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Summary
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Keywords: Coalition Stability, Dynamic Games, Endogenous Risk, Fish Stock Collapse, Fish War, Renewable Resource Exploitation
JEL Classification: C72, C73, Q22

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The Rise and Fall of the Great Fish Pact under Endogenous Risk of Stock Collapse.

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Abstract

Risk of stock collapse is a genuine motivation for cooperative fisheries management. We analyse the effect of an endogenously determined risk of stock collapse on the incentives to cooperate in a Great Fish War model. We establish that equilibrium harvest strategies are non-linear in stock and find that Grand Coalitions can be stable for any number of players if free-riding results in a total depletion of the fish stock. The results thus show conditions under which a Great Fish War becomes a Great Fish Pact. However, this conclusion no longer holds upon dropping the standard assumption that payoffs are evaluated in steady states. If payoffs in the transition between steady states are included, the increased incentives to deviate offset the increased benefits from cooperation due to the presence of endogenous risk and the Great Fish Pact returns to being a Great Fish War.

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1. Introduction

Risks of catastrophe or regime shifts, if endogenously determined, have been shown to be an important incentive for precaution in strategic resource use (Nikuiya et al., 2014, Ren and Polasky, 2014, Sakamoto, 2014). Further, such risks are relevant for understanding the decision to join climate treaties (Kolstad, 2007, Dellink and Finus, 2012 and Barrett, 2013) and are likely to affect the strategic harvest choices of fishing nations (Hannesson, 2014). From 1950 to 2000, 366 fisheries collapsed and the collapses are generally attributed to over-fishing (Mullon et al., 2005). Indeed, avoiding stock collapses was one of the principle motivations for the formation of Regional Fisheries Management Organisations (RFMOs), the institutions intended to facilitate cooperation in the management of high seas fish stocks. Surprisingly, the effect of endogenously determined catastrophes on the potential for cooperation in fisheries agreements has received little attention in the literature.

In this paper, we fill this gap using the Great Fish War model of Levhari and Mirman (1980) and consider the effects of a risk of stock collapse which increases in harvest. We ask, whether an endogenous risk of stock collapse can transform the Great Fish War into a Great Fish Pact. We modify the Great Fish War model of Levhari and Mirman (1980) (henceforth LM) to estimate Stochastic Markov Perfect Nash Equilibrium (SMPNE) harvest functions under an endogenously determined risk of irreversible collapse such that the stock after the collapse is zero, and remains zero, for all future time periods. It should be noted that "collapse", as defined in the fisheries literature does not require the stock to be completely extinct (Cooke, 1984). Instead, we define collapse as an economic collapse, meaning that the fishery is no longer viable and no profits can be made. Our study therefore relates generally to the literature on uncertainty in resource management such as Clarke and Reed (1994) and Tsur and Zemel (1998). More specifically, our study relates to literature which considers endogenous risk of regime shift in resource games, namely, Sakomoto's (2014) analysis of the subclass of dynamic renewable resource games of Sorger (2005) and Ren and Polasky (2014), who conduct a more general analysis. These two studies show that endogenous risk can lead to either more or less aggressive resource use. Additionally, Sakamoto (2014) demonstrates the importance of considering the transition between regimes, i.e. taking off-steady-state payoffs into account. Finally, our study fits directly into the literature using the LM model. Exogenous uncertainty in the LM model has been considered in three studies. Antoniadou et al. (2013) and Agbo (2014) consider exogenous uncertainty in stock dynamics. Fesselmeyer and Santugini (2013) consider exogenous uncertainty in the quality of the resource as well as the probability of regime shifts in the growth rate of the stock.

In our study, we compare analytically how incorporating endogenous risk affects the structure of the LM model. Due to the technical difficulties in analytically solving for non-linear harvest functions (Antoniadou et al., 2013), we use numerical methods to demonstrate that optimal harvests are non-linear in stock. Our numerical model is validated by removing the endogenous risk from the model and statistically analysing the similarity of the numerically derived harvest functions to those from analytical solutions. This provides an important bridge between analytics and numerical methods, demonstrates the robustness of the model to numerical error and validates our approach. Our model calculates the Internal Stability of Grand Coalitions across a range of growth and discount rates and for any number of players. In turn, this allows us to determine if an endogenous risk of stock collapse affects the potential for successful cooperation.

Our study is the first detailed exploration of non-linear harvest functions in the LM model and the first study to explicitly consider endogenous risk of stock collapse from a coalition theory perspective. We find that endogenous risk of stock collapse may provide an incentive to entirely deplete the fish stock. Because entirely depleting the stock is a response to the presence of endogenous risk, we term this "pre-emptive depletion". The effect of pre-emptive depletion on coalition stability depends on the assumptions adopted regarding how the payoff from deviation is calculated. Initially, we retain the standard and commonly used assumption implicit in the two-stage game *a la* d'Aspremont et al. (1983). In this approach, membership choices are made in the first stage. In the second stage, membership is fixed and players receive payoffs which calculated in steady state according to the coalition formed. Under this standard assumption, we find that, in general, an endogenous risk of stock collapse increases Grand Coalition stability. This is particularly so if non-cooperation would result in pre-emptive depletion. When this is the case, the incentive to cooperate is so strong that the Grand Coalition is stable for any number of players and can therefore be described as a Great Fish Pact. This study therefore suggests a solution to the "puzzle of small coalitions" (Breton and Keoula, 2014), whereby the size of theoretically stable coalitions is smaller than what is observed in reality. Notably, the puzzle of small coalitions can be solved without the use of transfer payments. Transfer or "side" payments combined with asymmetric players is a frequently invoked and powerful method which increases the number of players for which cooperation can be sustained (Kaitala and Lindroos, 1998, Kennedy, 2003, Lindroos 2008, Pintassilgo et al. 2010, Long and Flaaten, 2011, Ellefsen, 2012, Breton and Keoula, 2014, Walker and Weikard, 2014). However, transfers payments have met much resistance in the policy world in general (Folmer et al., 1993) and are not implemented in direct financial terms in fisheries agreements (Munro, 2008). Further, the puzzle of small coalitions is solved without the use of sequential move games (e.g. Long and Flaaten, 2011) or alternative solution concepts, such as farsightedness (e.g. Breton and Keoula, 2012, Walker and Weikard, 2014).

Thus, endogenous risk solves the puzzle of small coalitions (the Great Fish War becomes a pact). However, we find that this result is very sensitive to the assumptions implicit in the standard two-stage game. We relax the assumption that payoffs are determined in steady states by considering a transition period whereby the stock size gradually adjusts after a deviation has occurred (cf. Sakamoto, 2014). Deviators receive payoffs during this transition period ("transition payoffs"). Transition payoffs turn out to be a decisive incentive for non-cooperation. Without transition payoffs, if deviation leads to pre-emptive depletion, then the payoff of deviation is zero. With transition payoffs, the process of pre-emptively depleting provides a payoff. We find that transition payoffs motivate non-cooperation to the extent that the Grand Coalition is only stable in a two-player game, and then, only if the discount rate is sufficiently low and the stock grows sufficiently slowly. The Great Fish Pact thus returns to a Great Fish War. Overall then, the paper shows how endogenous risk of stock collapse leads to dramatic increases in the potential for cooperation but qualifies this with the important proviso that this result holds only if transition payoffs are not considered.

