A basis for understanding fishery management dynamics

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Abstract

Fishery management complexity conspires to defeat seemingly obvious solutions to overfishing. Management may not adequately include decisions of fishers, management, and politicians. A new, simple, but acceptably complex fish population model is meshed with both fishery activities and management decision making. The population component is based on the common single stock biomass dynamic model. Modifications allow biomass feedback on rates of addition to the stock due to growth and to entry of young fish. Delayed and seasonal entry of new fish biomass is possible. A co-flow structure tracks age of biomass without using cohorts. Fishers enter the fishery only if catch rates are sufficiently high. When catch rates are low fishers improve their efficiency. Excessive fishing damages ecosystem support of the fish population. Managers attempt to maintain fish stocks at acceptable biomass levels, but lobbying by fishers and varying support of politicians limits their efforts.

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Introduction

Many fisheries are seriously over-harvested, including those in countries with well-developed fishery management institutions. Canadian cod fisheries have not recovered from a collapse and closure of the fishery in 1992 (Mason, 2002; Roy, 1996; Schrank, 2005). Closures in the North Sea have also been implemented (Malakoff and Stone, 2002). In international waters major fishery declines of top predator species like tuna have been attributed to overfishing (Myers and Worm, 2003; Sibert *et al.*, 2006; Ward and Myers, 2005). The U.S. government has determined that 33 percent of its commercial fish stocks of known status were overfished (National Marine Fisheries Service, 2002), and over 80 marine fish species or stocks are vulnerable, threatened, or endangered with extinction from North American waters (Musick *et al.*, 2000).

The affected countries include those with sophisticated scientific communities dedicated to good fisheries management. Members of these communities, most members of the fishing industry, as well as political and governmental entities involved in fisheries, strive to make good decisions. Yet these decisions have largely failed to prevent overfishing.

Is scientific information lacking? Although good data are essential, it is unlikely that even more data will lead to significantly better decisions. In fact,

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some of the best biological and statistical information is associated with collapsed fish stocks (e.g., cod). In any case, we can't expect to have perfect knowledge for all fish stocks on a timely basis. In the U.S.A., sufficient data exist to determine abundance in only about one third of the 959 identified commercial fish stocks. In 2002 data regarding abundance, or fishery status, were available for only 40 percent of "major stocks" (National Marine Fisheries Service, 2002).

Many authors have examined causes of fishery management failure. Some have focused on highly variable climatic mechanisms affecting fish stocks (Cushing, 1982; King and McFarlane, 2006; Rothschild *et al.*, 2005; Yndestad and Stene, 2002). Others have examined delays in decision making, such as failure to implement needed restrictions on fishing in a timely manner due to social or economic pressures (Caddy, 2002; Jackson *et al.*, 2001). The complex mixture of biophysical and socio-economic elements is difficult to envision holistically. Management decisions tend to focus on desired short-term outcomes. This focuses management's interest on near-term fish stock size and the immediate income needs of the fishing community.

Inevitably, unintended consequences arise from these short-term decisions. One overriding influence derives from the lag times needed for consequences of actions to appear. Fishery overcapacity precedes evidence of overfishing. Excessive fishing capacity is then supported by economic and associated sociopolitical concerns. Actions to lower capacity become problematic. If the fishery rebounds, additional overcapacity develops (Hennessey and Healey, 2000; Ludwig *et al.*, 1993). Declining catches, and fishery restrictions, stimulate more effective fishing strategies. As catch rates decline, the rate of violation of regulations may increase as fishers try to maximize their ability to pay off debts in a declining industry. Such violations create unreported catches, decreasing the reliability of fishery data which are the basis for management decisions. Such feedbacks conspire to defeat the good intentions of decision makers.

Jentoft and Mikalsen (2004) report that the very complexity of the system contributes to its failure, and the creation of ever more regulation. Healey and Hennessy (1998) noted that efforts to make regulations more equitable increased special regulations for particular user groups, which made enforcement more complex and difficult, and further increased non-compliance. As the system becomes more complex uncertainties increase, making desirable outcomes less likely.

An increasingly complex decision-making environment also increases the likelihood of litigation. This causes, at best, longer time lags in imposition of regulations, and at worst proposed regulations are reversed, causing additional uncertainty for both regulators and fishers. In the U.S.A. in the 1970s and 1980s only one or two court challenges were made to governmental fishery rulings annually, but in the late 1990s this rose to more than 10 per year, reaching over 20 in 2001 (Gade *et al.*, 2002).

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Uncertainty in ecological and climatic variables affecting fish stocks is an additional complication for fishery managers. Inherent ecological variability in fish reproduction leads to a situation whereby fishing increases the likelihood of variability in the fish stocks (Hsieh *et al.*, 2006). While improved analytical techniques enhance our ability to predict probable outcomes of management decisions, the realistic incorporation of uncertainty into the management regime is still problematic (Charles, 1998; Cochrane, 1999; Lane and Stephenson, 1998). Lauck (1996) investigated the use of hedging in fishery management, but the increasing complexity of fishery management systems conspires to limit such options to address uncertainty. The multiplicity of regulations under complex management regimes can limit fishers' options to counteract uncertainty (Hilborn *et al.*, 2001). Increased uncertainty requires significantly lowered allowable catches (Walters and Pearse, 1996), but these may be politically difficult to implement.

As Gade *et al.* (2002: xi) state, discussing problems in the U.S.A., "In a real sense, the fisheries management system is in disarray. Management is increasingly exercised by the courts through litigation, by Congress through its annual appropriations and reports, and by constituencies that seek redress through these forums."

The need to examine fishery systems holistically has been pointed out by several authors. Walters (1980) highlighted the importance of viewing fisheries as dynamic systems with interacting biological, political, social, and economic components. Anderson (1984, 1987), in his discussion of "bioregunomics", specifically included lobbying of fisheries agencies by industry to influence policy, as well as the function of courts as arbiters, as part of a needed new paradigm for fishery management. Charles (2001) examined the concept of fishery systems, and included in that concept management decisions and the response of fishers to them.

Fishery managers are aware of problems of complexity in the decision-making system and decision makers are extending their analyses beyond bio-economic issues. There is an opportunity to modify management approaches to address issues created by the complexity and uncertainty inherent in the fishery management system. To do this several questions must be answered: How can fishery decision-making systems best be analyzed? How can these analyses sufficiently account for complexity and uncertainty, and still provide meaningful, sufficiently detailed decision and policy direction? How can the complex consequences of management decisions be better anticipated by inclusion of factors beyond the realm of fish population biology?

The model

There is a need for models that allow us to examine complex fishery issues in a transparent and understandable manner without becoming overly focused

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on details of population dynamics. Fishery modeling for stock assessment is a technical field using many specialized models which are not appropriate for building group understanding. The model presented here provides a general framework for examining the many interacting factors that make successful management of open access fisheries difficult. Hopefully it will stimulate others toward further investigation of these issues.

The purpose of this paper is not stock assessment, but it is nevertheless worthwhile to have a standardized starting point for the biological aspects of such a model. The Schaefer biomass dynamic model and its modifications are well known in fisheries, and are easily put into a system dynamics format. A series of modifications to this basic model can allow us to examine the effects of various fishery management policies within a complex but understandable framework. The model does not focus on details of population dynamics, but does address some needed modifications to the basic model. The modified model is then used as a starting point for examining some of the complex interactions between social, political, economic, and environmental issues affecting fisheries. System dynamics modeling can supply the needed framework for doing this. Previous applications of system dynamics modeling to fisheries have examined competition among fishers (Scheffran *et al.*, 2006), shrimp commodity cycles (Arquitt *et al.*, 2005), strategic planning for fisher groups (Otto and Struben, 2004), management of specific fisheries (McGlade, 1989; Wakeland *et al.*, 2003), understanding of resource management concepts (Moxnes, 2000), simple versus complex models (Moxnes, 2005), illustration of the value of system dynamics modeling (Dudley and Soderquist, 1999), and a variety of related issues (Ruth and Lindholm, 2002).

The basic model

The model developed here is based on the biomass dynamic model (Graham, 1935; Schaefer, 1954, 1957), which equates the rate of change of population biomass to biomass inflows minus biomass outflows.[1] From a system dynamics perspective it is best written as

$$\frac{\mathrm{d}B}{\mathrm{d}t} = rB - rB\frac{B}{k} - qEB$$

Increase in population biomass is a single inflow due both to growth and to the addition of new fish. It is equal to the biomass fractional growth rate r times the existing biomass B. Natural decrease in biomass is indicated by $-rB$ multiplied by the ratio of B to k, where k is the maximum possible population biomass. This causes fractional natural death rate to decline as biomass declines.[2] The outflow of population biomass caused by the catch is indicated by the instantaneous fraction of fish biomass caught by each unit of fishing gear q, times the number of gear units[3] E, times the biomass B.

