (Fig. 5b). The size of the *capital_artisanal* peaks at around 110 years and the harvest peaks at around 80 years. The risk here is that if we were only looking at the period before the peaks, we would see nothing alarming. Harvest doesn’t actually decrease significantly until the tail end of the drop in resources. A short-sighted response could be too little, too late.

Looking at the right end of the *resource* stock graph in Fig. 5b, we see that the remaining population starts to regenerate. For the sake of exploring potential long-term cycles, we prolong the run to a wholly unrealistic scenario of 3000 years, instead of 300. We can see that the very small surviving population retains the potential to rebuild, once harvesting has stopped (Fig. 6a). The pattern is repeated years later (if nothing else changes in the system). The cycles last about 1200 years (from the start of one peak to the next). If the fish population drops dramatically, the number of fish laying eggs is so small that the population could take a very long time to recover even when undisturbed by the fishing industry during

¹⁰ The gap between the highs and lows of an oscillation, i.e. its amplitude, is related to the (in)stability of the system. Wider amplitudes imply that the stock goes closer to potential extremes (full and empty), which may cause the system to collapse.

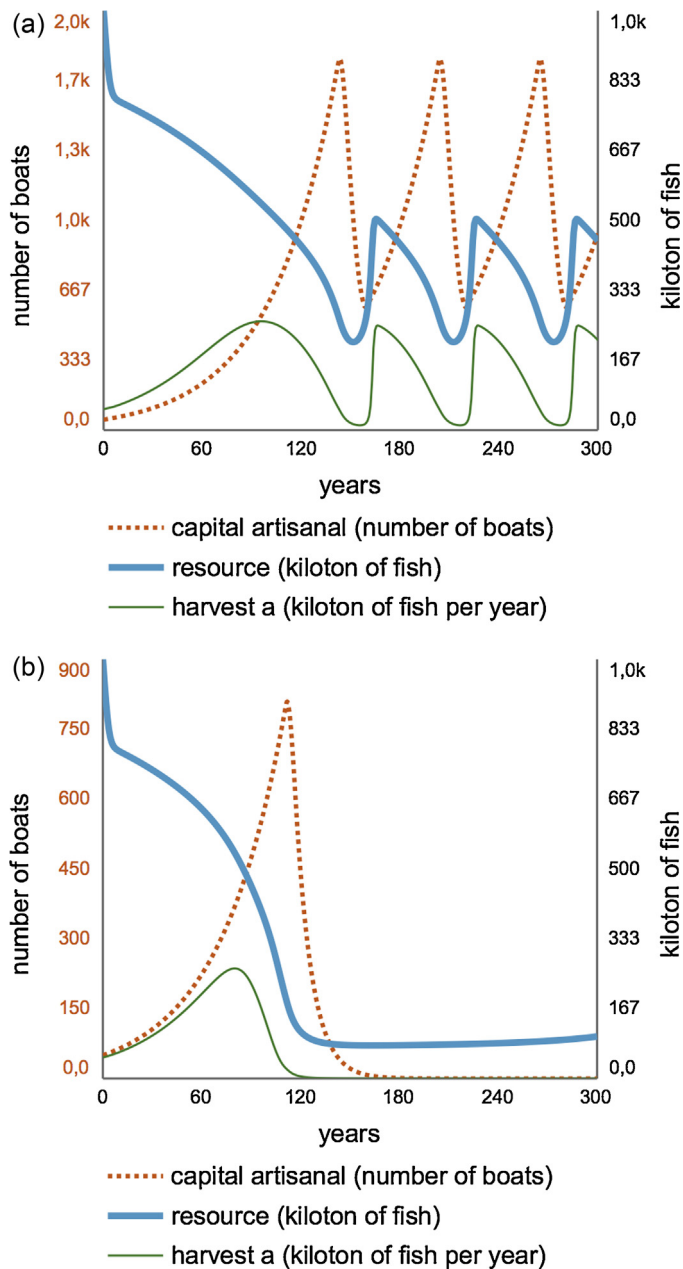


Fig. 5. (a) Oscillations with higher efficiency. (b) Collapse at even higher efficiency.

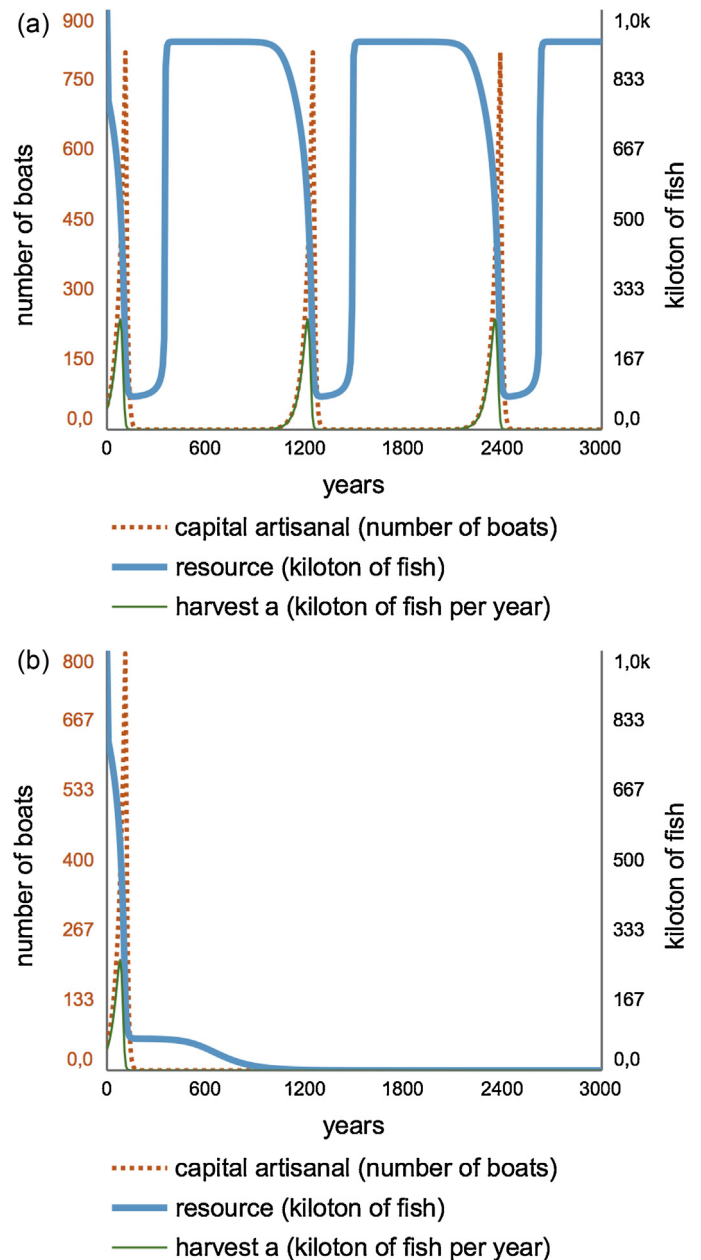


Fig. 6. (a) Scenario of a further increase in efficiency, 3000 years run time. (b) Tipping point and collapse scenario.

the regeneration period. Whether it will be able to recover at all is uncertain. Other stresses not included in our model will have an effect, like pollution, natural predators or the damaging effect of bottom trawlers on spawning areas.

In ecology, the capacity of systems to recover after perturbations is called 'resilience'. However, a point comes when the slightest further push can radically alter the outcome. This is when a system goes over a "tipping point" and is unable to return to its initial condition. A slight lowering of the *inefficiency factor* a is enough to trigger this outcome. The *resource* stock drops below a certain threshold, the *regeneration rate* becomes negative (see earlier Fig. 2c). At that point, the fish are too scattered to find each other and the population never rebuilds (Fig. 6b). Such an event is likely to be significant on dependent systems. The extinct fish specie could be important in the food web, for example. Removing it could impact on the entire ecosystem.