The following Section 2 describes the bio-economic model and derives and analyses the envelope condition. Section 3 explains how Grand Coalition stability is calculated. Section 4 numerically analyses the model in terms of the stability of Grand Coalitions. Section 5 proceeds to consider the effects of including transition payoffs. Section 6 concludes.

2. Bio-economic model

We will first describe the biology of the system and introduce the objective functions. The objective functions determine the payoffs for a given coalition membership choice, which are then used to determine coalition stability. The set N of identical players represents n nations, indexed by i. Let us first define escapement e (the stock remaining after harvest) in a given period, t as

$$e_t \equiv x_t - \sum_i h_{i,t}, \qquad (1)$$

where $h_{i,t}$ is the harvest of player i in period t. The stock in the next period depends on escapement in the current period and is determined by the function $f(e_t)$ as follows:

$$x_{t+1} = f(e_t) = \beta e_t^{\alpha}, \qquad (2)$$

where $\beta > 0$ and $0 < \alpha < 1$. If there is no harvest, x_t increases over time to its carrying capacity, which is given by

$$\bar{x} = \beta^{\frac{1}{1-\alpha}}. \qquad (3)$$

We normalise the model such that the carrying capacity is fixed and not affected by the growth parameters α and β. Specifically, we set $\beta = \bar{x}^{(1-\alpha)}$ (from Equation (3)) and thus the carrying capacity $\bar{x}$ can be treated as a parameter in the model and we only need to specify α, which we term the "growth parameter". Note that lower α entails a higher growth rate.

The probability of the fish stock surviving into the next period, $0 \leq r < 1$, is endogenously determined by the escapement and is given by

$$r(e_t) = max\left(0, 1 - \frac{\gamma\bar{x}}{e_t}\right), \qquad (4)$$

where $0 < \gamma < 1$ and therefore $0 \leq r(e) < 1$. The parameter γ determines the critical escapement level $\gamma\bar{x}$, below which collapse is certain. For any escapement level $e_t > \gamma\bar{x}$ such that $max\left(0, 1-\frac{\gamma\bar{x}}{e_t}\right) = 1-\frac{\gamma\bar{x}}{e_t}$, it is easy to see that there is a strictly positive survival probability which is increasing in escapement at a decreasing rate. This means that there is a strictly positive risk of stock collapse at all stock sizes. This is reasonable because, for certain species, pressures from habitat loss or invasive species may mean that a risk of stock collapse is present even in the absence of any fishing (Field et al., 2009, Gjøsæter et al., 2009).

The instantaneous utility function for player *i* is given by

$$u(h_i) = max(0, ln(h_i)). \qquad (5)$$

This utility function avoids the problem of being undefined when harvest is zero, which is useful in our numerical approach. Appendix 1 explains and validates the choice of utility function in more detail.

The value function of player *i* is given by

$$V_i(x) = u(h_i) + r(e)\delta V_i\big(f(e)\big), \qquad (6)$$

where $0 < \delta < 1$ is the discount factor. The value function depends on instantaneous utility and the value of the stock in the future, subject to discounting and risk of collapse. Both the risk of collapse and the future value of the stock depend on escapement. Escapement depends on h_i and the sum of the harvests of other players h_{-i}. Therefore $e = x - h_i - h_{-i}$. Optimal harvest varies with stock size. Therefore, harvest level is represented as a function of stock size such that $h_i = \hbar_i(x)$, which we term the harvest function. Similarly, escapement is also a function of stock size, i.e. $e = x - \hbar_i(x) \ - \hbar_{-i}(x)$.

We can now begin to investigate how the harvest functions of our model differs from the LM harvest functions and what drives these differences. Optimal harvest maximises the value function for a given stock size. The envelope of these maxima across all stock sizes is the envelope curve. The envelope condition is a necessary condition for the maximisation of the envelope curve and thus gives insight into the conditions under which optimal stock size and harvest are achieved.

Lemma 1: *The envelope condition is given by* $\frac{\partial V_i}{\partial x} = \left(1 - \frac{\partial \hbar_{-i}}{\partial x}\right)\frac{\partial u}{\partial h_i}$.

Proof: *See Appendix 2.*

The envelope condition shows that player i's harvest is optimal when the marginal value of the fish stock $\frac{\partial V_i}{\partial x}$ is equal to the marginal value of harvest $\frac{du}{dh_i}$, which is adjusted by the proportion of the marginal harvest of all other players. The general format of the envelope condition, as in Lemma 1, is identical to that of the LM model (Mirman, 1979). However, the values of the derivatives are different because the endogenous risk function $r(e)$ affects the value function V_i. Therefore, harvest levels which satisfy the envelope condition will not be identical to the LM case. We can conjecture that the value function will be particularly steep at low stock sizes because small increases in stock size lead to large reductions in risk of collapse. Furthermore, the slope of the harvest functions will depend on whether x is less or greater than $\gamma\bar{x}$. By contrast, in the LM model the slope of the harvest function is constant. For a full analysis of the effects of endogenous risk in terms of Grand Coalition stability, we employ a numerical method, which is explained in the following section.

3. Grand Coalition stability

We now proceed to explain how the value function is optimised and how we use these results to analyse stability[1]. We test for Grand Coalition stability across a parameter space Ω.

Elements of Ω are triples (n, γ, θ) where $\theta = (\alpha, \rho)$. The parameter ρ is the discount rate where $0 < \rho \leq 1$ and $\delta = \frac{1}{1+\rho}$. The set of players in the coalition is given by M, where $m \equiv |M|$. We consider and compare two coalition structures. The first is the Grand Coalition given by $M = N$. A coalition member may deviate and will do so immediately should this be beneficial. This results in the second coalition structure; the partial coalition $M = N/\{k\}$, where $\{k\}$ is the free-rider. Coalition members choose harvest levels to maximise their joint utility and the free-rider chooses harvest to maximise individual utility. For each element of Ω, and for an infinite time horizon, we optimise the value function $V_i(x)$ for a given Ω to derive the optimised value functions $U_i(x_t; \Omega)$ for Grand Coalition members and for free-riders. This is achieved via the Bellman equation. For a coalition member j, the optimised value function $U_j(x_t; \Omega)$ is given by

$$U_j(x_t; \Omega) = \frac{1}{m} \max_H \left\{ \sum_{j \in M} \left(\max\left(0, ln\left(\frac{H}{m}\right)\right) + \frac{r(e_t)}{1+\rho} U_j(x_{t+1}; \Omega) \right) \right\} \quad \forall \; j \in M \;, \tag{7}$$

where $H = \sum_{j \in M} h_j$ is the coalition harvest. The value function for a free-rider k playing against the coalition $N \backslash \{k\}$ is given by

$$U_k(x_t; \Omega) = \max_{h_k} \left\{ u(h_k) + \frac{r(e_t)}{1+\rho} U_k(x_{t+1}; \Omega) \right\}. \tag{8}$$