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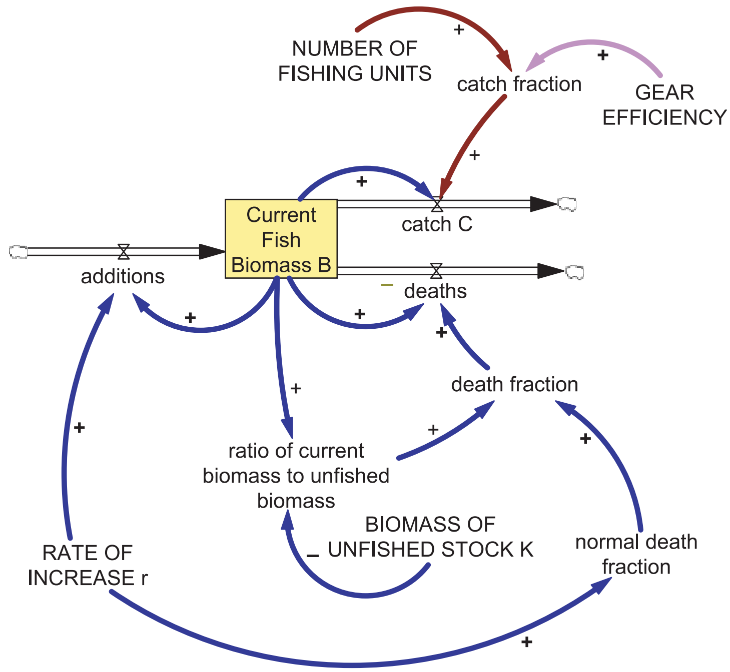

Fig. 1. The original biomass dynamic model as implemented for system dynamics use. Gear efficiency is the fraction of the current biomass that could be caught by a single fishing unit each year. The biomass of the unfinished stock represents the carrying capacity for that stock in the ecosystem

In system dynamics format the model is as illustrated in Figure 1. There is a difference in philosophy between the original formulation and the system dynamics approach. System dynamics models emphasize change over time, and the system dynamics modeler generally attempts to visualize each component of a model separately and define a structure linking components. Mathematical modelers, on the other hand, strive to develop a summary equation that will calculate an answer for a particular set of inputs. The biomass dynamic model was originally developed to calculate equilibrium yields under given conditions and was not intended as a structural model of a fish population.[4] However, it has been applied in other analysis frameworks due to its simplicity (e.g., see Hatton *et al.*, 2006; Ruth, 1995).

Importantly, because calculations are carried out numerically, modification to the system dynamics version of the model is not limited by analytical tractability. The model structure can be modified to examine increasingly dynamic and complex situations. Note that there have been numerous non-SD modifications to the underlying model, especially for stock assessment purposes (e.g., see Hilborn and Walters, 2004).

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Adjusting the basic model

Biomass influence on additions to biomass In the standard model any decrease in biomass, including decreases due to fishing, will lower the fractional rate of decrease in biomass. In the standard model there is no effect on the growth fraction. In the real world, any decrease in stock biomass below the "virgin" stock size would also cause an increase in growth and reproductive success— on the additions side of the model, because decreases in population density should improve conditions for growth and reproduction of remaining fish.

Also, from our knowledge of fisheries we know that mean age of biomass in a stock will decrease with increasing fishing pressure.[5] However, decreases in stock size in the standard biomass dynamic model do not alter mean retention time in the stock. In equilibrium both the fractional rate of additions and total death fraction (death fraction plus catch fraction) are equal to r. In equilibrium, regardless of fishing intensity, mean residence time in the stock will always equal $1/r$, which is constant.

A modification to the model which adjusts the fractional growth rate r upward as biomass in the stock decreases seems appropriate. The forms which this feedback might take are discussed below, but we expect that r will increase somewhat as the stock is diminished and will decrease somewhat as relative stock size increases. This change will also create the expected decrease in average age of biomass in the stock as stock size declines.

Providing for separate growth and recruitment additions The strength of the biomass dynamic model is its simplicity. It avoids the use of cohorts and there is no provision for separate consideration of biomass increases due to growth of fish already in the stock and increases from the addition of new fish to the stock (called recruitment).[6] We may wish to include recruitment, and the effect of delays in recruitment even if cohorts are not used. Young fish often become a part of the fishable stock only after several years (e.g., at age 3). Handling recruit additions as a separate inflow is important in the fairly typical situation where large inter-annual variations in recruitment occur. This phenomenon becomes particularly important in heavily fished stocks where variable recruitment can account for a significant proportion of the total fish stock.

Delays in the recruitment of new biomass to a population can be incorporated into the model, as *delayed recruitment*, without resorting to an age-based approach (Figure 4). Here recruitment is envisioned as the biomass of new fish when they first enter the fishery. We ignore what actually happens to these fish prior to their entering the fishable stock. A true two-stock model may be appropriate in cases when large pre-recruit biomass exists as a sub-part of the overall stock.

Partitioning delayed and non-delayed additions to biomass To account for delayed recruitment additions to a stock, non-delayed stock increases due to

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growth of biomass already present must be calculated as well. This can be accomplished by having additions to the stock composed of two components by partitioning the *fractional growth rate r* into a growth and a recruitment component (Figure 4).

How large is the *fraction of additions from recruitment*, and what proportion of the additions are due to growth of biomass already present? This question is important because dynamics of some fish stocks are dominated by fluctuations in reproductive success. The mean age of biomass in the stock is likely to have a feedback effect on the proportion of new biomass from recruitment. Mean age of biomass, in equilibrium, is given by $1/r$. When not in equilibrium the mean age of biomass in the stock can be determined with a co-flow structure.[7] While the exact nature of the relationship between mean age and fraction of additions from recruitment is not known, we can assume that as mean age of biomass in the stock approaches zero, the fraction from recruitment will approach 1. As mean age rises the fraction from recruitment will drop. The model incorporates a lookup function for this relationship.[8]

THE EFFECT OF STOCK SIZE ON RECRUITMENT AND GROWTH ADDITIONS If we opt to allow separate growth and recruitment additions to biomass, then we can consider the shape of relationship between biomass and each of these inflows. In the standard model total *additions* to biomass is a fixed fraction of current biomass (Figure 2A). However, the relationship of stock size to amount of recruitment has been intensively studied, and a direct proportional relationship of biomass to recruitment amount is clearly not realistic. In general, a curved relationship with either stable or decreasing recruitment at high stock biomass levels is typical. Growth of biomass in the stock would also be expected to level off at high stock biomass.

An approach, common in fisheries, is to assume that recruitment takes the form whereby recruitment additions approach an asymptote as stock size increases (Figure 2B).[9] This is the approach taken herein for both growth and recruitment additions to the stock, although the constants, and underlying fractional growth rate r, for these can be varied independently.

An alternate formulation allows the effect of biomass ratio on r to be 1.0 (r keeps its original, typical, value) when B/k is 0.5, to have this effect increase linearly by a small amount (10–30 percent) as B/k approaches zero, and to decrease by a similar amount as B/k approaches 1.0. With this formulation, as the stock biomass decreases effective fractional growth rate will increase, and mean age of biomass in the stock will decrease. The strength of this effect will undoubtedly vary among populations (Figure 2C).

Either modification causes the fractional growth rate r to change as biomass changes. This permits the additional influence of mean age of biomass on fraction of new additions from recruitment. In the model this relationship is indicated by a lookup function with a value near 1 when mean age is very low (when almost all new biomass is from fish just entering the population) and a

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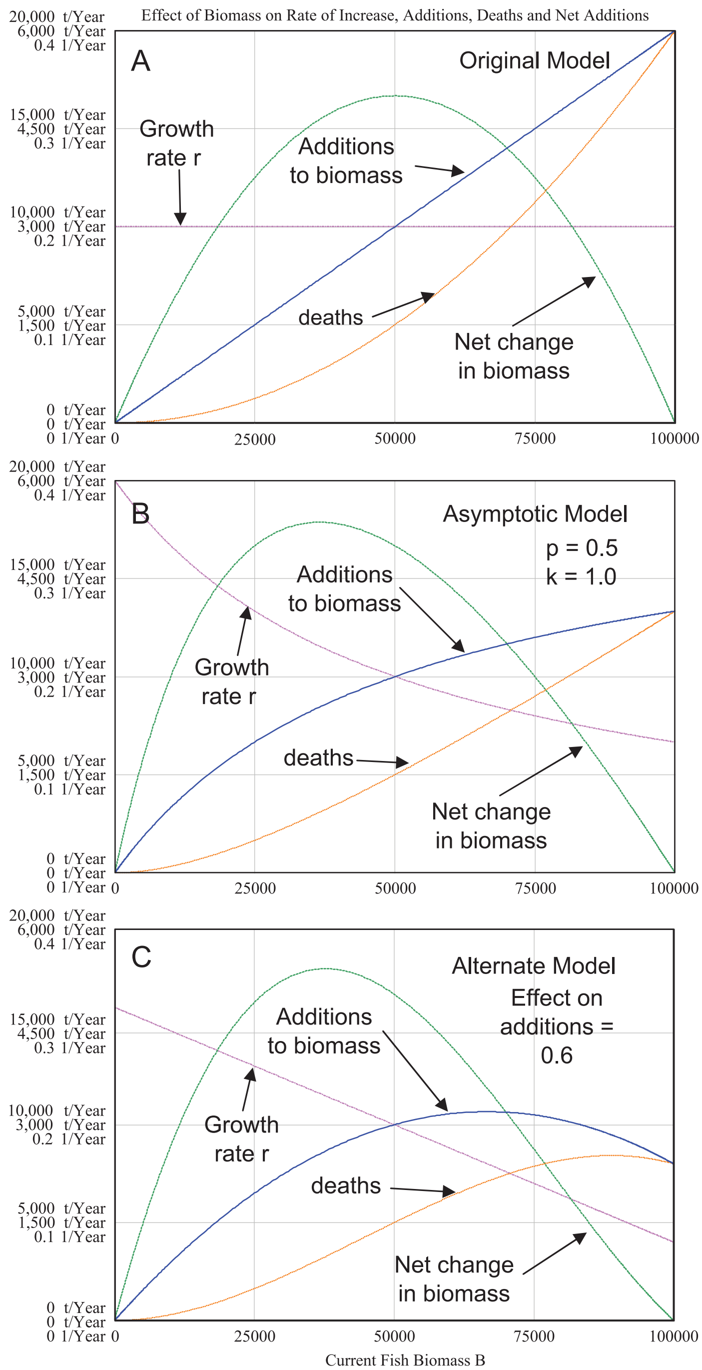
Fig. 2. An illustration of the effects of model alterations that allow changing biomass to influence additions to biomass. In the traditional model (A) additions to biomass are a constant fraction of existing biomass. Two alternatives presented here allow the fractional growth rate to change. The asymptotic model (B) is the one used in the remainder of this paper. In these examples factors affecting growth and recruit additions are identical, and there is no feedback effect of age of biomass on fraction of additions due to recruitment