3.2. Unequal resource extraction scenarios

We now take the model adjustment involving two *capital* stocks, i.e., industrial and artisanal sectors as depicted in Fig. 3. We start with a sustainable scenario of a stock of inefficient artisanal boats, and zero industrial ships (Fig. 7). At first, the stock of *capital artisanal* and flow of *harvest a* grow. The fish population drops and at some point the balancing feedback of reduced harvest kicks in by making it more difficult to invest in additional boats. As the oscillations dampen, the fish population and fleet size find equilibrium. At that point, a steady harvest rate can potentially be maintained forever. For centuries, this was indeed the case for fishing industries in the North Sea. However, gradual changes in the *yield per unit capital* have radically altered the outcome as explored earlier.

We now introduce a relatively smaller stock of very efficient industrial ships in the system. We also set higher *capital lifetime* i

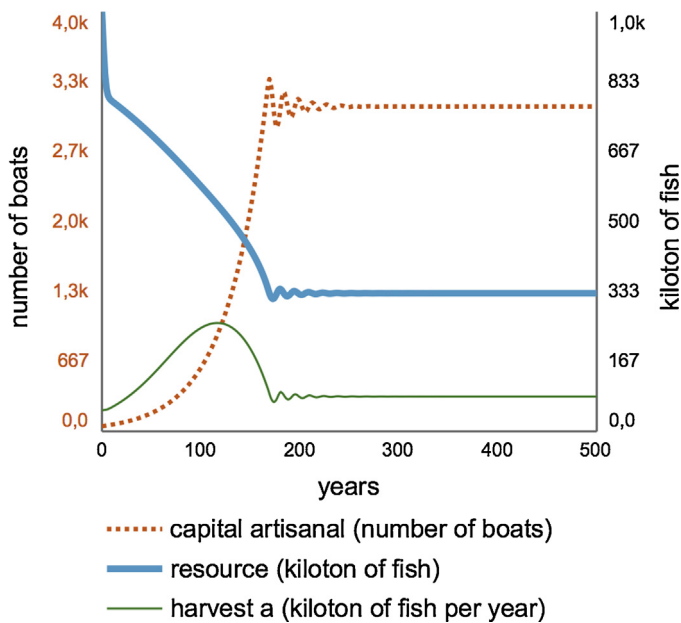


Fig. 7. Artisanal fisheries and sustainable harvest.

and *growth_goal.i* parameters. In the graphs below, the shared *resource* stock falls as both *capital* stocks accumulate. At some point artisanal boats cannot keep up with the falling *resource* stock and the effect this has on the *harvest.a* rate. The more advanced industrial sector is still able to operate despite the falling *resource* stock. As the industrial sector continues to grow, the artisanal sector is disseminated (see Fig. 8b). Typical predator-prey oscillations appear: as *capital.industrial* expands, harvest drops, which temporarily brings down capital, which then raises harvest again (see Fig. 8a)

3.3. Intervention scenarios

Let us now reflect on various possible interventions in the dual fish economy. We translate these leverage points conceptually into variables and feedback loops within our model (see Fig. 10). We start with an unsustainable scenario as shown in Fig. 9. After about 400 years the fish population has been rebuilt, but by then both fishing sectors have disappeared entirely and are not returning. Note that compared to the previous scenario depicted in Fig. 8, we have merely raised the efficiency of industrial ships.

The following intervention scenarios involve adding regulations to industrial fishing in the area. In the absence of industrial ships, artisanal fishing was considered ecologically sustainable (see Fig. 7). As mentioned earlier, we explore the following interventions: (1) a tax levied on the investment in new ships, (2) a quota to cap the fish harvest flow, (3) a tax levied on industry profits, (4) a restriction on building additional ships when catches decline, and (5) setting a fixed amount of ships and restricting further growth.

3.3.1. Investment tax adjustments

One regulatory policy could be to levy an investment tax on new ships (a fraction of *capital.industrial*), thereby raising the cost and curtailing new investments. This could act as a disincentive to overcapitalization and thus to overfish. This translates to adding an *investment_tax* constant, say 3.3%, and a connector to the *investment_rate.i* as shown in Fig. 10. We use the following adjusted settings:

- $\text{investment_rate.i} = \text{capital.industrial} * (1/\text{capital.lifetime.i} + \text{growth_goal.i}) - \text{capital.industrial} * \text{investment_tax}$

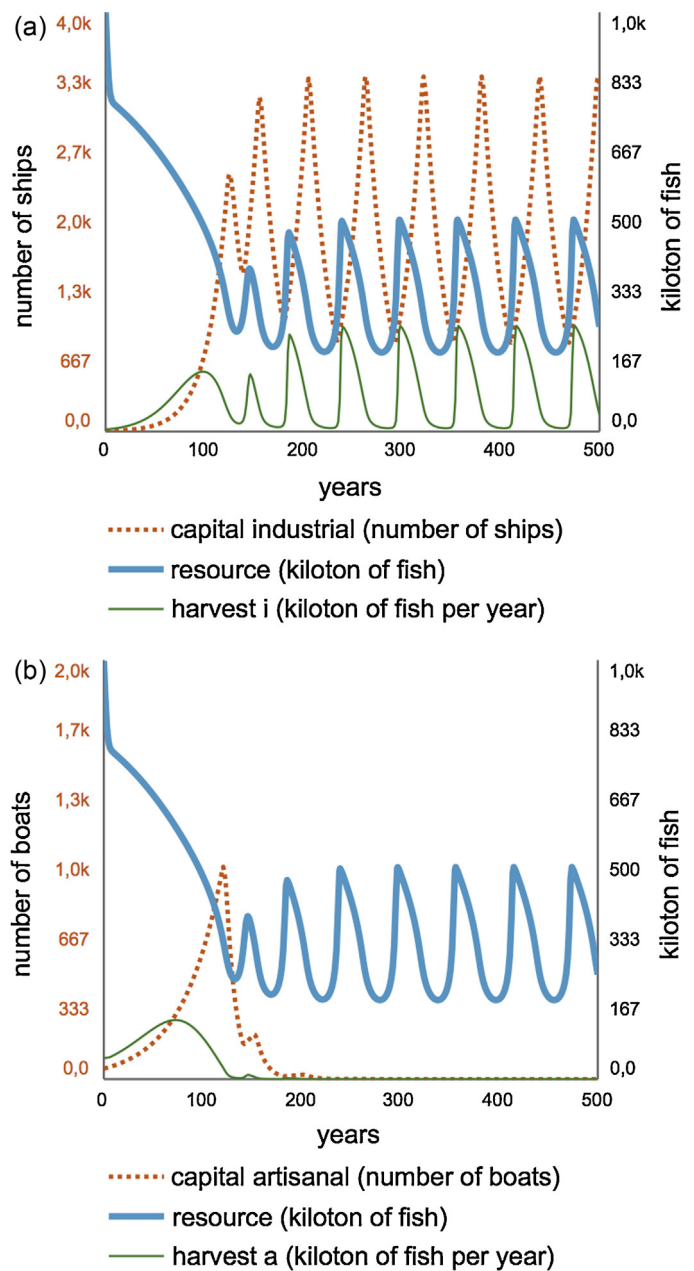


Fig. 8. (a) Industrial fishery capital and harvest. (b) Artisanal fishery capital and harvest.

- initial value for *investment_tax* = 0.033

With the tax, industrial fishing grows at a slower rate, allowing artisanal fishing to establish itself. The graphs in Fig. 11 shows the start of a potentially sustainable scenario for artisanal fishing (resembling, at first, the dynamics of Fig. 7). At some point, however, the size and efficiency of industrial fishing starts to have its effect, ultimately also leading to the (delayed) dissemination of artisanal fishing, which starts well before 200 years (resembling the dynamics of Fig. 8b). Industrial fishing continues to grow and peaks at around 300 years. Harvesting has continued for too long, which takes the *regeneration_rate* over the tipping point (it becomes negative). The industrial sector also collapses. Further increasing the *investment_tax* merely delays the breakdown of both sectors. This policy fails on ecological as well as distributional grounds.