The optimised value function $U_k(x_t; \Omega)$ is equivalent to that in the sole owner case, i.e. where $n = 1$. Optimised value functions are calculated numerically using value function iteration. The harvest functions $\hbar_i(x) \; \forall \; i \in N$ which result in optimised value functions over an infinite time horizon thus constitute Stochastic Markov Perfect Nash Equilibrium (SMPNE) harvest functions. SMPNE harvest functions allow us to determine the steady state stock size with harvesting at the stock size x^* for which the following equality holds;

$$x^* = \beta(x^* - \sum_{i \in N} \hbar_i(x^*))^{\alpha}. \tag{9}$$

Evaluating the optimised value functions at x^*_{GC} (the steady state under a Grand Coalition) and x^*_{FR} (the steady state if free-riding occurs) gives payoffs, which determine Grand Coalition stability if transition payoffs are not included. We use an Internal Stability solution concept, under which the Grand Coalition is stable if the payoff to a Grand Coalition member is greater than that of a free-rider playing against the coalition of remaining members. If transition payoffs are not included, the Grand Coalition is therefore internally stable if

$$U_j(x^*_{GC};\Omega) \geq U_k(x^*_{FR};\Omega) \quad (10)$$

The internal stability condition is also applied under the inclusion of transition payoffs, but in that case, payoffs in the transition between steady states after a deviation from the Grand Coalition are accounted for. For more details and discussion of the numerical techniques used, see Appendix 1.

4. Results of the standard two-stage game

This section presents stability results for our game under the assumption that transition payoffs are excluded. We begin by validating the numeral accuracy of our model. The validation demonstrates high statistical similarity of harvest functions from a numerical LM model with analytically derived LM harvest functions; see Appendix 1 for details. We thus proceed to analyse the numerical model of endogenous risk of stock collapse. We consider a range of parameters[2] for α and ρ such that $\alpha \in A = [0.01, 0.02, \ldots, 0.99]$ and $\rho \in P = [0.01, 0.02, \ldots, 1]$. We denote the set of all possible $\theta = (\alpha, \rho)$ as Θ such that $\Theta = A \times P$. The disaggregation of A and P allows us to determine the stability of coalitions across a full range of parameters and therefore to acquire insights of a similar depth to those provided by analytical results. We do not analyse $\alpha = 1$ in order to retain strict concavity in the growth function. Further, we begin by analysing a low value for the parameter, γ. Lower critical escapement levels $\bar{x}\gamma$ mean that certain and immediate stock collapse occurs for a smaller range of stock sizes. We therefore set $\gamma = 0.01$ and consider the effect of changing γ later.

Figure 1 presents the resource stock in steady state for the parameter space Θ using $n = 2$ as a representative example. The analysis will distinguish results for the Grand Coalition (Panel A) and the case where free-riding occurs (Panel B). Note that the free-rider case for $n = 2$ coincides with the Cournot-Nash equilibrium. For each element of Θ, multiple steady states can exist. We first present and analyse the largest stable steady state for each element of Θ and later, we will describe the different steady states which can exist for each element of Θ in more detail.

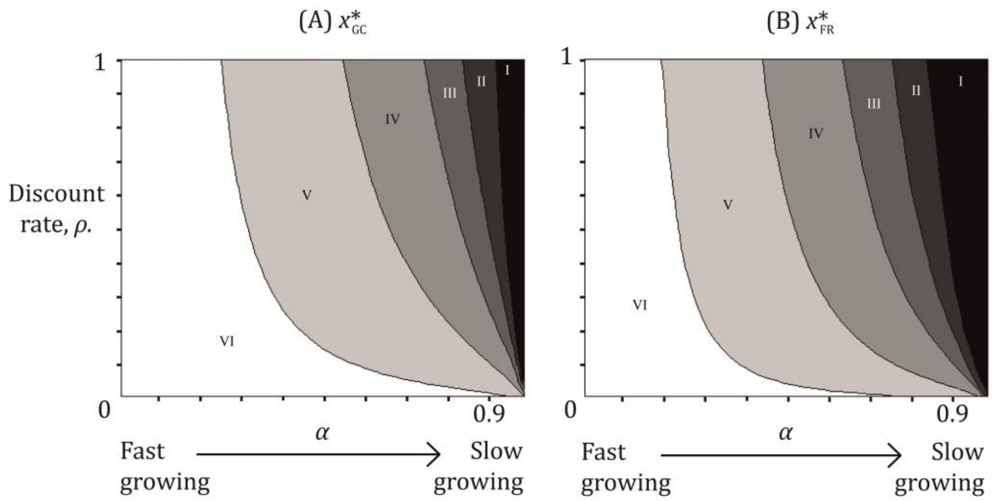

Figure 1: Largest stable steady states in the Grand Coalition case (Panel A) and the free-rider case (Panel B) in Θ space where $n = 2$, as an example. Using x_I^* to denote the steady state stock in Region I, x_{II}^* to denote the steady state stock in Region II and so on, the regions are defined as $x_I^* = 0$, $0 < x_{II}^* \leq 1000$, $1000 < x_{III}^* \leq 2000$, $2000 < x_{IV}^* \leq 4000$, $4000 < x_V^* \leq 7000$ and $7000 \leq x_{VI}^* < 10000$.

Figure 1 shows that the largest stable steady state is either zero, as in Region I, or positive as in all other regions. In Region I, it is optimal to fish the stock to extinction rather than waiting in the hope that stocks will increase and thus the risk of collapse will drop. We refer to this effect as “pre-emptive depletion”. Pre-emptive depletion occurs when α is high (the growth rate is low) and occurs for a greater range of α as the discount rate, ρ increases. Larger α and ρ mean that the stock has less value in the future: stock regeneration is limited, and any gains occurring in the future will be discounted. Further, the presence of endogenous risk makes those future gains uncertain. Hence, the choice is made to pre-emptively deplete the stock, thus gaining an immediate and certain payoff. In all other regions, “conservative management” occurs, whereby the largest stable steady state is positive. Conservative management occurs when the value of the future (in terms of α and ρ) is greater and thus maintaining a positive steady state becomes optimal, despite the risk of stock collapse.

Pre-emptive depletion occurs in a smaller area of the parameter space in the Grand Coalition than under free-riding. In general, free-riding reduces the steady state stock and therefore increases the risk of collapse. The increased risk of collapse stimulates pre-emptive depletion for lower values of α.

To build intuition for the above result, we proceed to analyse the differences in harvest functions between cases where pre-emptive depletion occurs and where conservative management occurs. In principle, each stock size can support a certain harvest level in equilibrium, as is usually visualized in the Sustained Yield (SY) curve (Clark, 2010). In this case, the SY curve requires that the following equality holds

$$x = \beta(x - h)^{\alpha}. \qquad (11)$$

Solving Equation (11) for harvest gives the SY curve as follows

$$\mathcal{y}(x) = x - \left(\frac{x}{\beta}\right)^{\frac{1}{\alpha}}. \qquad (12)$$

The intersection of the SY curve with a given harvest function is thus a steady state, though not necessarily a stable one. The relationship between the SY curve and the harvest function determines whether pre-emptive depletion or conservative management occurs. In Figure 2, we provide generic figurative representations of SY curves and harvest functions under conservative management and pre-emptive depletion. We also show stock dynamics in order to aid in interpreting the steady states.