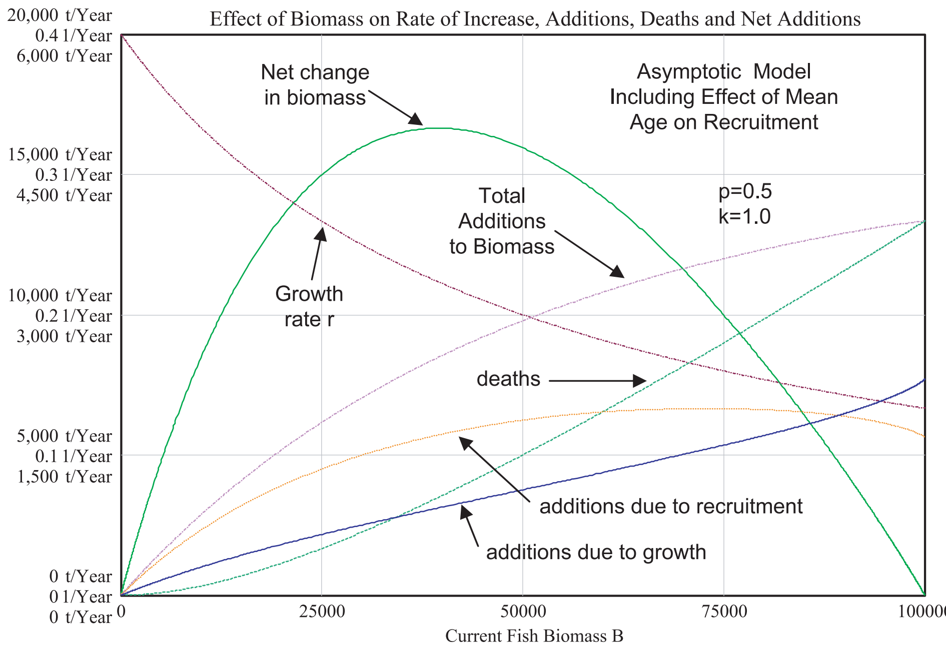


Fig. 3. Results as in the asymptotic model (Figure 2B), but with the fraction of additions due to recruitment dependent on the mean age of stock biomass. As in Figure 2, the unmodified underlying value for both growth and recruitment additions is the same ($r = 0.2$)

value below 0.5 when mean age of biomass is high (when a substantial portion of the biomass is from growth). The results of this addition on the overall behavior of the fishery portion of the asymptotic model is indicated in Figure 3.

Fisheries literature reflects the significant efforts that have gone into fitting stock recruitment data to various models. Nevertheless, most models provide a very poor fit to data due primarily to large inter-annual fluctuations in recruitment found in nature. Gilbert (1997), controversially, provided evidence that the state of the environment is at least as good at predicting recruitment as is stock size. Following that idea, the model can optionally generate random recruitment biomass above a selected minimum stock biomass, but below that minimum one of the above recruitment relations is used.

The completed fish stock portion of the model Combining the feedback from the stock biomass with the partitioning of growth and reproductive additions to the stock gives us the final formulation for the fish stock aspects of the model (Figure 4). Note that in keeping with the concept of the original model, that the unmodified fractional death rate should equal the fractional growth rate, the basic fractional death rate will now equal the *average growth rate*, which is a weighted average of the modified rates for growth additions and recruitment additions.

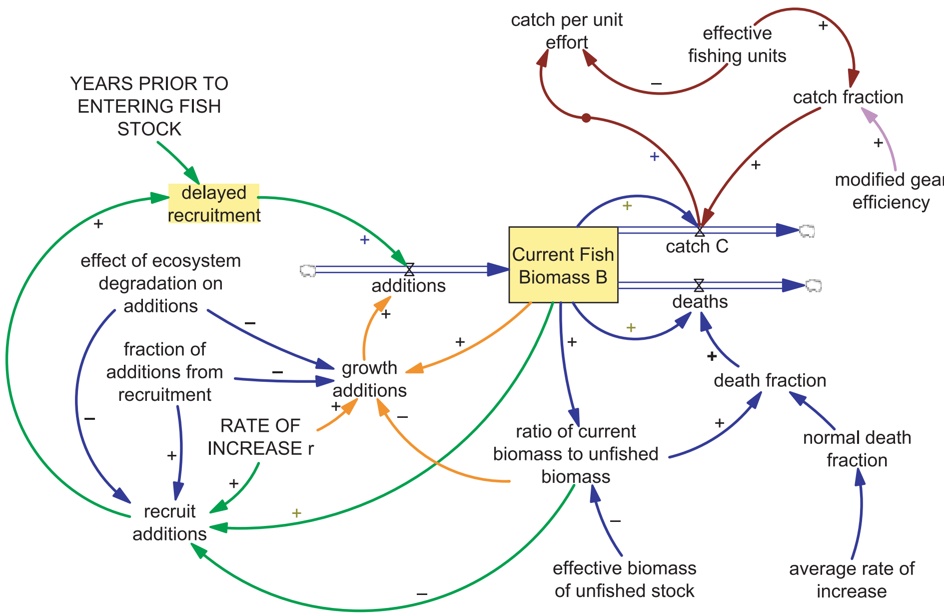


Fig. 4. The fish population portion of the final model showing the feedback effects from biomass to growth, and the partitioning of additions into additions due to growth and additions due to potentially delayed recruitment. Note that fraction of additions from recruitment is affected by mean age of biomass (not shown). A number of model components have been omitted for the sake of clarity

At this point the model, still without fishery or management components, allows for: (1) feedback from current biomass ratio to stock additions; (2) the partitioning of additions to the stock into growth and delayed recruitment; (3) the determination of the mean age of biomass; and (4) an increase in the fraction of additions due to recruitment as mean age of biomass drops.

Adding fishery components

Prior to modeling management decisions, a model of an unmanaged fishery is developed. This model, in addition to the simple stock dynamics shown above, allows for: (1) the entry and exit of vessels from the fishery in response to fishing success which is, in turn, determined by prices of fish and required profitability; (2) the accelerated improvement of fishing gear when catch rates drop; and (3) the possibility of fishery damage to the underlying ability of the ecosystem to support the fish population.

CATCH PER UNIT EFFORT DETERMINES VESSEL NUMBERS Many factors determine whether fishers enter and remain in a fishery (e.g., see Branch *et al.*, 2006), but typically vessels[10] enter a fishery because profits appear attractive. Normally profits are linked to some acceptable level of catch per unit of effort (referred to as CPUE) which provides sufficient monetary return over and above total costs of fishing operations. Some minimum acceptable CPUE attracts vessels to the fishery. If

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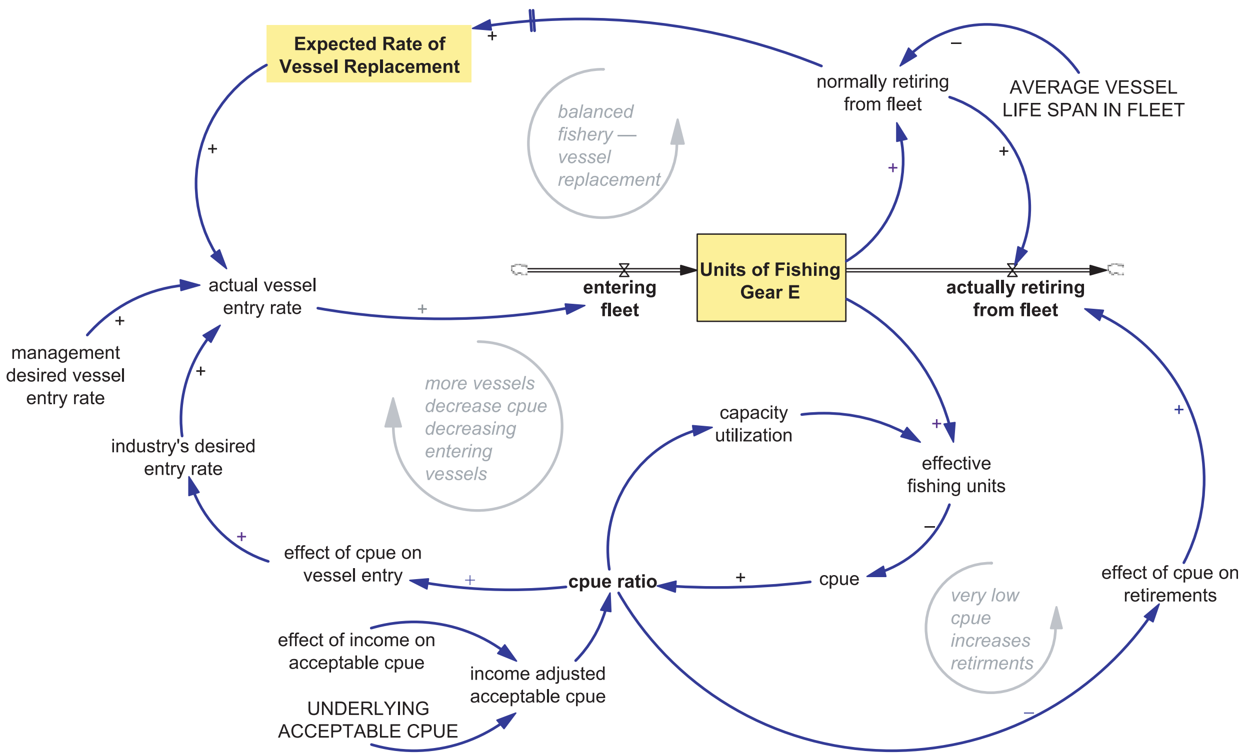

Fig. 5. Schematic representation of factors which affect the number of fishing gear units

the actual CPUE falls below this, fewer vessels will be attracted and eventually there will be a net loss of vessels from the fishery. As CPUE rises above this critical CPUE, more vessels will be attracted to the fishery. If CPUE falls well below the acceptable level, vessels' retirement from the fishery will also be accelerated (Figure 5).