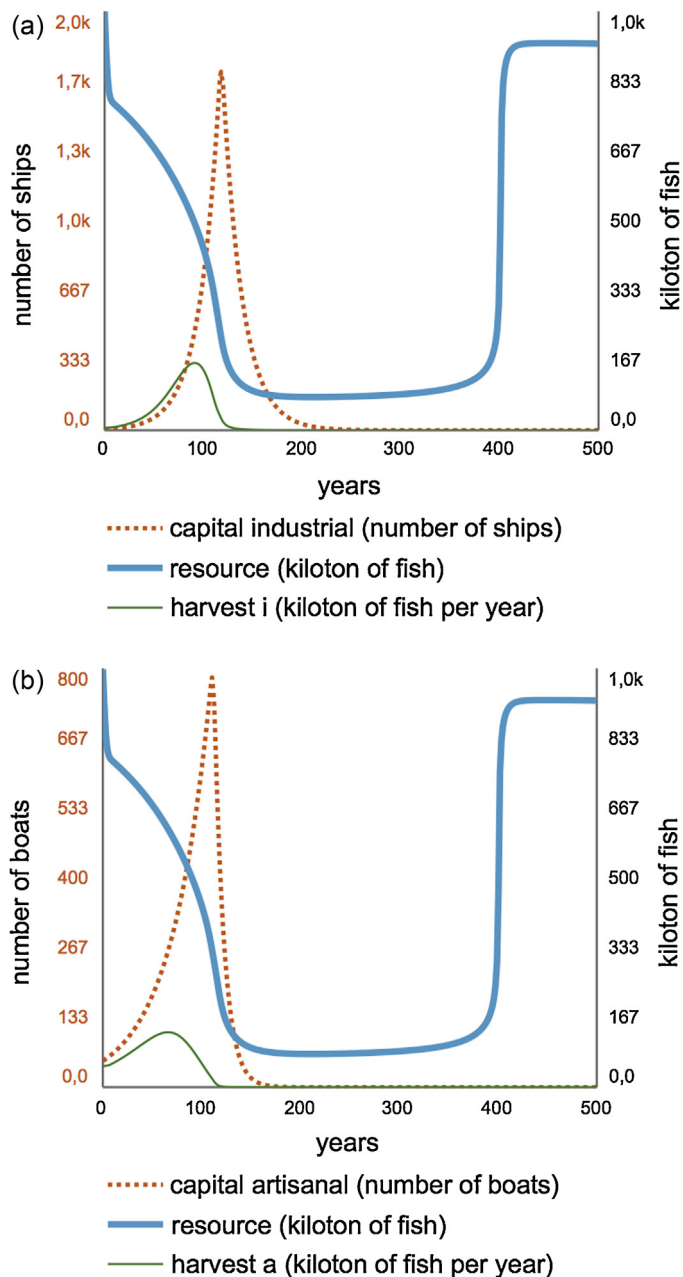


Fig. 9. (a) Unsustainable base scenario, industrial capital. (b) Unsustainable base scenario, artisanal capital.

3.3.2. Harvest restrictions

An alternative policy is to set a maximum fishing quota (restricting the *harvest* flow). We add this policy to our diagram by creating a *quota* constant (see Fig. 10) and connecting it to *harvest.i*. We initially set the quota to 20 kilotons of fish per year. We use the following adjusted settings:

- $\text{harvest.i} = \text{IF } \text{yield_per_unit_capital.i} * \text{capital.industrial} < \text{quota} \text{ THEN } \text{yield_per_unit_capital.i} * \text{capital.industrial} \text{ ELSE } \text{quota}$ (originally $\text{yield_per_unit_capital.i} * \text{capital.industrial}$)
- starting value for *quota* = 20

From an ecological perspective, the policy is only mildly successful, and only at a very low maximum quota; higher values hardly have any effect. The graphs in Fig. 12 show that harvest in the industrial fishing sector indeed stops at the set level. The *resource*

stock doesn't drop too low; *capital* doesn't grow too high. From a distributional perspective, however, both artisanal and industrial fisheries undergo wide fluctuations in the size of their *capital* stocks, which implies unstable employment and income—especially in the artisanal sector.

As could be expected, this policy adjustment is potentially successful if the quota is really low. As shown in Fig. 13, this further reduces the amplitudes, lowers the size of *capital.industrial* considerably (to below 300 ships) and increases the size of *capital.artisanal* (close to 3000 boats).

3.3.3. Revenue tax adjustments

Another regulatory policy takes the form of a tax on the price of fish. This might reduce fishing industry revenue, slow down the expansion of capital and hence slow down overfishing. We add this policy to our diagram by creating a *revenue_tax* constant linked to the profit variable (see Fig. 10). Our system diagram now reflects the fact that the government levies a tax on industry revenue, such as the Value-Added Tax. We set the *revenue_tax* to 40%. We use the following adjusted settings:

- $\text{profits.i} = (1 - \text{revenue_tax}) * \text{price.i} * \text{harvest.i} - \text{investment_rate.i}$
- starting value for *revenue_tax* = 0.4

The *resource* and *capital.industrial* stocks oscillate. The artisanal sector is still disseminated. Further raising the tax dampens the oscillations, which may be better for the stability of employment and lower capital losses in the industrial sector (Fig. 14).

From both an ecological and a distributional perspective, the policy is only mildly successful when the *revenue_tax* is significantly raised to around 65% (Fig. 15). However, *capital.artisanal* is considerably smaller (650 boats) compared to a situation without an industrial sector. If the tax is raised beyond this level, the industrial fishing sector becomes unviable and disappears, which defeats the purpose of the intervention.

3.3.4. Capital investment restrictions

Another possible policy alternative is to stop building ships once there is a noticeable problem with the fish population. Since the only feedback signal from the fish population that fishermen receive is from the fish catch (*yield_per_unit_capital.i*), the policy could make building ships illegal once the yield per ship decreases to a particular rate. We add the feedback in the diagram by adding a connector from the *yield_per_unit_capital.i* to *investment.i* (see Fig. 10). Shipbuilding must be limited when the yield drops below 0.05 kilotons of fish per year (a *yield_threshold* constant). We use the following adjusted settings:

- $\text{Investment.i} = \text{IF } \text{yield_per_unit_capital.i} > \text{yield_threshold} \text{ THEN } \text{MIN}(\text{profits.i}, \text{investment_rate.i}) \text{ ELSE } 0$ (originally $\text{MIN}(\text{profits.i}, \text{investment_rate.i})$)
- starting value for *yield_threshold* = 0.05
- Note that this also means that the investment will be the minimum of profit or investment_rate. In other words, if profits are lower than the investment_rate then the industry invests whatever it can (in this case, all of its profits).

The policy is somewhat successful for industrial fishing (Fig. 16). The outcome eventually resembles the oscillations of the predator-prey scenario (Fig. 4), which is potentially unstable, so there is room for improvement from an ecological perspective. With higher and lower growth goals, the oscillations start earlier/later and the amplitude is wider/narrower, respectively. Moreover, by raising the minimum *yield_threshold*, the amplitude of the oscillations become narrower. From a distributional perspective, however, there has been no benefit. Artisanal fishing remains disseminated,