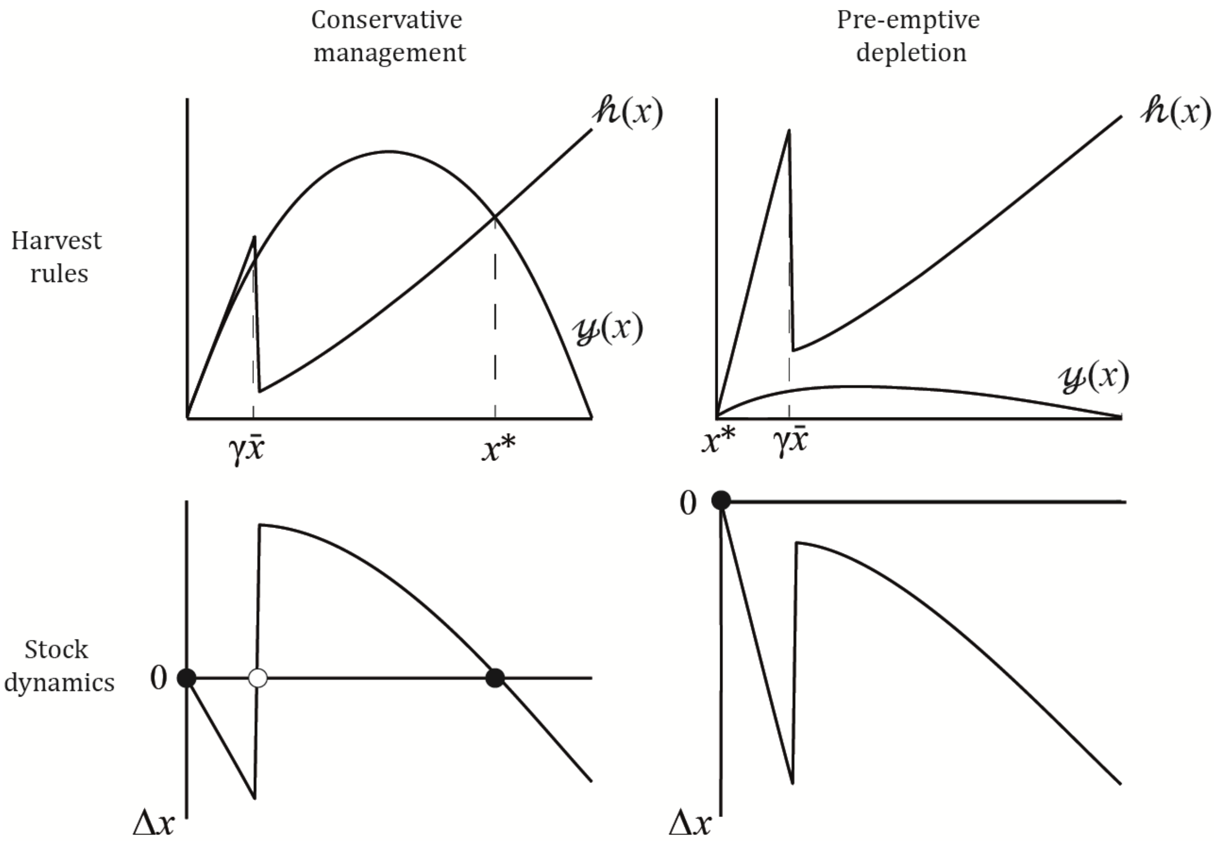

Figure 2: Generic representation of harvest functions, stock dynamics and steady states under conservative management and pre-emptive depletion where $\Delta x \equiv x_{t+1} - x_t$. Open circles indicate unstable steady states and closed circles represent stable steady states.

A more detailed analysis of the properties of harvest rules is given in Appendix 3. Both harvest functions in Figure 2 are linear and have a slope of 1 when $x \leq \gamma\bar{x}$. For these stock sizes, collapse is certain and therefore the entire stock is harvested immediately. A stock size of zero thus satisfies Lemma 1 and is a stable steady state under both conservative management and pre-emptive depletion. In the case of pre-emptive depletion, harvest is greater than growth for all stock sizes, and thus $x = 0$ is the only steady state. In the case of conservative management, harvest will be less than growth in some range of the harvest function. Therefore, both an unstable and stable steady state exist in addition to the zero steady state. Lemma 1 is satisfied for both stable steady states. Thus, pre-emptive depletion is formally defined as the existence of only one stable steady state, which is zero, and conservative management is defined as the existence of a positive stable steady state in addition to the zero stable steady state.

Payoffs are determined in the stable non-zero steady state if it exists (i.e. conservative management is adopted). If it does not exist (i.e. pre-emptive depletion occurs) then payoffs are zero because the steady state is zero. Payoffs are shown in Figure 3.

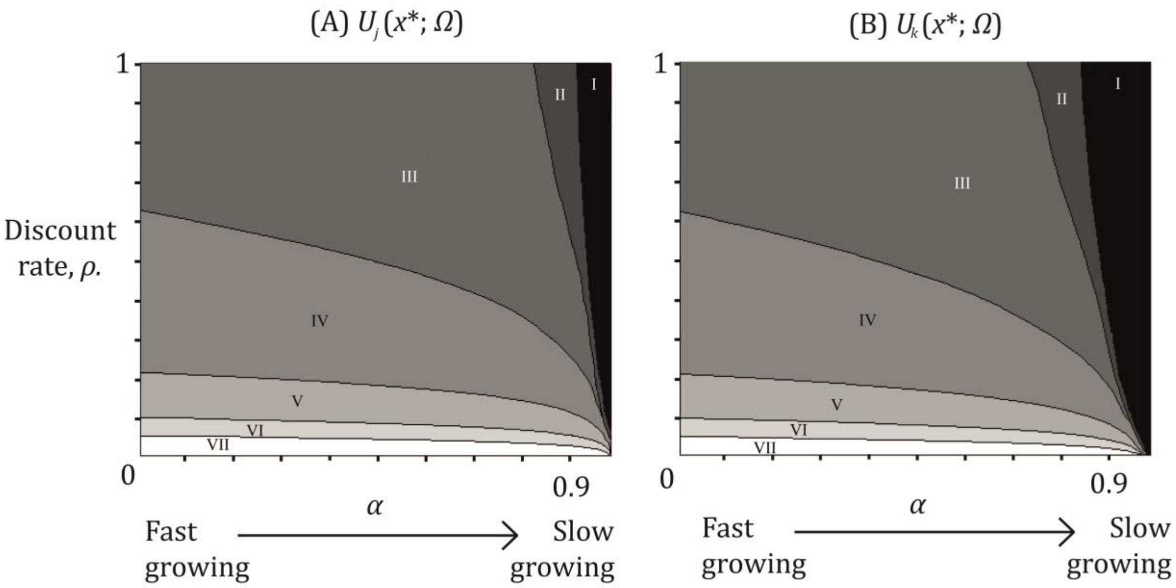

Figure 3: Payoffs for a Grand Coalition member (Panel A) and a free-rider (Panel B) in Θ space where $n = 2$, as an example. Using U^I to denote the payoff value in Region I, U^{II} to denote the payoff in Region II and so on, the regions are defined as $U^I = 0$, $0 < U^{II} \leq 10$, $10 < U^{III} \leq 20$, $20 < U^{IV} \leq 40$, $40 < U^V \leq 70$, $70 < U^{VI} \leq 110$ and $U^{VII} > 110$. Region I thus refers to parameterisations for which pre-emptive depletion occurs.