The acceptable CPUE incorporates factors related to the profitability of fishing such as cost of operation and investment, and the expected price of the fish. Within the model, the fish price is influenced by catch levels and income is determined by price of fish and the existing CPUE. Current income levels compared to those in the recent past determine the acceptable CPUE. If current income is comparatively low then acceptable CPUE will drop and fishers will be more likely to continue fishing.

The model also includes the effect of recent CPUE on capacity utilization. At high existing, compared to acceptable, CPUE, vessels will expend additional effort to catch fish. If CPUE drops below currently acceptable levels then fishers will lower the use of their fishing capacity.

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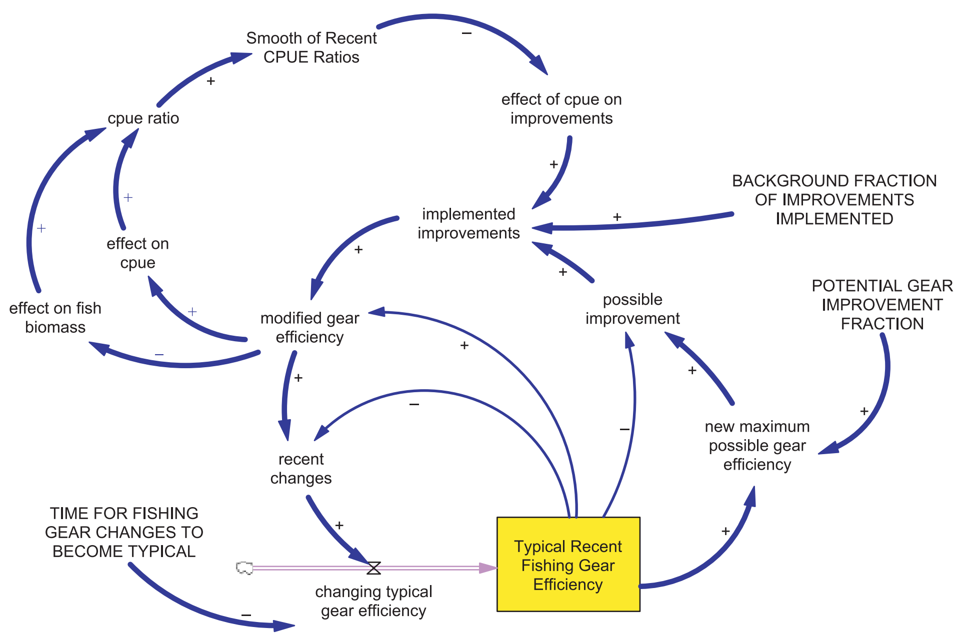
Fishing units can maintain catch rates by increasing efficiency When catch per unit effort drops below acceptable levels, fishers who remain in the fishery will respond by attempting to improve the efficiency of their fishing gear. These improvements may be in the form of better application of known technology (e.g., using their sonar more effectively) or applying recently developed techniques (e.g., adjusting fishing gear design). We can assume that at any given time some small amount of improvement, maybe 5–20 percent, to existing gear efficiency is possible. Importantly, these improvements gradually become absorbed into standard fishing practice and therefore will permanently increase gear efficiency. Over time these small changes in gear efficiency accumulate (Figure 6). Optionally in the model, a constant background improvement in efficiency is also possible.

Fishing decreases carrying capacity In some fisheries, fishing activity decreases ecosystem carrying capacity. The most widely cited example of this phenomenon is the damage which trawling gear inflicts upon bottom habitat (e.g., Watling and Norse, 1998).

Damage to carrying capacity is cumulative and is proportional to the amount of fishing taking place. In the model each effective fishing unit inflicts a small amount of damage on the habitat. This damage in turn affects the maximum possible biomass which the habitat can support. Habitat recovery time may be

Fig. 6. An illustration of the way in which fishing gear efficiency changes, how these changes affect catch per unit effort (CPUE), and how CPUE affects changes in gear efficiency. Several model components are not shown, and some shown are substitutes for more complex structure



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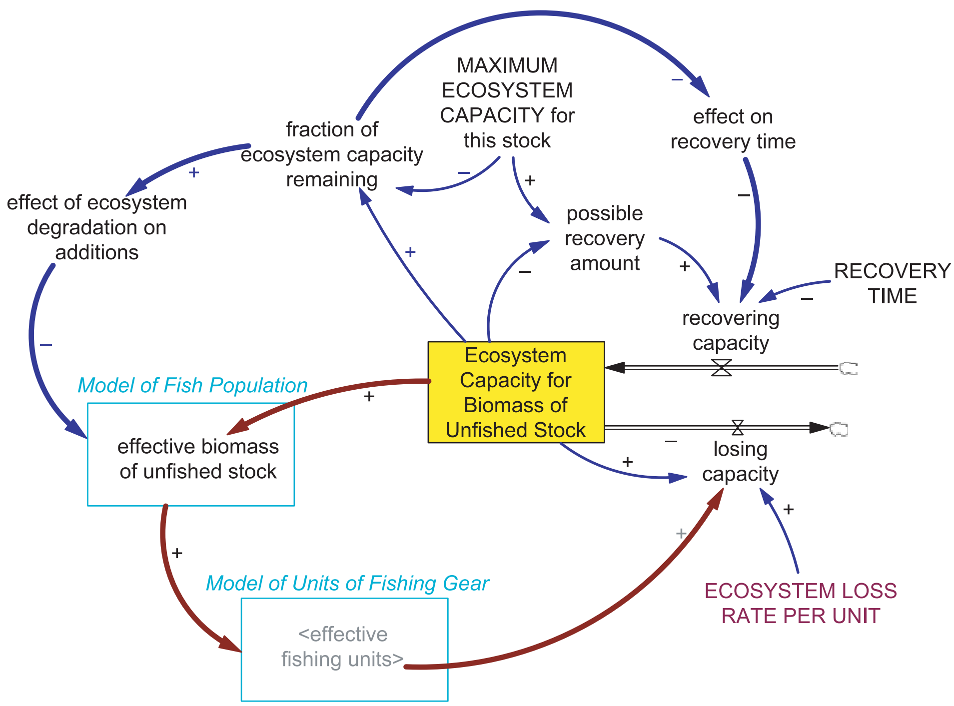

Fig. 7. The relationship between the number of fishing units and possible degradation of the ecosystem which supports the fishery. Effects on the fishery occur because the underlying maximum potential biomass is degraded and also because of a more direct effect on additions to the stock

several years, perhaps tens of years in the case of serious physical damage. Further, the model assumes that the rate of recovery will be slower if habitat damage is extensive (Figure 7).

Within the framework of the underlying model, a lowered carrying capacity k will increase the loss of biomass since the underlying loss fraction is $-r * B/k$. In the modified model the additions side of the model is also affected. If the asymptotic growth and recruitment functions are used, additions to biomass are lowered.

However these effects are relatively small even when the ecosystem is severely degraded. Consequently an additional effect is included whereby additions to the stock are also limited by an S-shaped lookup function. At full carrying capacity this function will yield the full amount of expected additions for the current biomass. A completely degraded ecosystem will yield no additions to biomass.

Adding management strategies

Management attempts to maintain optimum biomass by adjusting fishing gear numbers In the model, management of the fishery is carried out by a management entity that strives to maintain the fish stock at a fixed fraction of its unfished biomass. The target value for management is one half the assumed unfished stock.[11]

Management formulates a revised perception of stock health based on recent stock assessment information. If the stock estimates are near the desired level the new perception is neutral: the stock is in reasonable health. If new data indicate that the stock size is different from the desired size then the perception of stock status is revised upward or downward accordingly. Based on new information, management's perception of the fishery is gradually changed, and that determines the desired changes in fishing gear numbers. If the perception of the stock is negative, a fractional decrease in gear numbers will be proposed. If perception of the stock is positive, the suggested fractional change will be positive. These fractional changes become greater the further management's perception is from neutral. A change in fishing gear numbers is then proposed to be implemented over some implementation time. If management proposals have perfect influence, the proposed changes in fishing gear numbers are fully implemented (Figure 8).

LOBBYING AND POLITICS Typically fishery management entities cannot merely dictate changes in fishing effort. Many social, economic, legal, and consequent political issues come into play. Fishers lobby for more liberal regulations. Environmental groups lobby for more restrictive regulations. Both groups seek political backing for their particular view. If unsuccessful then they may seek redress in the courts.

The model incorporates a simplified version of lobbying whereby fishers and managers attempt to have their own desired adjustment to fishing gear numbers implemented. Firstly a negotiated vessel entry rate is calculated as a weighted average of the two desired rates. The weighting is based on the relative strength of management's mandate. Secondly, there is an option allowing an increasing level of lobbying as management's and fishers' views diverge (Figure 8). If the view of the two parties diverges considerably, and that divergence is large compared to current fleet size, then, in the model, lobbying can reduce management's current effectiveness by up to 80 percent.