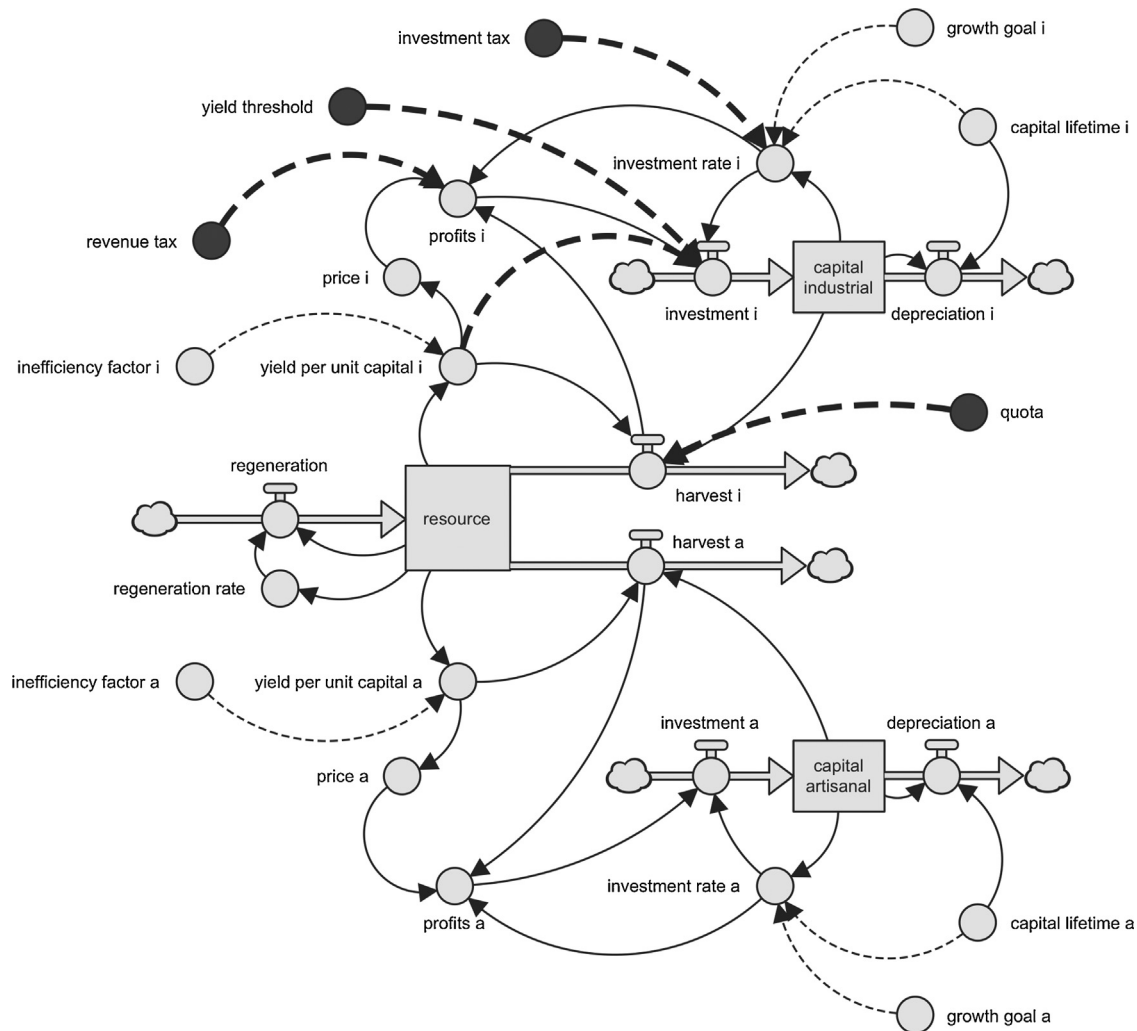


Fig. 10. Policy interventions in the dual fishing economy.

unless the *yield_threshold* is raised high enough, in which case both fishing sectors could potentially co-exist (Fig. 17).

This policy relies on the assumptions that *yield_per_unit_capital* is an accurate indication of the state of the *resource* stock and that a drop in yield would give sufficient warning long before a catastrophe. The problem is that the system might be sensitive to initial conditions. When lowering the minimum *yield_per_unit_capital* below 0.06 kilotons of fish per year, we see wider and deeper oscillations. As before, there is resilience in the system, but the system can also go over a “tipping point” with the slightest further push, which makes the policy quite risky.

3.3.5. Capital growth rate restriction

Our last policy alternative is to restrict the growth in the number of industrial fishing ships in the area. The *growth_rate_i* is set to zero and the industrial fishing *capital* stock is set to, say, 500 ships. The intervention is successful from both perspectives (Fig. 18). Of course, removing the industrial sector entirely would raise the number of artisanal boats from 2000 to 3100.

4. Conclusions and discussion

Modelling exercises are never a perfect representation of reality, but offer valuable insight into the dynamics of complex systems with multiple interacting components. In this case, an economy and an ecosystem were investigated with a special focus on ecological

and equitable management. Although the dynamics investigated here have been explored before, the incorporation of mathematically defined distributions makes the exploration much more robust and effective. The relative ease of modification of this modelling solution facilitates comparison between scenario's, for example to investigate the potential effects of policy interventions. This is especially useful in the STELLA modelling environment, in which a parameter can be manipulated with real-time system-wide recalculation of its effects.

From an ecological perspective, we were inspired by the implementation of policy interventions in a stock-flow model in Whelan (1994). By further adapting the model to include a dual capital stock structure, we assessed the success of these policies on distributional as well as ecological grounds. The outcomes of the policy interventions are summarized in Table 1.

In our model, investment tax adjustments were unsuccessful on both fronts. The dissemination of artisanal fishing is unavoidable, and an investment tax simply delays the collapse of the fish population. Moreover, in the current global market economic system, it is likely that such a tax would be transferred onto consumers, which might lead to import of cheaper fish (overfishing elsewhere). Harvest restrictions in our model are potentially successful, but only at very stringent quotas, which radically reduces the size of capital of the industrial sector. As we know, there are already tremendous difficulties in agreeing upon a weak quota system. Revenue tax adjustments are unsuccessful and generate wide fluctuations

Table 1
Summary of policy interventions.

Policy intervention	Model adjustment	Change relative to baseline scenario
Investment tax adjustments (a tax levied on the investment in new ships)	Add an <i>investment_tax</i> constant and connect it to <i>investment_rate.i</i>	Industrial fishing grows at a slower rate. Artisanal fishing establishes itself and temporarily stabilises, but is eventually decimated. As in the baseline, industrial fishing grows and eventually overfishes the resource.
Harvest restrictions (a quota to cap the fish harvest flow)	Add a <i>quota</i> constant and connect it to <i>harvest.i</i>	The intervention is ecologically successful at low maximum quota. Distributional problems remain as capital fluctuates, which corresponds with unstable income, particularly in the artisanal sector.
Revenue tax adjustments (a tax levied on industry profits)	Add a <i>revenue_tax</i> constant and connect it to <i>profits.i</i>	Resource and industrial capital stocks oscillate. The artisanal sector is disseminated. Higher taxes dampen oscillations and even higher taxes allows for a (very small) artisanal sector to survive.
Capital investment restrictions (a restriction on building additional ships when catches decline)	Add connector from <i>yield_per_unit_capital.i</i> to <i>investment.i</i> . Add <i>yield_threshold</i> and connect <i>investment.i</i> .	Oscillations comparable to predator-prey dynamics occur with potential stabilisation by adjusting the capital growth goal. Raising the yield threshold also narrows oscillation, but artisanal fishing is still disseminated.
Capital growth rate restriction (setting a fixed amount of ships and restricting further growth)	<i>growth_rate.i</i> is set to zero and <i>capital.i</i> is set to 500.	The intervention is successful from both ecological and distributional perspectives. Lowering the number of industrial ships creates space for the artisanal fishing sector to expand.

unless the tax is substantial. Capital restrictions were somewhat successful, but led to oscillations. In reality, it would only work if all countries adopt such a policy. Other practical challenges would be to collect data on the catch per boat and to prove the relationship between a drop in yield and the growth of capital. Capital growth restrictions is perhaps the most clear-cut intervention and is potentially successful from both ecology and equity perspectives. A challenge in practice would be to set an acceptable stock size of industrial ships, as there will be a consequent reduction in economic opportunities for local fisheries.

Interventions are 'ecologically successful' only when the accumulation of physical capital comes to a halt at a particular size and yield that is in balance with the size and regeneration of the resource stock. At that point, there is insufficient profit to invest in new ships; there is only enough to compensate for their depreciation. This state represents dynamic equilibrium in the system. In reality, of course, this is unlikely to occur unaided. A population of predators in an ecosystem naturally declines after prey decreases, but in an economy, it can find other sources of investment to increase yield outside of its 'biome' (of fishery). Our dominant economic system does not just promote growth, it "can no more be 'persuaded' to limit growth than a human being can be 'persuaded' to stop breathing" (Bookchin, 1990, 94). This seems to imply that in the absence of very fundamental systemic changes, ecological harm is likely to be perpetuated as well.