Both panels in Figure 3 show the same general pattern. Payoff increases as the discount rate decreases. The marginal effect of the discount rate is very pronounced at low discount rates. Also, payoff decreases as α increases. Recall, high α means that the stock grows more slowly. We also see an area for very high α where payoff is zero due to pre-emptive depletion.

To further the analysis, it is useful to formally define the threshold in the parameter space Θ which determines where payoffs change from non-zero to zero due to pre-emptive depletion – referred to as the depletion threshold. The depletion threshold is given by the borders between Region I and Region II in Figure 3. By comparing the relative locations of the depletion thresholds, we can see that pre-emptive depletion occurs for a larger area of Θ in the free-rider case, and the intuition is as follows. Free-riding reduces x^*, which increases the risk of stock collapse, and therefore provides greater incentives to harvest the entire stock in response to the higher risk.

Endogenous risk of stock collapse thus has profound effects on the incentives whether or not to free-ride. Free-riding reduces x^* which increases risk at an increasing rate due to the functional form of Equation (4). This means that free-riding leads to increases in risk which are disproportionally larger than the reduction in x^*. In turn, this risk amplification reduces the payoff of free-riding relative to Grand Coalition membership. We term this effect the "risk amplification effect"[3] of free-riding.

In order to analyse the stability of Grand Coalitions for different numbers of players *n*, we calculate payoffs in the free-rider and Grand Coalition cases in Θ space for each *n*. We can then explain how the risk amplification effect and changing numbers of players affect the stability of the Grand Coalition.

The results are shown in Figure 4(A) and will be discussed according to the effects of changing α, ρ and *n* and finally, we discuss the area marked ψ. Figure 4(A) shows "stability thresholds" which divide the parameter space into areas where the Grand Coalition is stable and unstable for a given number of players. Concerning α, in general, we see that for a given ρ, as α increases, the Grand Coalition can shift from being unstable to being stable. Higher α means a lower growth rate which in turns results in a lower x^*. Grand Coalitions maintain a higher x^* than coalitions when free-riding occurs. In this way, the risk amplification effect discourages free-riding disproportionally more at lower x^*. Accordingly, increasing α can result in a shift from unstable to stable.

Concerning ρ, in general, we see that for a given α, as ρ increases, the Grand Coalition can shift from being unstable to being stable. This is caused, again, by the risk amplification effect. Higher ρ means that the future is less valuable. Therefore, players prefer current harvest relatively more than future harvest. Accordingly, x^* decreases, the risk amplification effect increases and concurrently, Grand Coalition stability increases. Note also that the risk amplification effect explains the curved shape of the thresholds in Figure 4. This is because x^*decreases in ρ and the risk amplification effect increases in x^* at an increasing rate.

Concerning *n*, we see that in general, increasing the number of players decreases the number of parameterisations for which the Grand Coalition is stable. Grand Coalition stability relies on internalising the externalities of fishing, which are two-fold. Firstly, harvest by one player reduces the amount of fish available for the other player in the future. Secondly harvest by one player increases the risk amplification effect. Grand Coalitions internalize these externalities, but the benefits to each player of doing so are reduced as *n* increases because the socially optimal catch must be shared by more members. Thus, as *n* increases, we see a decrease in the number of parameterisations for which the Grand Coalition is stable.

As *n* increases from 3 to 32, the stability threshold approaches the free-rider depletion threshold in progressively smaller steps. At $n = 32$, the stability threshold is identical to the free-rider depletion threshold. This implies that the decision to free-ride by a single player will result in pre-emptive depletion, which gives a payoff of zero in steady state. As n increases beyond 32, the socially optimal harvest must be shared by more players, but always remains non-zero, while the free-rider payoff remains zero. Hence, the stability threshold does not change for $n \geq 32$. In other words, the stability threshold has thus converged at $n = 32$.

The grey area ψ in Figure 4 refers to the subset of Θ for which $U_j(x^*;\ \Omega\ ) = U_k(x^*; \Omega) = 0$, i.e. where pre-emptive depletion occurs in both the Grand Coalition and free-rider cases. When this is the case, stability is trivial because, when payoffs are evaluated in the steady state, there are no incentives for players to fish either in or out of the coalition. Therefore, Grand Coalitions are non-trivially stable for some values of Θ for all $n > 1$. Grand Coalitions are non-trivially stable for stocks which are slow growing, but not so slow growing that the stock is pre-emptively depleted. This result is due to endogenous risk.

The above analysis of stability raises the question, what determines the location of the stability thresholds? Also, why do the stability thresholds converge at $n = 32$? We will now demonstrate that this finding is sensitive to the parameter γ, which determines the critical escapement level $\gamma\bar{x}$ below which stock collapse is certain. We do so by increasing γ from 0.01 to 0.05. Increasing γ leads to an increase in the probability of collapse for all stock sizes. Therefore, as would be expected, increasing γ leads to an increase in the size of the area of Θ displaying pre-emptive depletion. This, in turn has an effect on the stability thresholds as demonstrated in Figure 4(B).

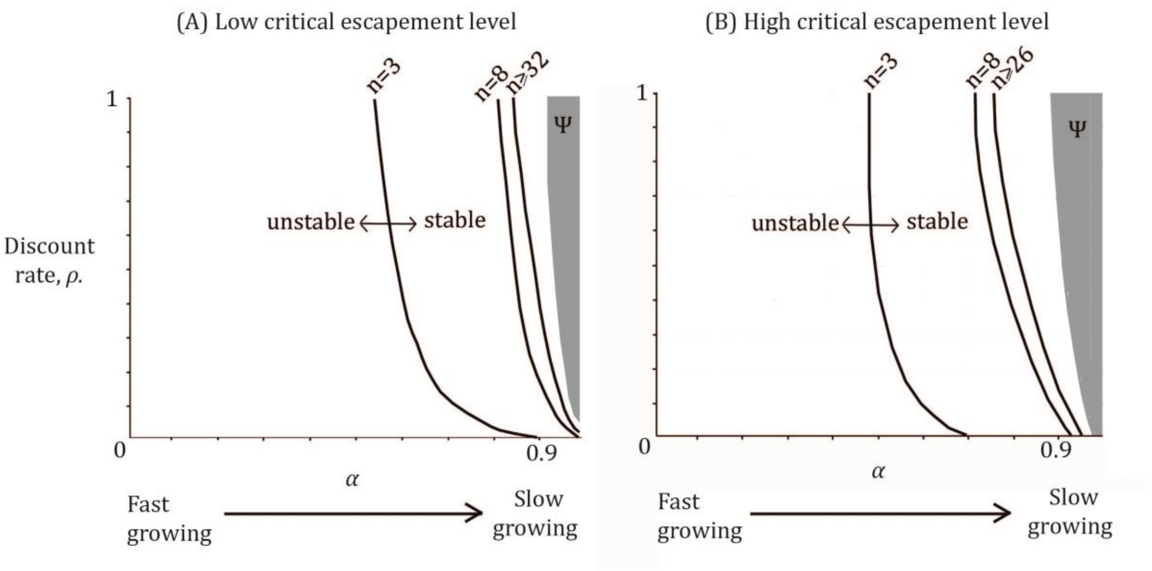

Figure 4: Stability thresholds between stable and unstable Grand Coalitions for selected numbers of players in Θ space with $\gamma = 0.01$ (Panel A) and $\gamma = 0.05$ (Panel B). We illustrate the interpretation of the thresholds explicitly for $n = 3$. For all stability thresholds, to the left of the stability threshold, the Grand Coalition is unstable. To the right of the stability threshold, the Grand Coalition is stable. For $n = 2$ the Grand Coalition is stable for all parameters. The grey area, marked ψ, is the subset of Θ for which $U_j(x^*; \Omega) = U_k(x^*; \Omega) = 0$, i.e. where pre-emptive depletion occurs in both the Grand Coalition and free-rider cases.