The relative strength of management's views may also be influenced by politics. As the fishery becomes obviously overfished in the eyes of politicians, the management entity will be given strengthened authority. In the model the politicians' views are represented by an indicator of the need for stronger management: the relative size of current fish catches compared to fish catches in the past. Low recent catches compared to the longer-term "historical" catches will result in more influence for the management entity and its views.

Overall, this model, in a general sense, embodies a concept of fishery management whereby managers view success in terms of stock level, fishers view success in terms of catch per unit of gear, and politicians view success in terms of total fish catch which should be at least as good as it was in the recent past.

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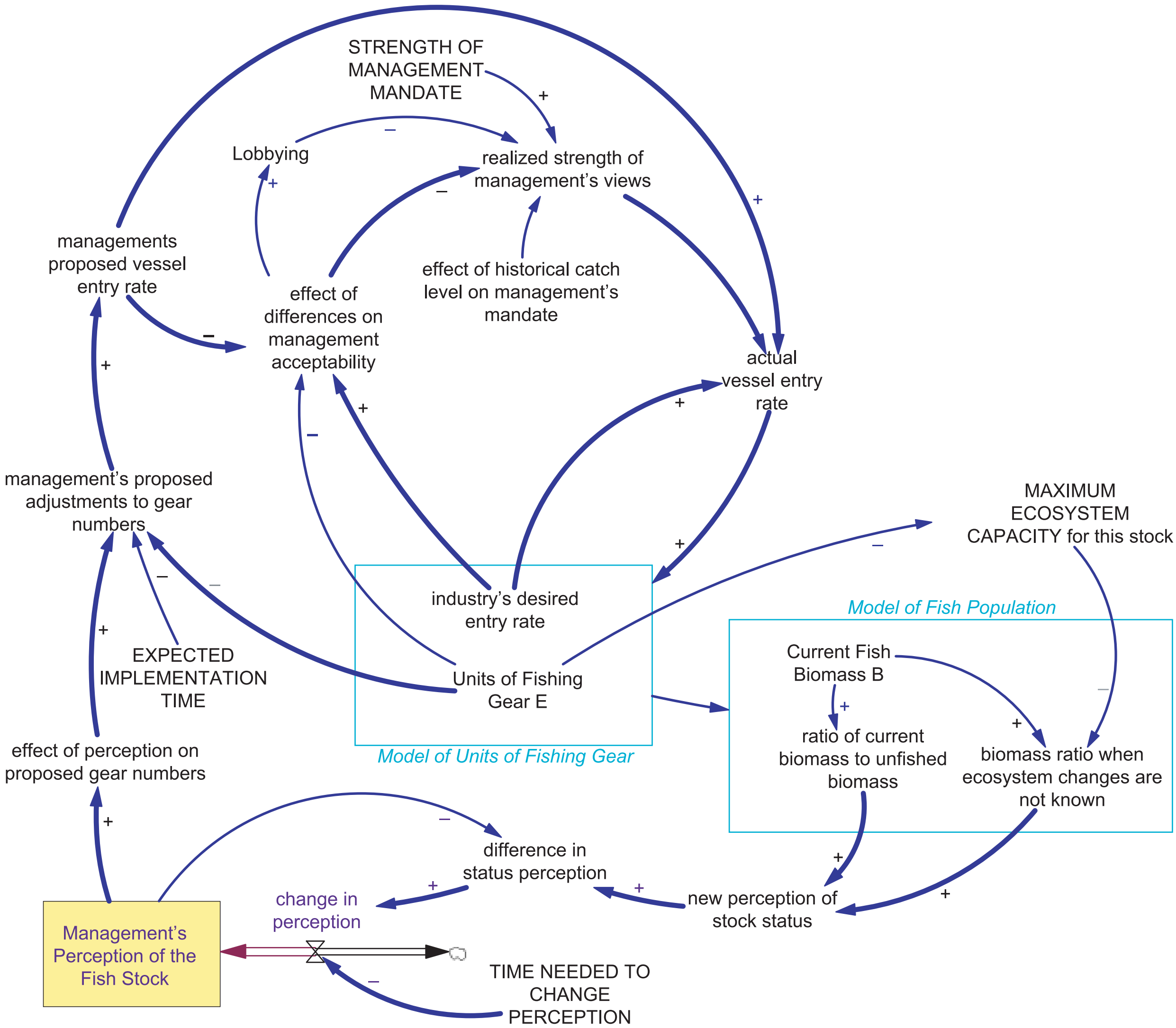

Fig. 8. Factors affecting the determination of the appropriate number of fishing units by a fishery management entity

Model outcomes

A fishery with no management

This example illustrates a typical developing fishery for a moderately slow growing species (such as cod) with starting parameters as indicated in Table 1.[12]

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Table 1. Key constants and switches used. Only changes are shown in the last column

Name of constant	Units	Declining fishery, no management Figs 9–12	Recovering fishery, four levels of management Fig. 13
Fish stock			
Rate of increase *r*	1/year	0.2	
Initial biomass	ton	95,000	25,000
k growth	dmnl	1	
k recruitment	dmnl	1	
p growth	dmnl	0.5	
p recruitment	dmnl	0.5	
Years prior to entering fish stock	year	1	
Fishery			
INITIAL NUMBER OF FISHING UNITS	unit	25	100
Initial gear efficiency	1/year * unit	0.001	
UNDERLYING ACCEPTABLE CPUE	*t*/(year * units)	35	
Average vessel lifespan in fleet	year	10	
potential gear improvement fraction	dmnl	0.1	
BACKGROUND FRACTION OF IMPROVEMENTS IMPLEMENTED	dmnl	0.05	
Ecosystem loss rate	1/year * unit	0.001	
Options for fish stock			
Standard deviation for pink noise	dmnl	0	
Switch ecosystem affects additions on–off	dmnl	1	
Switch on–off seasonal recruitment	dmnl	0	
Switch to use ALT growth	dmnl	0	
Switch to use asymptotic growth	dmnl	1	
Switch to use asymptotic recruitment	dmnl	1	
Options for fishery			
Switch on off CPUE affects capacity utilization	dmnl	1	
Switch on–off effect of CPUE on gear improvement	dmnl	1	
Switch to turn on effect of income on acceptable CPUE	dmnl	1	
Options for management			
STRENGTH OF MANAGEMENT MANDATE	dmnl	0	0, 0.5, 0.75. 1.0
Switch—lobbying feedback	dmnl	0	
Switch on–off historical catch effect on mgmt	dmnl	0	

When vessels first enter a new fishery, catch per unit effort is well above the level necessary to attract additional participants to the fishery. As more fishers enter the fishery, fish stock biomass drops, as does CPUE. Even though stock biomass and CPUE are dropping, catches continue to rise due to the continuing influx of new fishers. CPUE drops below initial minimum acceptable levels by year 6 (in this example), but by this time the acceptable level has also dropped

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somewhat due to income needs. By year 7 even income-adjusted CPUE levels become unacceptable and, in year 11, vessel numbers start to drop. By this time the fish stock is already seriously overfished as too many vessels have entered the fishery. Even though participants now rapidly exit the fishery, CPUE and catches continue to drop until year 15 and 24, respectively (Figure 9).

Once CPUE rises high enough to attract more fishers, the cycle starts again. Because of the decreased fishing, fish stocks have started to recover by year 16, and by year 30 participants are returning to the fishery. However, stock biomass never recovers to its former size because fishers are rapidly re-entering the fishery, preventing its recovery. Also, fishers have increased their gear efficiency, especially during the period when CPUE was low. In this example, the third and subsequent cycles are progressively less productive, although CPUE is better than might be expected because fishers have improved gear efficiency.[13] The downward trend with periodic partial recoveries is typical of overfished fisheries (Hennessey and Healey, 2000; Ludwig *et al.*, 1993).

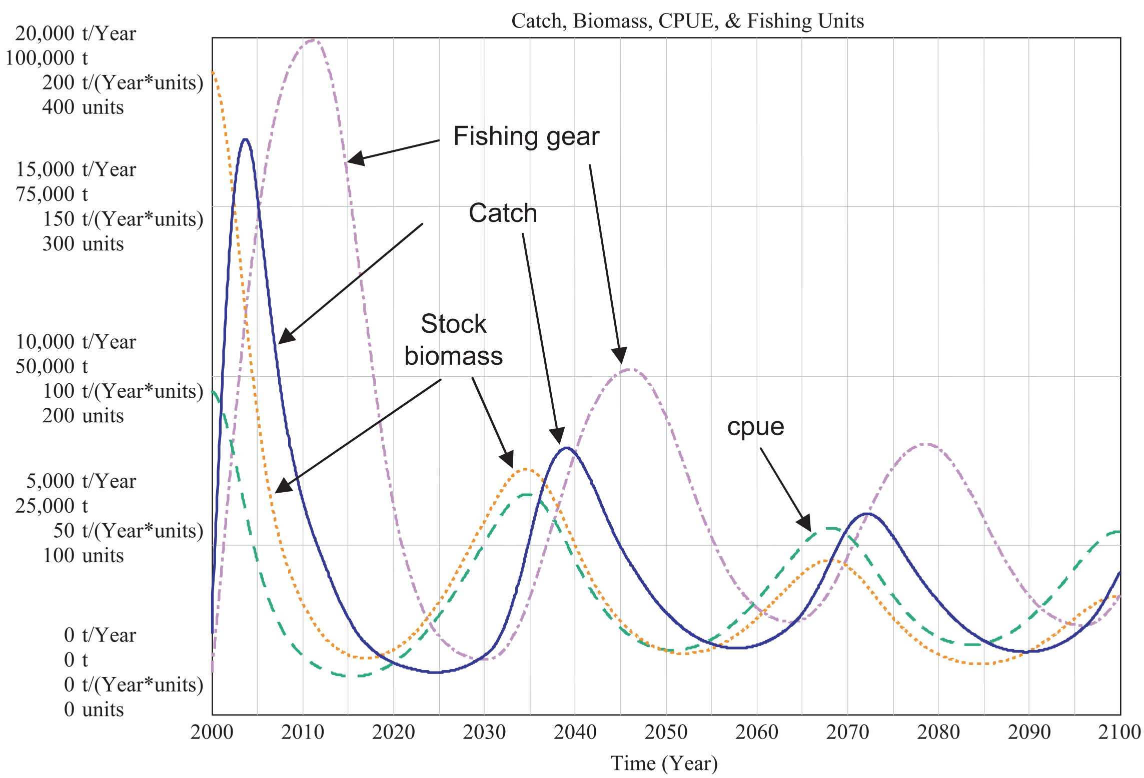

Fig. 9. Outcome for an unmanaged fishery where acceptable CPUE is sufficiently low to cause overfishing to occur. Constants as in Table 1