Several observations can also be made in relation to the three inequities brought up by the dual capital framework (Rammelt and Boes, 2013). First, the unequal distribution of ownership is reflected not necessarily in the total number of industrial ships versus artisanal boats, but in their relative efficiencies—in other words, in the qualities of the two capital stocks. The artisanal sector can potentially survive when the physical size of the industrial sector, its growth rate and/or its productivity are kept within bounds. A second form of inequity exists in terms of access to the benefits and services generated by capital, including food security as well as employment and income stability. The capital stock fluctuations that occur in some of our scenarios could be used as an indicator for employment instability, as in the capital investment restrictions scenario for example (Fig. 17). Resource stock fluctuations on the other hand have a bearing on the instability of food security. We have explored how these can sometimes be dampened by policy interventions. The third form of inequity is that of control over maintenance and investment, i.e., over the inflow into

the capital stock. It is the most significant inequity, because this is where the system is being regulated and where the other inequities (ownership and entitlement) can either be reinforced or potentially reduced. As long as this inequity persists, interventions may not be geared at maintaining a vibrant artisanal sector.

While it can potentially be applied to other cases of political ecology or environmental injustice, our system diagram is also clearly incomplete. One limitation, for example, is that rising profit follows from rising price, which implies that consumers keep buying fish even as it becomes more expensive. In reality, there are substitutes for overpriced fish and demand might drop. In an adapted model, price would not be directly linked to profit, but to a supply and demand sub-model that in turn regulates prices (Whelan and Msefer, 1996). Such an expansion of the model would allow for testing demand-side intervention scenarios. An adapted model would also have to consider (global) income distribution patterns. A rising price for rare fish delicacies might not stop their impending extinction as long as the higher income brackets keep rising too.

Other feedback mechanisms could also be added. A blatant illustration of the incapacity of the market to solve the overfishing problem was reported a few years ago. A corporation within Mitsubishi conglomerate began importing large amounts of Bluefin tuna from Europe, despite stocks plummeting towards extinction in the Mediterranean. The fish was then frozen to be sold for astronomical sums if Atlantic Bluefin becomes extinct as forecast (Hickman, 2009). For our model, this means an additional feedback loop: as the depletion of the resource stock becomes more imminent exorbitant future profits can be expected, as a result of which the industry actually increases the harvest, making collapse even more imminent.

In terms of policy, other interventions are also worth considering. For example, certain nets have a mesh-size that allows undersized fish to escape and grow to maturity. In order to reduce overharvesting in certain places in Alaska, fishing regulations require the replacement of undetectable gill nets with nets that the fish can actually see. These restrictions do not stop boats from tracking down fish populations, but they do impose restrictions on the harvesting process. This means that some part of the resource stock always remains unharvested, thus protecting a lower-limit regeneration capacity of the fishing stock and increasing the recovery rate. Marine protected areas could also serve this purpose. Minimum mesh-size fishing is also interesting because it aims to leave

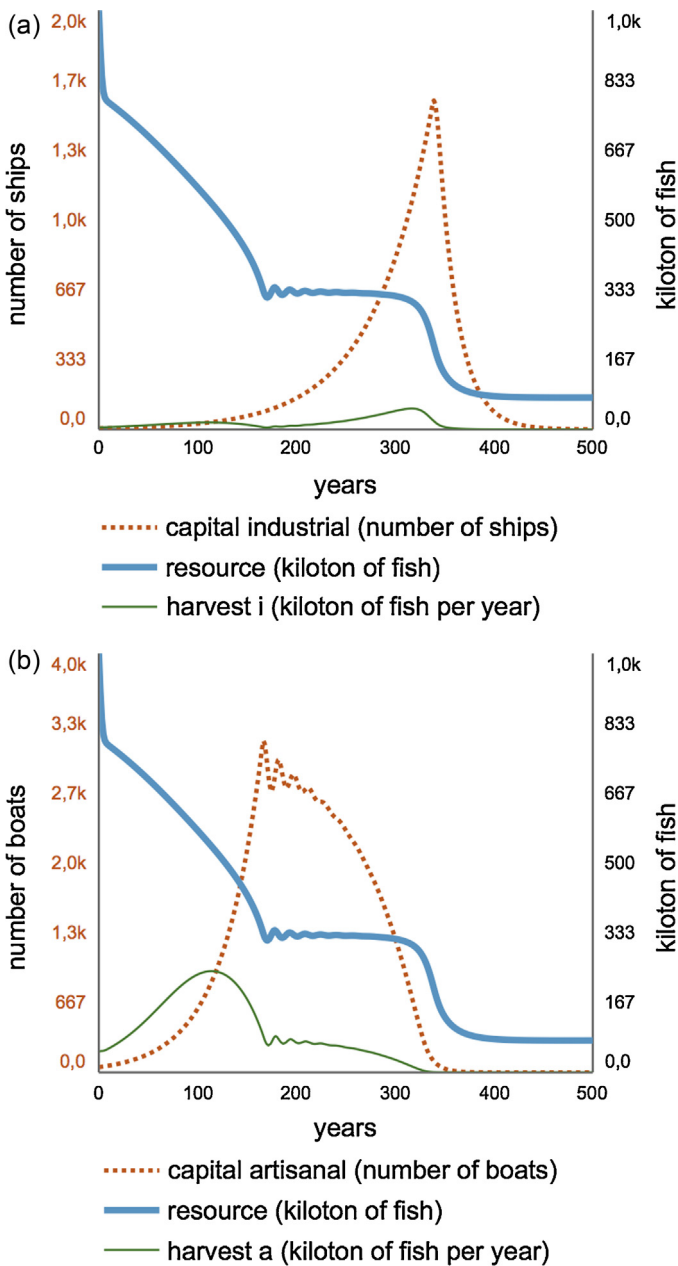


Fig. 11. (a) Investment tax intervention scenario, industrial capital. (b) Investment tax intervention scenario, artisanal capital.

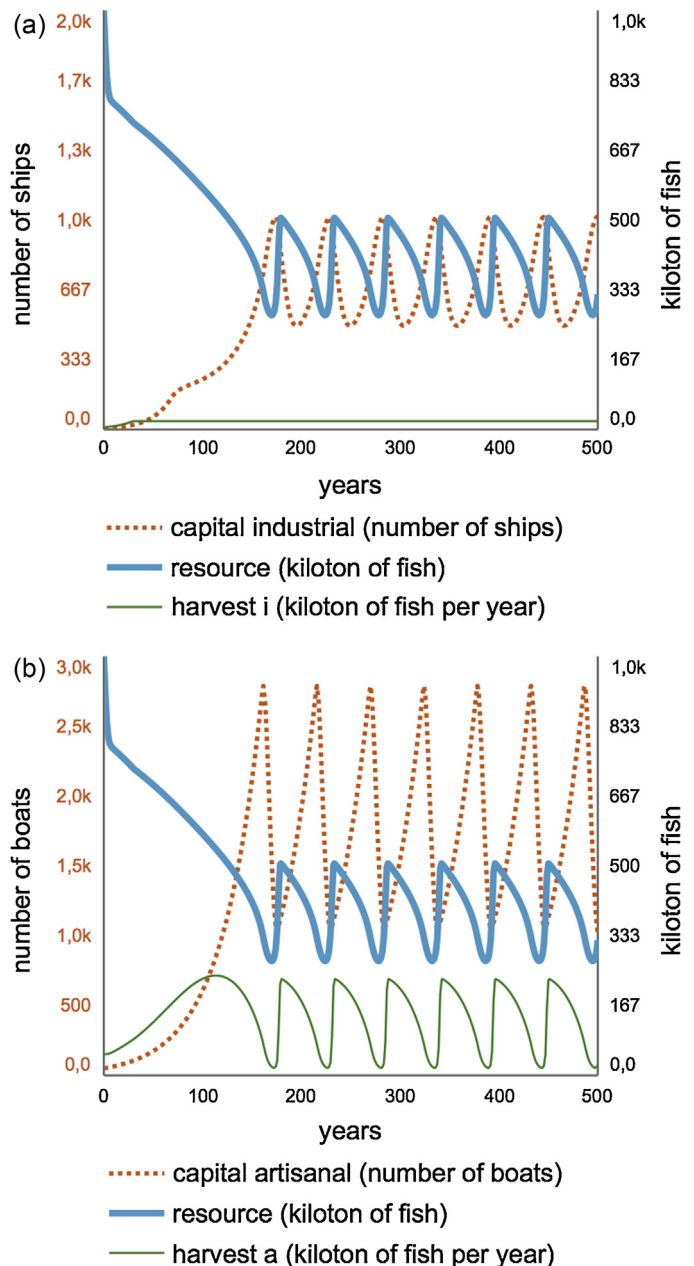


Fig. 12. (a) Harvest restrictions intervention scenario, industrial capital. (b) Harvest restrictions intervention scenario, artisanal capital.

a so-called spawning stock intact. For our model, we could add such a stock that would contribute to the regeneration of the total stock, but that would not have an outflow of harvest. The total fish population would never drop below a certain level and the regeneration rate would never get too low.