In comparison to Figure 4(A), Figure 4(B) shows that an increase in γ from 0.01 to 0.05 shifts all stability thresholds for $n > 2$ to slightly lower values of α and reduces the number of players at which the stability thresholds converge 32 to 26. To recap, the parameter γ determines the critical escapement level below which collapse is certain. Therefore, for stocks with a higher critical escapement level, we observe more pre-emptive depletion. At the same time, cooperation exists for a larger part of the parameter space because there are greater benefits to internalising the risk of stock collapse.

5. Including transition payoffs

The previous section has shown that a player receiving strictly positive payoffs in the Grand Coalition can receive a zero payoff upon deviation. This effect drives the possibility for a stable Grand Coalition for any number of players. However, zero payoffs from deviation are due to the assumption that the state of the stock jumps immediately from x_{GC}^* to x_{FR}^*. We therefore relax this assumption and thus account for transition payoffs.

5.1. Method for including transition payoffs

In order to test the effects of including transition-payoffs between steady states, we construct a forward model. Generally speaking, forward models take backwardly induced optimal control functions and applies them to a model which runs forward in time in order to fully identify the dynamics of the system. In our case then, for a given element of Θ, the forward model takes the harvest functions, $\hbar_i(x)\ \forall\ i$ corresponding to the free-rider case with a starting stock size of x_{GC}^*. In the first period, we apply the harvest functions to the stock, thus calculating utility and escapement. Escapement and the growth function determine the stock in the next period and the process is repeated until the stock size converges to x_{FR}^*. The time taken for convergence is given by T. The total payoff is given by the instantaneous utility in the Grand Coalition, plus the discounted expected sum of payoffs in the transition, plus the discounted lifetime value of the fisheries in the free-rider steady state. The payoff in the free-rider steady state is reduced as a result of these payoffs being pushed further into the future and the probability that collapse occurs during the transition period. Hence, we adjust the free-rider steady state payoffs by the function $\xi(\rho, T, R)$ where $0 < \xi(\rho, T, R) < 1$ and $R \equiv \prod_{t=1}^{T} r(e_t)$. Thus the total payoff including the transition period is given by

$$u(\hbar_k(x_{GC}^*)) + \sum_{t=1}^{T} \delta^t r(e_{t-1})\, u\big(\hbar_k\big(f(e_{t-1})\big)\big) + \xi(\rho, T, R) U_k(x_{FR}^*). \qquad (13)$$

We can thus repeat the analysis of Section 4, accounting for transition payoffs.

5.2. Results of including transition payoffs

This section presents the results of including transition payoffs. We find that the maximum size of a stable Grand Coalition is two. We find that stability only exists for a small area of the parameter space, as shown in Figure 5.

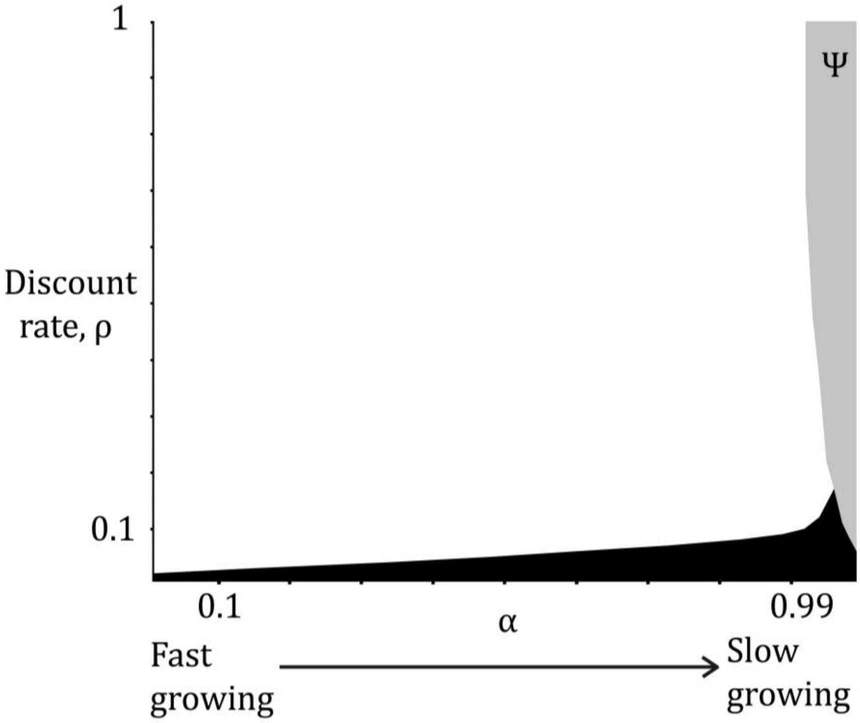

Figure 5: Stability of a two-player Grand Coalition in Θ space with transition payoffs where $\gamma = 0.01$. The black area shows elements of Θ for which the 2-player Grand Coalition is stable. The grey area, marked ψ, is the subset of Θ for which $U_j(x^*; \Omega) = U_k(x^*; \Omega) = 0$, i.e. where pre-emptive depletion occurs in both the Grand Coalition and free-rider cases.

The potential for stability is lower when transition payoffs are included due to the increased payoff to deviators available in the transition period. Grand Coalitions of two-players are stable when the discount rate is sufficiently low. Stability can also exist for slightly higher discount rates when α is larger. This conforms closely to the result of Kwon (2006) who studies partial coalitions and finds that partial coalitions of two players are stable only if $\alpha(1 + \rho)^{-1}$ is sufficiently high. In our case however, the area of stability has a long tail which encompasses progressively lower discount rates. This is due to endogenous risk. Players who are more concerned with the future prefer Grand Coalition membership due to the reduced risk of stock collapse.

6. Conclusions

This study analyses the classic Levhari and Mirman model of the Great Fish War (1980) under an endogenous risk of stock collapse. The objective is to analyse the effects of endogenous risk of stock collapse on the stability of Grand Coalitions. The results of the standard two-stage game show that a risk of stock collapse increases the potential for cooperation. Further, the results show that cooperation can be sustained for any number of players if the stock is sufficiently slow growing, but not so slow growing that exploitation is not sustainable in the long run (i.e. if pre-emptive depletion occurs). Because the potential for cooperation exists for any number players under an endogenous risk of stock collapse, the Great Fish War becomes a Great Fish Pact.

Further considering the standard two-stage game, the result relating to the growth parameter α has interesting management implications, particularly for deep-water fisheries which are often slow growing (Gordon, 2003). Slow growing stocks are more vulnerable to over-exploitation (Roberts, 2002, Neubauer et al. 2013). This paper supports this proposition for very slow growing stocks. Indeed, the results suggest that the stock would be fished to extinction. However, because Grand Coalitions are stable for slow (not very slow) growing stocks regardless of the number of players, the potential for sustainable management is somewhat less bleak.