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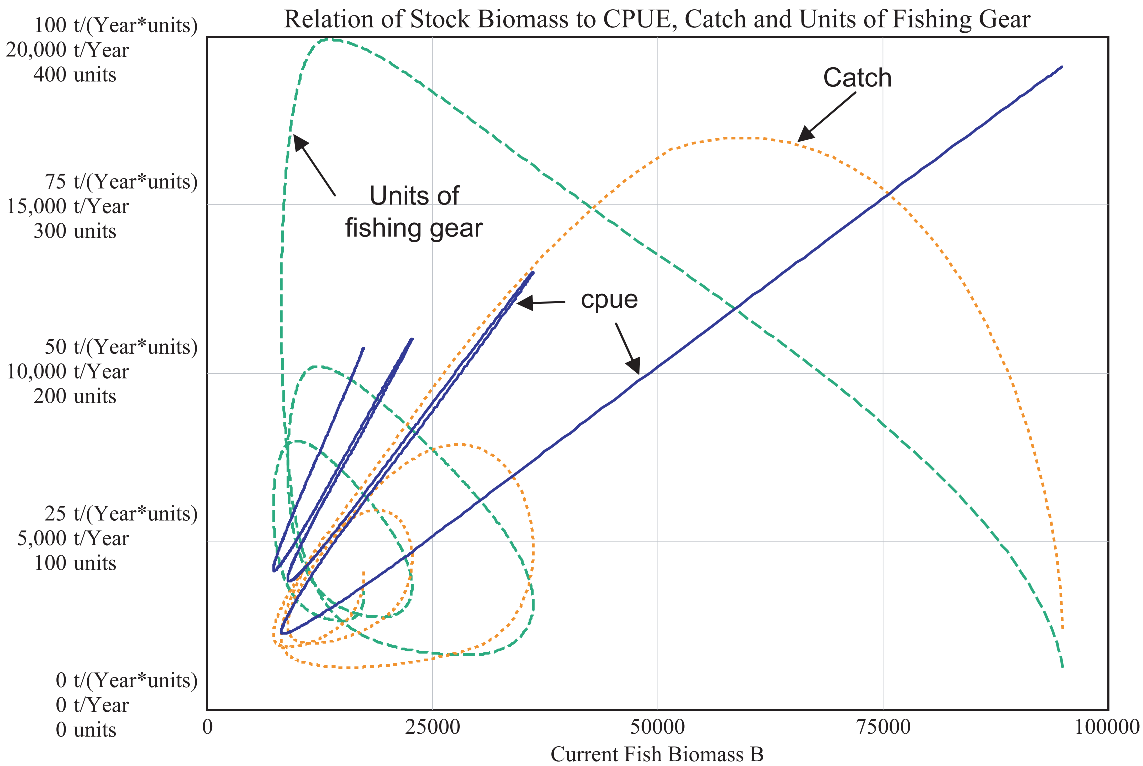

Fig. 10. Relationship of biomass to catch, units of fishing gear, and CPUE when overfishing occurs. Each cycle of overfishing drives the stock biomass lower. During the periods of low stock biomass fishers improve their fishing effectiveness, resulting in a steeper slope of the CPUE versus biomass line (solid line) during the next cycle

The overfishing scenario and its effect on the fish stock is also illustrated by the relationship between biomass and the fishing process (Figure 10). Catch and number of fishing units spiral downward, and during each decline catch efficiency is ratcheted upward with each cycle as indicated by the increasing slope of the CPUE versus biomass relationship.

As modeled here, declining biomass causes a decline in the mean age of biomass in the stock, which in turn increases the fraction of additions due to recruitment. That is, as the stock declines, the fraction of additions due to recruitment increases (Figure 11). In this example this has little effect, but in the common situation where recruitment fluctuates, this will increase the influence of such fluctuations on the stock. Also illustrated in this example, fishing gear degrades ecosystem capacity, which causes a decline in additions to the stock (Figure 12).

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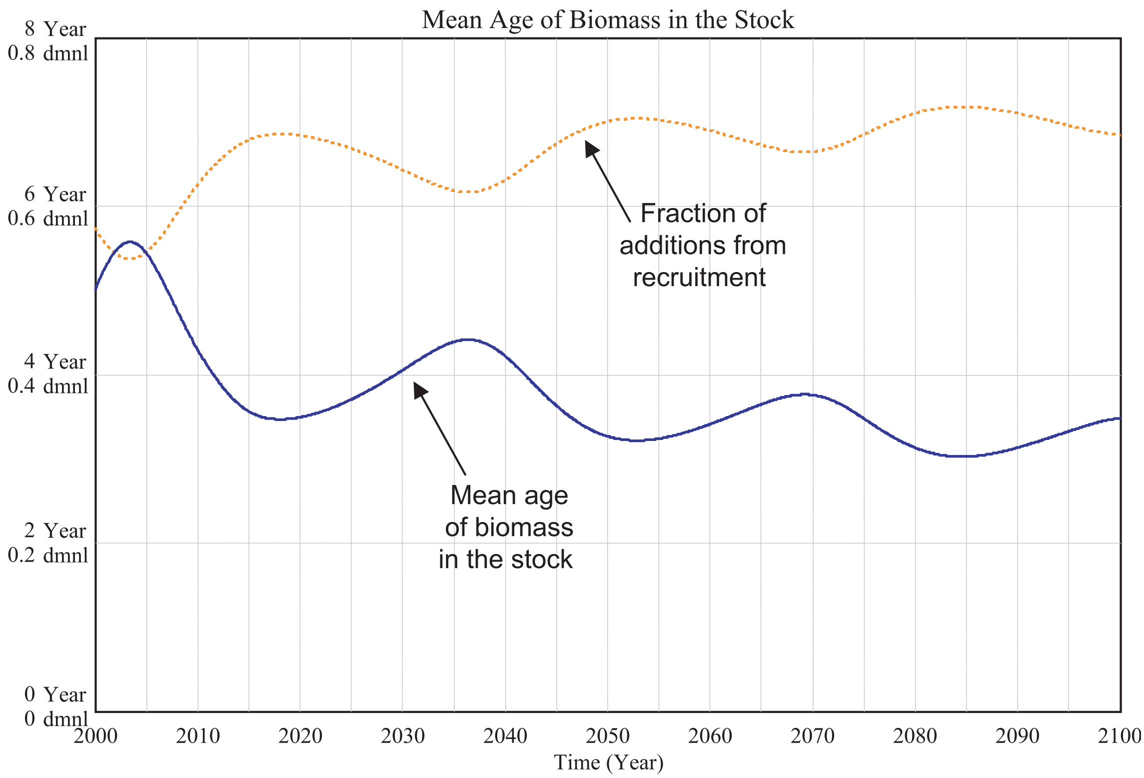

Fig. 11. Mean age of biomass in the stock declines if the stock is fished intensively. Decreasing mean age is a determinant of the fraction of additions to the stock that are due to recruitment. If the stock is fished hard a larger proportion of additions to the stock comes from recruitment

Managing the fishery

In the model, management adjusts fishing gear numbers entering the fishery in order to gradually change fishing effort so that stock size drops, or rises, to the desired level. In a typical realistic situation management can be expected to be successful in implementing perhaps 75 percent of suggested changes to gear numbers. In the model this percentage is represented as a fractional multiplier: the underlying strength of the management mandate (Figure 8). Further weakened authority can result from lobbying by fishers and by changing political support.[14] In the following discussion four levels of management are compared: no management, 50, 75, and 100 percent (good) management. In this and the following examples the fishery is initially somewhat overfished (Figure 13).