It is important to remember that the outcome of the interventions in the model is dictated by the structure of the simplified system diagram and the way the interventions are added to it. The real challenge is always to test them in practice, to devise and adopt a policy that combines interventions, implement a monitoring system, observe and learn from practice, adjust or abandon the policy, etc. Although we need models to predict the outcome of changes to the system, and although policy makers may expect useful predictions of the behaviour of natural resources under stress, many such resources unfortunately behave in a complex manner. The modeller is therefore always confronted with the dilemma between representativeness (of the system) and representability (to the policy

maker). One cannot hope to model all fish populations in all marine environments with all their peculiar life cycles, regeneration rates and so on, while at the same time still provide urgently needed and digestible insights to policy makers.

Appendix A. Equations

Base model

```
capital_artisanal(t) = capital_artisanal(t - dt) + (investment_a
- depreciation_a) * dt
INIT capital_artisanal = 50
INFLOWS:
investment_a = MIN(profits_a, investment_rate_a)
OUTFLOWS:
depreciation_a = capital_artisanal/capital_lifetime_a
```

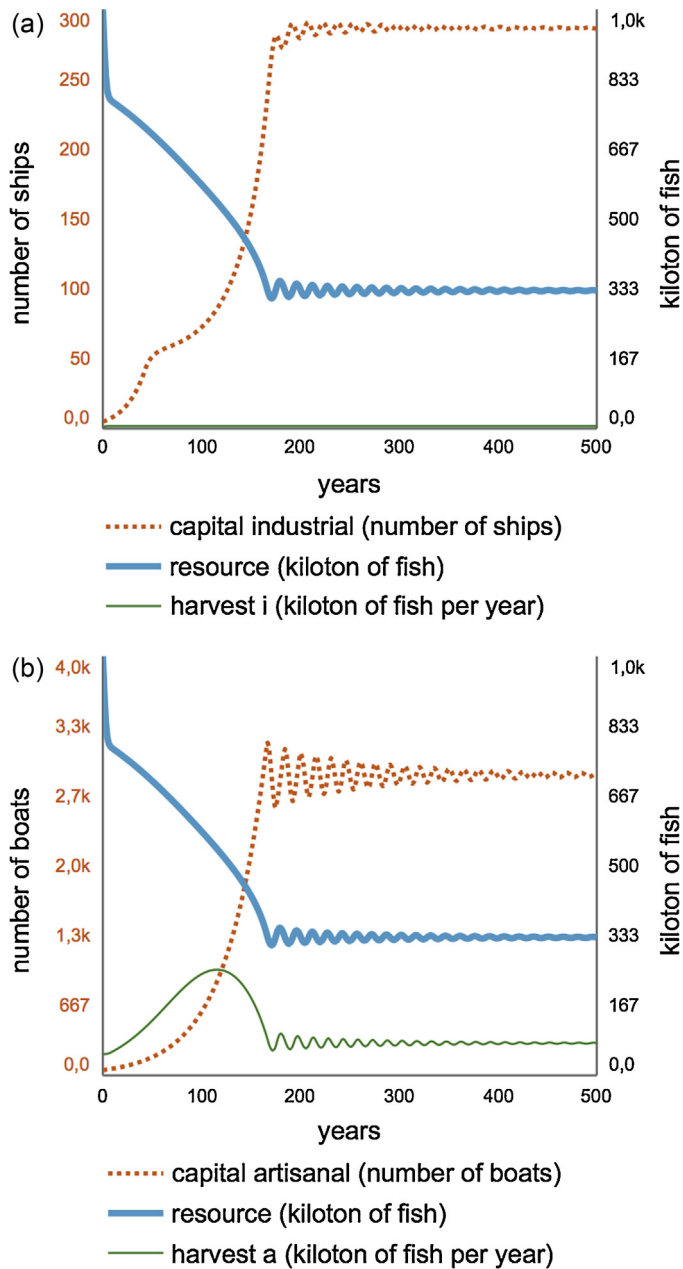



Fig. 13. (a) Harvest restrictions intervention scenario, highly restrictive quota, industrial capital. (b) Harvest restrictions intervention scenario, highly restrictive quota, artisanal capital.

```

capital_industrial(t) = capital_industrial(t - dt) + (investment_i
- depreciation_i) * dt
INIT capital_industrial = 5
INFLOWS:
investment_i = MIN(profits_i, investment_rate_i)
OUTFLOWS:
depreciation_i = capital_industrial/capital_lifetime_i
resource(t) = resource(t - dt) + (regeneration - harvest_i
- harvest_a) * dt
INIT resource = 1000
INFLOWS:
regeneration = resource * regeneration_rate
OUTFLOWS:
harvest_i = yield_per_unit_capital_i * capital_industrial

```

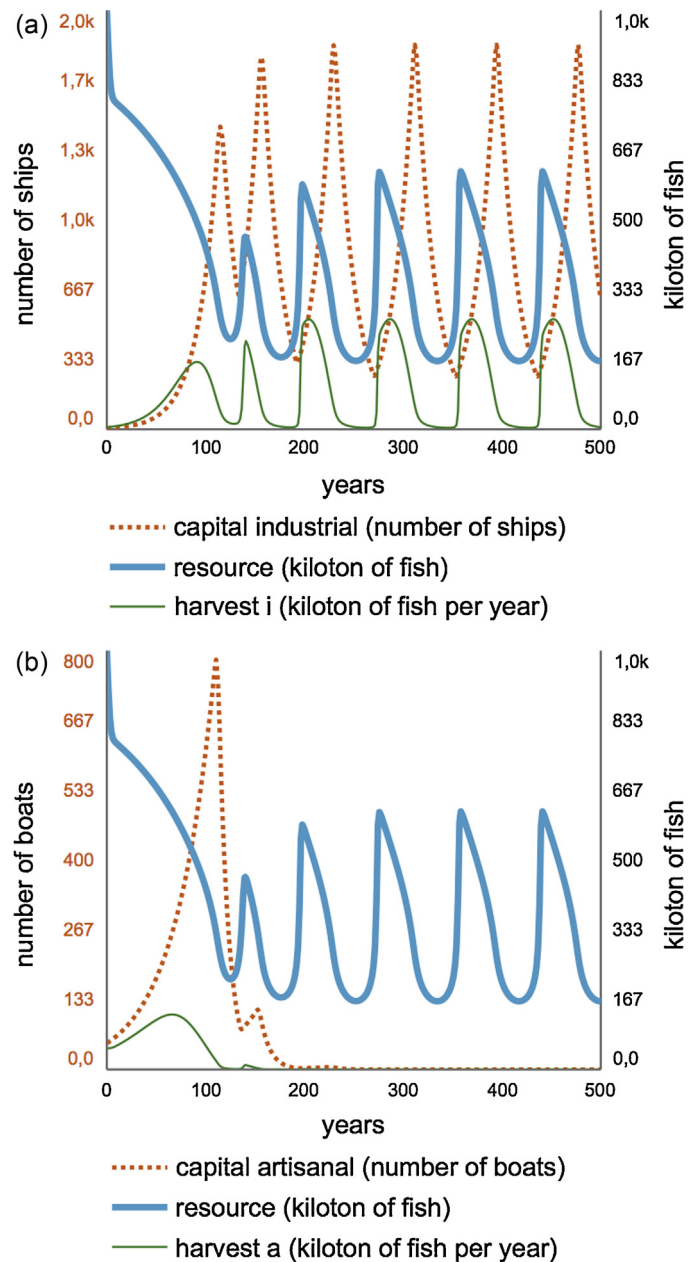


Fig. 14. (a) Revenue tax intervention scenario, industrial capital. (b) Revenue tax intervention scenario, artisanal capital.

```

harvest_a = yield_per_unit_capital_a * capital_artisanal
capital_lifetime_a = 10
capital_lifetime_i = 20
growth_goal_a = 0.025
growth_goal_i = 0.05
inefficiency_factor_a = 590
inefficiency_factor_i = 540
investment_rate_a = capital_artisanal * (1/capital_lifetime_a
+ growth_goal_a)
investment_rate_i = capital_industrial * (1/capital_lifetime_i
+ growth_goal_i)
price_a = IF yield_per_unit_capital_a > 0 THEN
1/(0.1 + yield_per_unit_capital_a/1.4) ELSE 10
price_i = IF yield_per_unit_capital_i > 0 THEN
1/(0.1 + yield_per_unit_capital_i/1.4) ELSE 10
profits_a = price_a * harvest_a - investment_rate_a
profits_i = price_i * harvest_i - investment_rate_i