Most importantly, the results offer counter-evidence to a long-running implicit conclusion in the literature, namely that the number of players is the most important determinant of potential for stable Grand Coalitions. This study shows that when there are more than a certain number of players, further increases in the number of players has no effect on the area of the parameter space for which the Grand Coalition is stable. The reason for this is that in previous models, increasing the number of players results in lower steady state stocks and these low steady states can be sustained *ad infinitum* with no risk that the stock might collapse. The result presented in this paper regarding the independence of stability from the number of players is entirely the result of relaxing this very common, yet inappropriate, assumption.

In general, this study contributes to the discussion regarding what makes coalitions in fisheries management stable. We observe empirically that coalitions can be stable for large numbers of players but theoretical models tend to be more pessimistic (Hannesson, 2011). Breton and Keoula (2014) refer to this as the "puzzle of small coalitions" and show that larger coalitions can be achieved by using asymmetric players in a game with first mover advantage, thus partly solving the puzzle. Asymmetric players combined with transfer payments can contribute to solving the puzzle (e.g. Pintassilgo et al. 2010), as can the type of solution concept used (e.g. Breton and Keoula, 2012, Walker and Weikard, 2014). We have shown that endogenous risk of stock collapse allows the potential for cooperation for any number a players; a possibility which has not yet been identified in the literature. Further, cooperation for any number of players can be sustained without the use of transfer payments.

However, our results are sobering in the sense that the potential to seize transition payoffs swamps out the prospects for cooperation and hence, the Great Fish Pact returns to being a Great Fish War. Under the Great Fish Pact, farsightedness, sequential move games and transfer payments are not required to address the puzzle of small coalitions. However, because the Great Fish Pact does not hold if transition payoffs are included, farsightedness, sequential move games and transfer payments still have an important role to play in addressing the puzzle of small coalitions. Further study is required to determine the effects of these assumptions on coalition stability when transition payoffs are included.

Acknowledgements

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Appendix 1: Utility function and numerical accuracy

This appendix discusses numerical accuracy with respect to our utility function and interpolation error.

The utility function

The utility function $u(h) = ln(h)$ is undefined when $h = 0$. A risk of stock collapse implies that harvest level $h = 0$ may occur. We therefore require a utility function which avoids this problem but is sufficiently similar to $ln(h)$, such that we know that differences in the stability of Grand Coalitions between our model and the LM model can be attributed solely to the presence of endogenous risk. Therefore, we use the utility function $max\big(0, ln(h)\big)$ which is equal to $ln(h)$ if $h \geq 1$. The range of the utility function is bounded in that it is non-negative and harvest cannot exceed the carrying capacity. We set the carrying capacity at $\bar{x} = 10{,}000$ (by setting $\beta = 10{,}000^{1-\alpha}$) such that our utility function differs from $ln(h)$ only for a small fraction of its range. Hence, using a large values for $\bar{x}$ ensures h is extremely infrequently between zero and 1 and thus the utility function $max\big(0, ln(h)\big)$ performs, in practise, the same as $ln(h)$ for all $h > 0$. Where $h = 0$ however, the function $max\big(0, ln(h)\big) = 0$ and thus performs differently from the original LM model.

In order to evaluate whether our utility function has any effect on the outcome of the model, we numerically solve the deterministic (original) LM model with the utility function

$max(0, ln(h))$ and evaluate the similarity of the numerically derived harvest function to the analytical solution of the original LM model. We consider the sole-owner case and consider all harvest functions in Θ space, as defined in Section 4. To test the similarity, we calculate a standard R^2 statistic to evaluate the extent to which the numerical harvest function can be explained by the analytical harvest function. The results are reported in Figure A1.

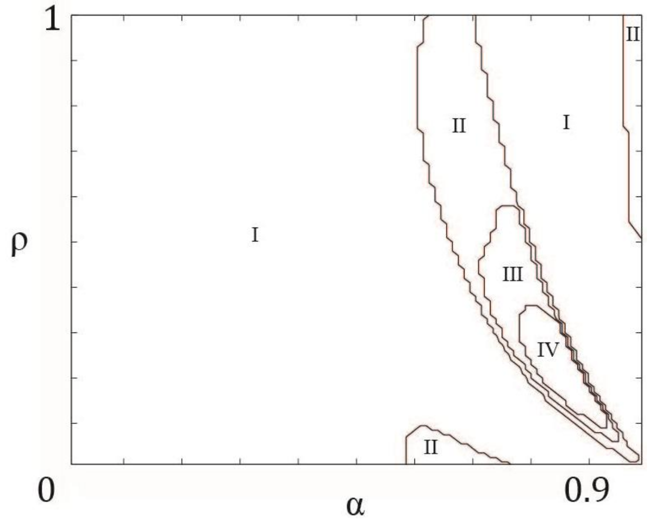

Figure A1: R^2 statistics in Θ space determining the accuracy of a numerical 1-player deterministic LM model. Each region (I through IV) represents a range of R^2 statistics. Using R_I^2 to denote the R^2 value in Region I, R_{II}^2 to denote the R^2 in Region II and so on, the regions are defined as $0.9998 < R_I^2 \leq 1$, $0.9994 < R_{II}^2 \leq 0.9998$, $0.9990 < R_{III}^2 \leq 0.9994$ and $0.9984 \leq R_{IV}^2 \leq 0.9990$.

The results show that the numerical model can recreate analytical results to a high degree of accuracy. It also shows that particular areas of Θ space are more numerically challenging to estimate than others. The location of the area of largest error, consisting of the union of Regions III, IV and the larger of the two areas marked as Region II is particularly important. The accuracy of stability thresholds in this particular region is therefore somewhat reduced. Overall, the high R^2 values confer confidence in the accuracy of the numerical method, thus supporting our use of the $max(0, ln(h))$ utility function. While numerical accuracy is high, we cannot be sure whether the inaccuracy is due to the utility function or due to interpolation error.

Interpolation Error

Error in the model may also result from interpolation error. Interpolation error results from the discretised state space. We set the state space as $x_t \in X = [0, 1000, 2000, \dots ,10000]$. In the case that the steady state x^* is less than 1000, the model increases the number of elements in the state space in order to more accurately identify the steady state. Discretisation of the state space means that $U_i(x_{t+1}; \Theta)$ is only known for each element of X. Almost always, x_{t+1} is not an element of X and therefore we use interpolation to estimate $U_i(x_{t+1}; \Omega)$. Error in interpolation means that future value in the value function deviates from its true value and this results in deviations of the harvest function from their true form. The effect of any interpolation error on the harvest function is reduced when the value function is determined by instantaneous utility relatively more than future value. Future utility has relatively less of an effect on the value function when the discount rate is high. This can be seen in Figure A1, where error in the numerically estimated LM model tends to be higher for lower discount rates. This suggests that some of the inaccuracy in A1 is due to interpolation error. Finally, it is useful to note that future value also has relatively less of an effect on the value function if future value is reduced due to endogenous risk. Therefore, endogenous risk has the side effect of reducing the effect of interpolation error in our model, thus increasing our confidence in the results.