Fish biomass, one measure of management success, remains significantly higher with good management (Figure 13A). Mean age of biomass, another

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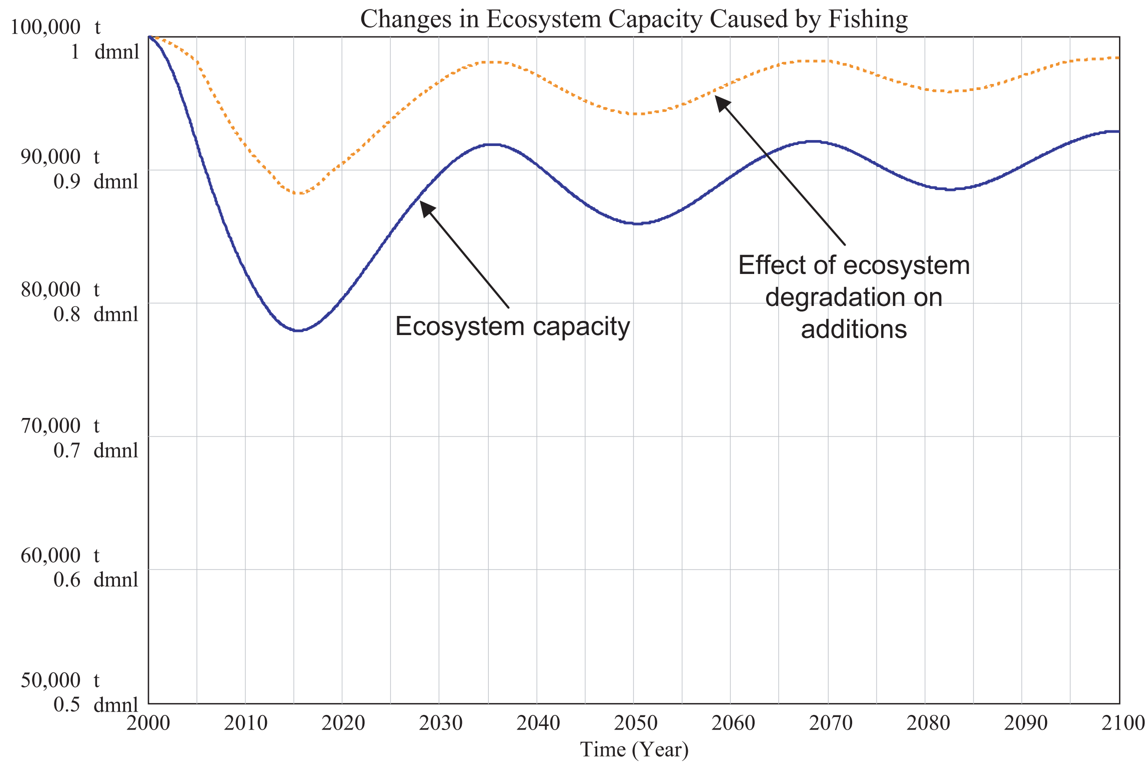

Fig. 12. Fishing adversely affects the ability of the ecosystem to support a fish population. Any lower ecosystem capacity results in higher mortality. A decreased ecosystem capacity also directly reduces additions to the fish stock

stock health indicator, is also higher. Units of fishing gear (e.g., vessels) are fewer under good management, and CPUE is considerably higher (Figure 13C, D). Furthermore, the number of units and the CPUE are stable, thus avoiding problems associated with boom and bust cycles. Fewer fishing units also means less damage to ecosystem capacity.

Total catch under good management is not always higher than that obtained with the other options examined here (Figure 13B), and the number of fishing units is significantly lower. These outcomes may conflict with desires of the industry and fishers because catches provide food, and raw materials for processing plants and restaurants, and fishing units provide jobs. Although fisheries employment under poor management exhibits boom–bust cycles, total benefits to workers may still be higher, on average, under those conditions.

The total value of the catch (to the fishers) can periodically be higher in the poorly managed situations, especially if fishers enhance fishing efficiency, and if fish prices rise, during periods of low catch (Figure 13E).[15] On the other

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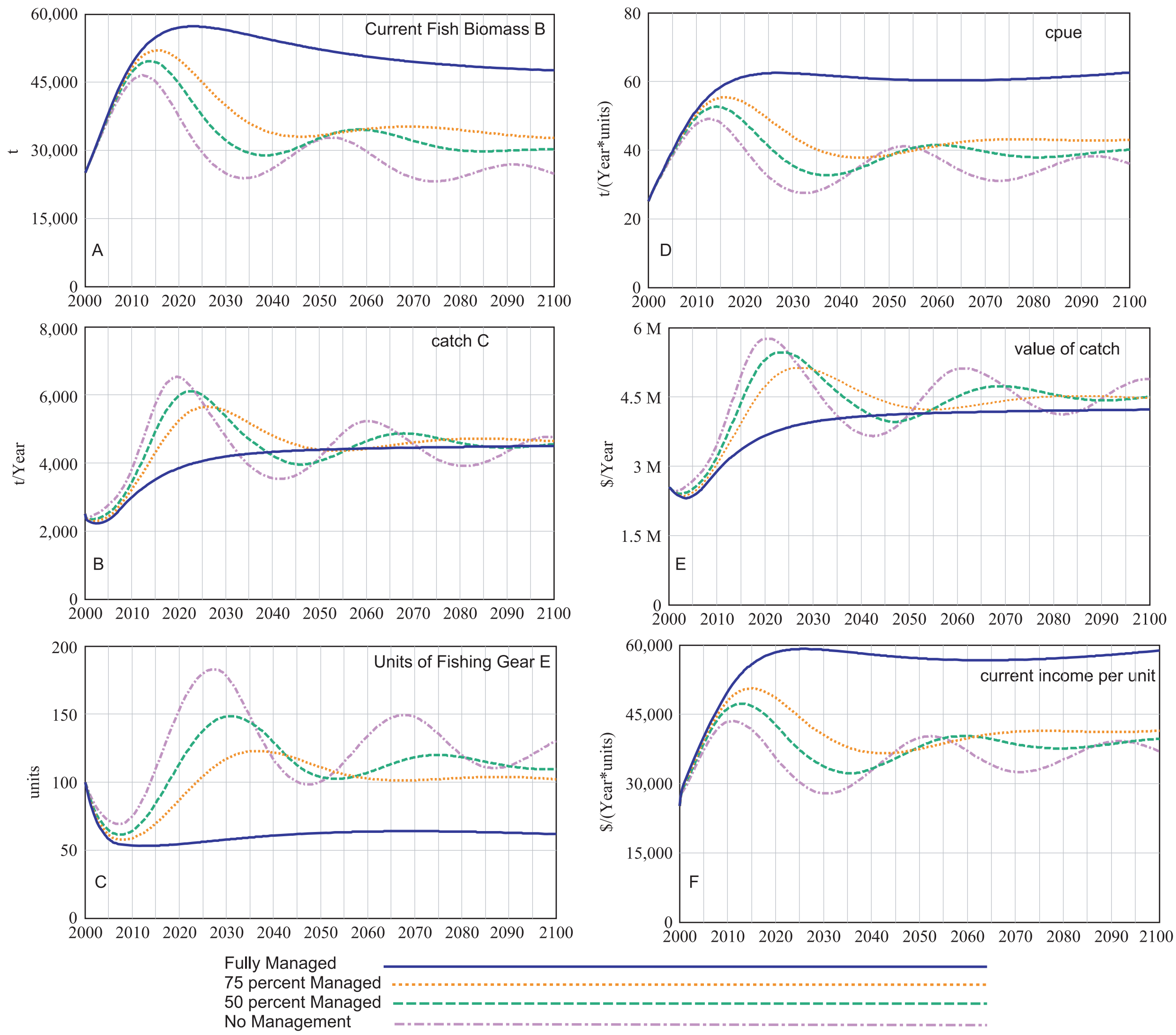

Fig. 13. Outcomes of four model runs representing different levels of management of a fishery recovering from overfishing

hand, income per fishing unit is always significantly higher under good management and is free of boom–bust problems (Figure 13F).

Poorly managed real world fisheries appear to regularly produce lower catches, compared to those expected under good management, than the examples here indicate. In the model too, catches will be consistently lower if fishers continue fishing even after CPUE drops below original desired levels.

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This will occur if dropping incomes more strongly influence the need to accept an ever lower CPUE.

These examples serve to illustrate that using reasonable assumptions it is fairly easy to recreate a fishery situation that is all too familiar to managers and users of such resources. Mangers and fishers and politicians all follow “rules of thumb” that seem reasonable to them but which result in an outcome disliked by all.

Other issues

Large variations in recruitment into a fish population are quite common, and incoming biomass from recruitment plays a larger role if the stock is diminished. Fluctuations in recruitment can cause fairly rapid and significant changes in stock abundance which may persist for several years. Such changes affect catches, CPUE, and the entry of new fishers. As an illustration, random uniform pink noise (Sterman, 2000) with a mean of zero and standard deviation of 1 is added to recruitment (Figure 14). Even if a fishery is started in approximate equilibrium, variations in recruitment can lead to boom and bust cycles in the fishery.[16]

Lobbying by fishers and varying political support for management entities is explicitly incorporated into the model. Figure 15 illustrates these facts where a

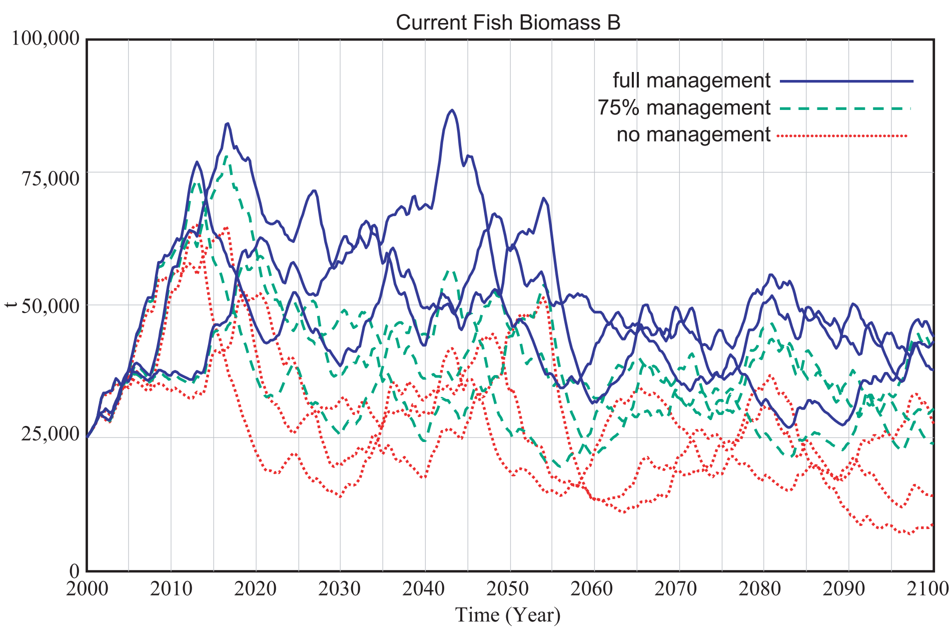

Fig. 14. Nine model runs representing a combination of three management approaches and three random additions to recruitment. Under given circumstances full management results in higher biomass than the other options even though biomass will fluctuate considerably