```

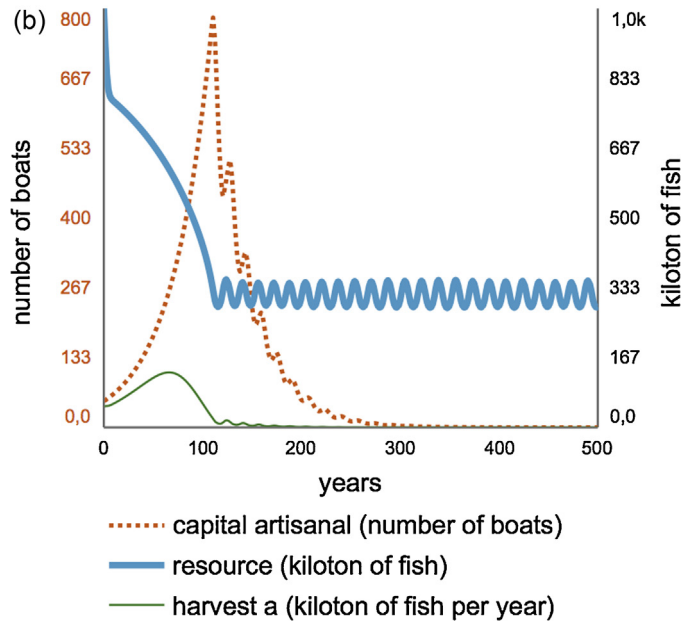
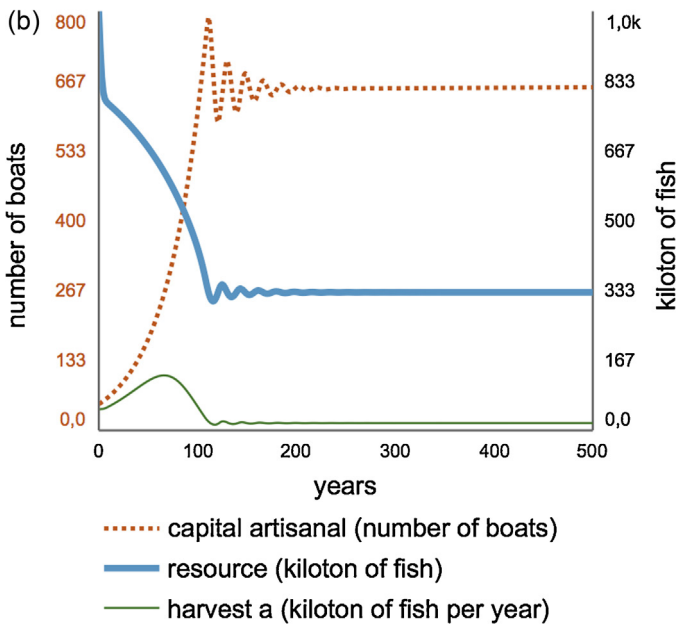
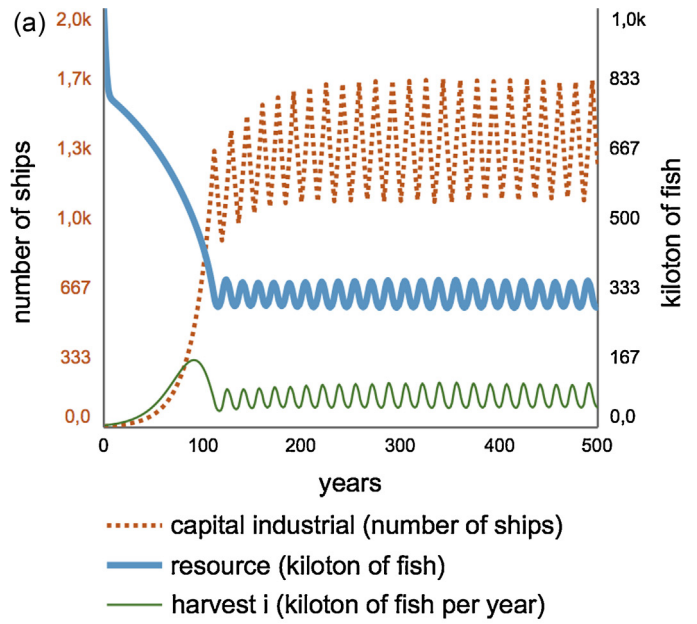
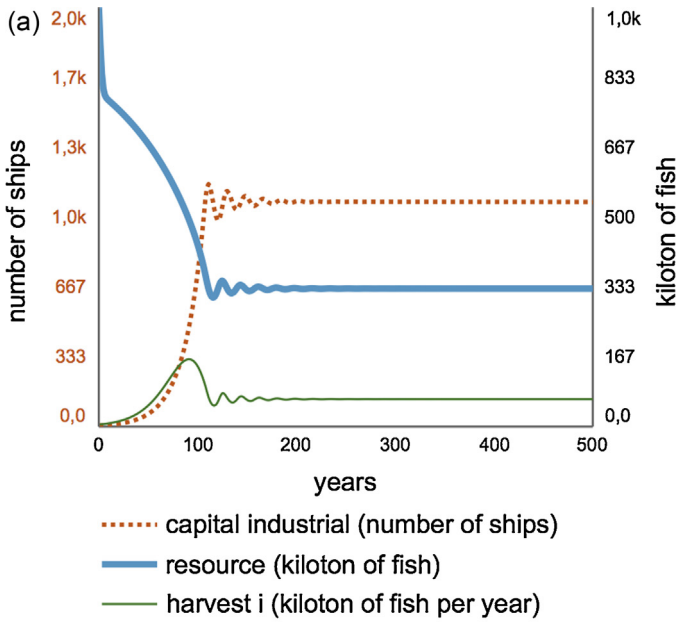


Fig. 15. (a) Revenue tax intervention scenario; high tax, industrial capital. (b) Revenue tax intervention scenario; high tax, artisanal capital.