Appendix 2: Deriving the envelope condition

Deriving the envelope condition requires determining the first order conditions of Equation (6) with respect to harvest and stock. The first order condition w.r.t. harvest h_i is given by

$$\frac{\partial V_i}{\partial h_i} = \frac{du}{dh_i} + \frac{\partial r}{\partial e}\frac{\partial e}{\partial h_i}\delta V_i\big(f(e)\big) + r(e)\delta\frac{\partial V_i}{\partial f}\frac{\partial f}{\partial e}\frac{\partial e}{\partial h_i} = 0. \quad \text{(A2.1)}$$

From Equation (1) it follows that $\frac{\partial e}{\partial h_i} = -1$. Equation (A1.1) therefore simplifies to

$$\frac{du}{dh_i} = \frac{\partial r}{\partial e}\delta V_i\big(f(e)\big) + r(e)\delta\frac{\partial V_i}{\partial f}\frac{\partial f}{\partial e}. \quad \text{(A2.2)}$$

Substituting $\hbar_i(x)$ for h_i and $\hbar_{-i}(x)$ for h_{-i} in Equation (6) such that $e \equiv x - \hbar_i(x) - \hbar_{-i}(x)$ and differentiating Equation (6) w.r.t. x gives

$$\frac{\partial V_i}{\partial x} = \frac{\partial u}{\partial \hbar_i}\frac{\partial \hbar_i}{\partial x} + \delta\left[\frac{\partial r}{\partial e}\left(1 - \frac{\partial \hbar_i}{\partial x} - \frac{\partial \hbar_{-i}}{\partial x}\right)V_i\big(f(e)\big) + r(e)\frac{\partial V_i}{\partial f}\frac{\partial f}{\partial e}\left(1 - \frac{\partial \hbar_i}{\partial x} - \frac{\partial \hbar_{-i}}{\partial x}\right)\right]. \quad \text{(A2.3)}$$

Substituting $\frac{\partial u}{\partial \hbar_i}$ in the above with $\frac{du}{dh_i}$, then substituting $\frac{du}{dh_i}$ with the right hand side of Equation (A2.2), then simplifying gives

$$\frac{\partial V_i}{\partial x} = \left(1 - \frac{\partial \hbar_{-i}}{\partial x}\right)\left(\frac{\partial r}{\partial e}\delta V_i\big(f(e)\big) + r(e)\delta\frac{\partial V_i}{\partial f}\frac{\partial f}{\partial e}\right). \quad \text{(A2.4)}$$

Equation (A2.2) is substituted into Equation (A2.4), thus giving the envelope condition

$$\frac{\partial V_i}{\partial x} = \left(1 - \frac{\partial \hbar_{-i}}{\partial x}\right)\frac{du}{dh_i}. \quad \text{(A2.5)}$$

Appendix 3: The properties of harvest functions.

This appendix discusses the properties of harvest functions in terms their monotonicity and their form in relation to point $x = \gamma\bar{x}$. We present the harvest function for $\alpha = 0.99$, $\rho = 0.01$, $\gamma = 0.02$ and $x \in X = [0, 100, 200, \ldots, 10000]$ in the sole-owner case in Figure A3. We find that harvest functions are not necessarily monotonic, which is expected given that it may be optimal to harvest the entire stock at low resource levels. Furthermore, Figure A3 also indicates that the harvest function does not necessarily attain a (local) maximum where $x = \gamma\bar{x}$. It can still be optimal to harvest all of the stock immediately, even if collapse is not certain. Thus the maximum of the harvest function occurs at $x = 300$ whereas $\gamma\bar{x} = 200$.

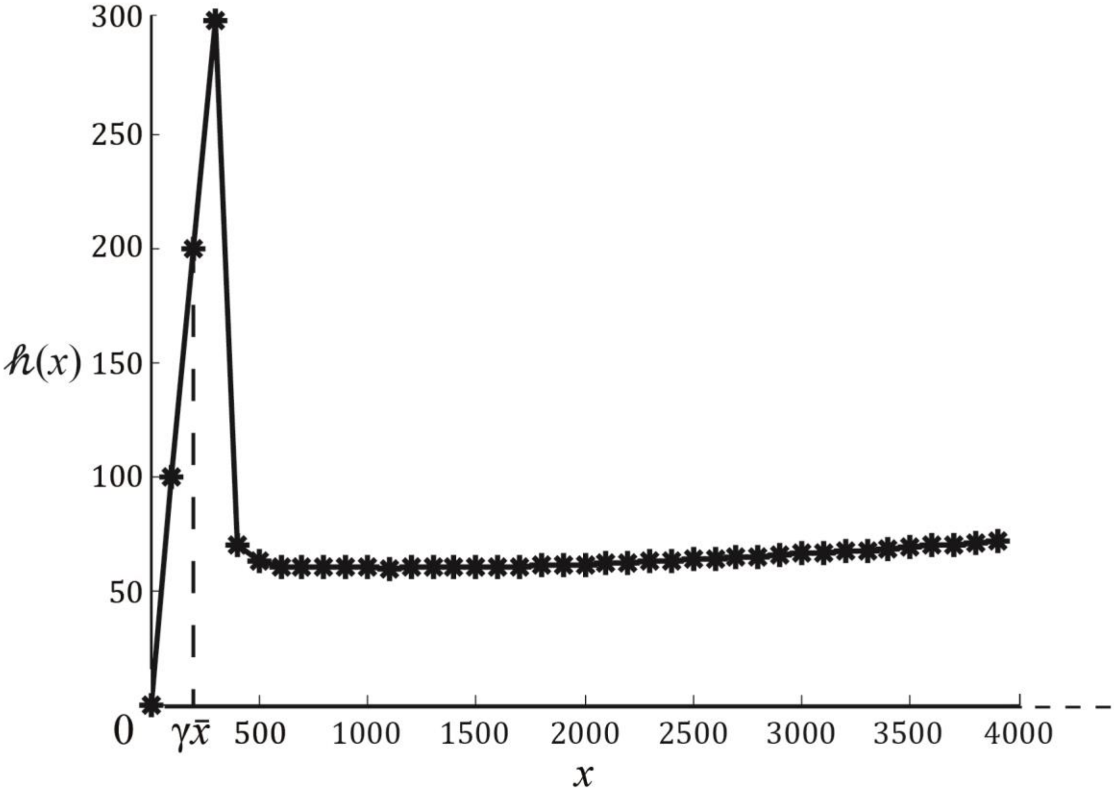

Figure A3: The harvest function where $\alpha = 0.99$, $\rho = 0.01$ and $\gamma = 0.02$ demonstrates non-monotonicity. Stars are actual data points. The harvest function is defined up to $x = 10000$. We limit the x axis to focus on lower values of x.

Footnotes

1. All numerical analyses were performed in MATLAB 7.14 (R2012a) (Mathworks Inc.). The code for calculating payoffs and steady states as well as the code for validating the model (Appendix 1) are available from the corresponding author on request.

2. In the original LM model the discount factor is between 0 and 1 whereas we test the discount rate between 0 and 1. This means that we test discount factors between 0.5 and 1.

3. The risk amplification effect is similar to the "risk reduction effect" of Ren and Polasky (2014). The risk reduction effect refers to the reduction in endogenous risk when stock increases.

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