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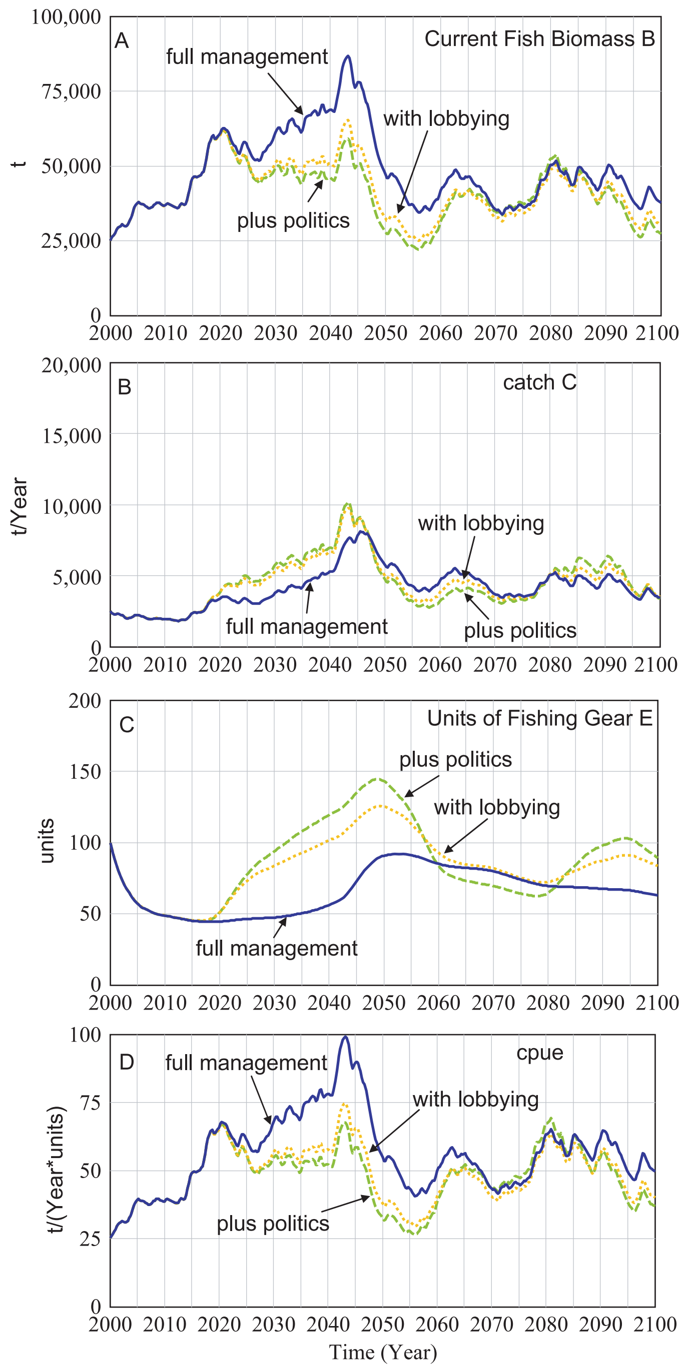

Fig. 15. A single model run which incorporates variations in recruitment, showing the potential effects of lobbying by fishers and varying political support from political entities. The solid line shows full management without interference. The dashed line indicates the effects of lobbying, and the dotted line indicates the effects of both lobbying and varying political support for management

single run of the model incorporates varying recruitment and full management. The same run is also shown with lobbying by fishers and varying political support. Strength of lobbying in the model is based on the difference in desired vessel numbers of fishers and management. Political influence tends to decrease support for management when catches are rising, but catches tend to peak after stocks start to drop, and vessel entry continues even beyond that point. Thus varying political support for management may exaggerate overfishing problems.

These examples use a fractional growth rate of 0.2, a value appropriate for a species like cod. Populations with a higher basic fractional growth (e.g., 0.4 for tuna) rate can sustain heavier fishing pressure, while extremely slow-growing species ($r \approx 0.1$ for orange roughy, some sharks) can be easily overfished.

Because the catch fraction at any given time is the product of gear efficiency and the number of gear units operating, higher gear efficiency results in more rapid overfishing. The related, acceptable CPUE at which vessels will enter a fishery is also an important consideration. If acceptable CPUE is easily attained, new fishers will continue to enter the fishery long after the stock has fallen below the optimum biomass. This is typical of fisheries of high value (e.g., bluefin tuna, lobster), or where operating costs or income needs are very low. If acceptable CPUE is high (i.e., a very large catch must be expected for vessels to enter the fishery) then little management is needed unless excess vessels are forced into the system (from adjacent failed fisheries for example).

The model assumes that managers compare current stock size to a desired size of half the unfished stock. Many other reasonable formulations for management decision making exist. Herein, the direction of change in the fish stock is mostly ignored. Management would normally make different decisions at a given stock ratio if the stock were increasing or decreasing. Also, the management system modeled here relies on management's knowledge of recent stock size. A more sophisticated model would provide recommended fishing levels based on predicted stock sizes and on inaccuracies in those predictions.

Discussion

This modeling effort was designed to provide a system dynamics framework for examining fisheries management issues. Modified from an established fishery paradigm, the model presents a straightforward approach which incorporates some of the complexity found in real fisheries. Additional fishery components might be added, possibly incorporating such things as multiple fish species and multiple types of fishing gear. On the other hand, such additions might dilute the understanding gained by using a relatively understandable, transparent model structure.

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Rather than adding additional model structure related to fish populations and other traditional aspects of fishery models, more emphasis could be placed on examining complex issues that perplex fishery managers and users. For example: Which management and regulatory approaches can best adapt to fluctuating fisheries with minimal risk for the resource and its users? Which management regimes best encourage cooperation between managers and users, and among users? How might fisheries be managed under the umbrella of ecosystem management? Can the use of marine reserves be merged with more traditional management approaches? In a more general sense, can transparent system dynamics models be used more widely to encourage discussion of complex fishery management issues in an open and constructive atmosphere?

Complex fishery issues are in need of a paradigm that can help managers, scientists, and resource users communicate across disciplinary boundaries (Caddy, 1999) and system dynamics is one available, well-tested, approach. Ideally it can be used to investigate and solve some of the complex fishery problems mentioned in the Introduction to this paper.

Notes

1. Excluding catch, this form of the model is mathematically identical to the classic logistic model of Verhulst (1838). However, that model considers net growth in numbers (rather than biomass). As used in fisheries the model is variously called the biomass dynamic model, surplus production model, Schaefer model, or Graham–Schaefer model. There are numerous modifications with other names.
2. Most fishery scientists assume there is no natural mortality component in this model, because they focus on the net change in biomass. I assume that the basic model implicitly includes natural mortality of biomass.
3. Note that units of fishing gear can be variously defined as boats, nets, hooks, traps, etc.
4. An important aspect of the biomass dynamic model is that data needed to determine its parameters are relatively easy to obtain from a fishery without the need for determining abundance of fish of different ages.
5. Typically this evidence is manifested as a decrease in average age of individuals in the fish stock. In fact, the mortality rate is often determined by the slope of a graph of numbers in each cohort versus age. If the mortality rate rises the relative abundance of older fishes decreases.
6. The term *recruitment* refers to fish first entering that portion of the fish stock that is vulnerable to fishing. That is, fish too small to be caught by the fishing gear are pre-recruits. Note that fish entering the stock via migration are usually not included in the term recruitment, nor are they included in this model.

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7. I gratefully acknowledge the helpful discussion on the system dynamics mailing list regarding use of a co-flow to determine average age (see http://www.systemdynamics.org/pipermail/sdmail/2007-April/thread.html).
8. The model also incorporates an optional fixed proportion of inflowing biomass due to recruitment. Proportion of additions to biomass due to recruitment is probably in the range of 30–70 percent, with the higher proportions more typical of short-lived fishes. Note that in a cohort model the age and thus size of fish at recruitment is a major determinant of the weight of the incoming biomass.
9. In fisheries work this is commonly referred to the Beaverton–Holt recruitment function, most typically applied to numbers, rather than biomass, of recruits.
10. Units of fishing gear could be defined as number of vessels, nets, traps, hooks, etc. Here I use the term in a general sense.
11. In theory this is the point where the sustained harvest from the stock is maximum (Figure 2A). However, if there is feedback from biomass ratio to the growth rate as described in the text, then the stock level where the catch is maximum will be somewhat below 50,000 t.
12. For default settings of these and other model constants see model equations. A listing of model equations and the Vensim model are available for download from http://pws.prserv.net/RGDudley/dudspbs.html.
13. If we start with an overfished stock (rather than the virgin stock) the results are similar to the second and subsequent cycles.
14. Such influences can induce oscillations similar to those in a less well-managed situation, so these influences are excluded in the following discussion.
15. These model runs do not incorporate natural fluctuations in reproduction that could also affect prices.
16. The model also incorporates the possibility of seasonal recruitment, but implementation of this option makes little difference to the overall outcome of a given scenario.

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