Fig. 16. (a) Capital investment restrictions intervention scenario, industrial capital. (b) Capital investment restrictions intervention scenario, artisanal capital.

```

regeneration_rate = IF resource > 0 THEN
0.5 * EXP(-((resource - 500)^2)/(2 * 150^2)) - 0.5 * EXP(-300^2/150^2)
ELSE 0
yield_per_unit_capital_a = 1/(1 + EXP(-2 * PI * (resource
- inefficiency_factor_a)/500))
yield_per_unit_capital_i = 1/(1 + EXP(-2 * PI
*(resource - inefficiency_factor_i)/500))

```

Policy model

```

capital_artisanal(t) = capital_artisanal(t - dt) + (investment_a
- depreciation_a) * dt
INIT capital_artisanal = 50
INFLOWS:
investment_a = MIN(profits_a, investment_rate_a)
OUTFLOWS:

```

```

depreciation_a = capital_artisanal/capital_lifetime_a
capital_industrial(t) = capital_industrial(t - dt) + (investment_i
- depreciation_i) * dt
INIT capital_industrial = 5
INFLOWS:
investment_i = IF yield_per_unit_capital_i > yield_threshold THEN
MIN(profits_i, investment_rate_i) ELSE 0
OUTFLOWS:
depreciation_i = capital_industrial/capital_lifetime_i
resource(t) = resource(t - dt) + (regeneration - harvest_i
- harvest_a) * dt
INIT resource = 1000
INFLOWS:
regeneration = resource * regeneration_rate
OUTFLOWS:

```

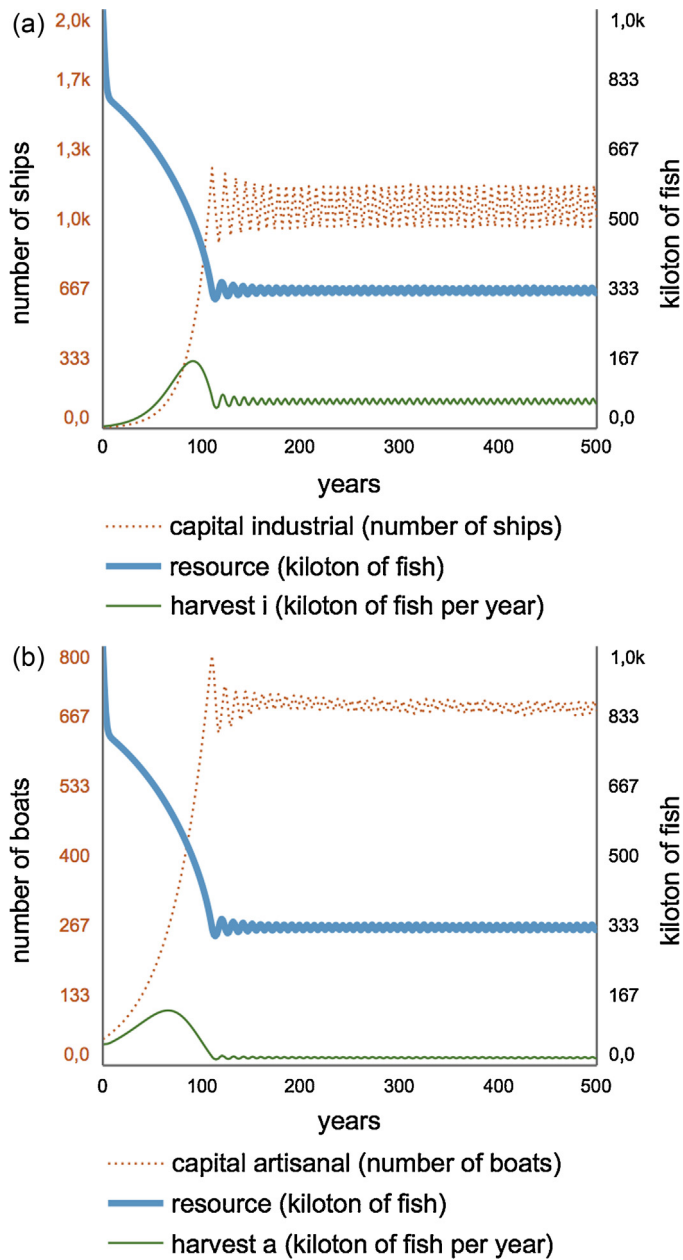


Fig. 17. (a) Capital investment restrictions intervention scenario, high yield_threshold, industrial capital. (b) Capital investment restrictions intervention scenario, high yield_threshold, artisanal capital.

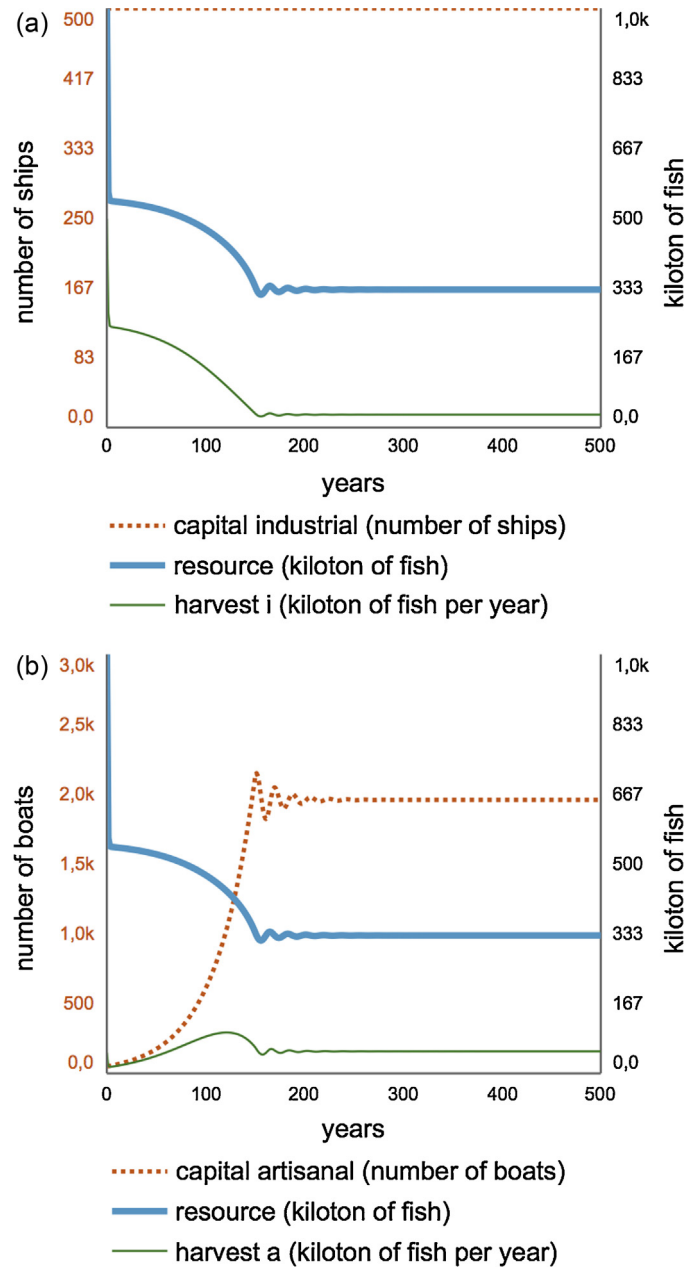


Fig. 18. (a) Capital growth intervention scenario, industrial capital. (b) Capital growth intervention scenario, artisanal capital.

```

harvest_i = IF yield_per_unit_capital_i * capital_industrial < quota
THEN yield_per_unit_capital_i * capital_industrial ELSE quota
harvest_a = yield_per_unit_capital_a * capital_artisanal
capital_lifetime_a = 10
capital_lifetime_i = 20
growth_goal_a = 0.025
growth_goal_i = 0.05
inefficiency_factor_a = 615
inefficiency_factor_i = 546.6
investment_rate_a = capital_artisanal * (1/capital_lifetime_a
+ growth_goal_a)
investment_rate_i = capital_industrial * (1/capital_lifetime_i
+ growth_goal_i) - capital_industrial * investment_tax
investment_tax = 0.033 or more
price_a = IF yield_per_unit_capital_a > 0 THEN
1/(0.1 + yield_per_unit_capital_a/1.4) ELSE 10

```

```

price_i = IF yield_per_unit_capital_i > 0 THEN
1/(0.1 + yield_per_unit_capital_i/1.4) ELSE 10
profits_a = price_a * harvest_a - investment_rate_a
profits_i = (1 - revenue_tax) * price_i * harvest_i - investment_rate_i
quota = 20 or less
regeneration_rate = IF resource > 0 THEN
0.5 * EXP(-(resource - 500)^2/(2 * 150^2)) - 0.5 * EXP(-300^2/150^2)
ELSE 0
revenue_tax = 0.4 or more
yield_per_unit_capital_a = 1/(1 + EXP(-2 * PI * (resource
- inefficiency_factor_a)/500))
yield_per_unit_capital_i = 1/(1 + EXP(-2 * PI * (resource
- inefficiency_factor_i)/500))
yield_threshold = 0.05 or more

```

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