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GROWTH AND MEASUREMENT UNCERTAINTY IN AN UNREGULATED FISHERY

ANNE B. JOHANNESEN*
Department of Economics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway
E-mail: anne.borge@svt.ntnu.no

ANDERS SKONHOFT
Department of Economics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

ABSTRACT. Complete information is usually assumed in harvesting models of marine and terrestrial resources. In reality, however, complete information never exists. Fish and wildlife populations often fluctuate unpredictably in numbers, and measurement problems are frequent. In this paper, we analyze a time-discrete fishery model that distinguishes between uncertain natural growth and measurement error and in which exploitation takes place in an unregulated manner. Depending on the parameterization of the model and at which point of time uncertainty is resolved, it is shown that expected harvest under ecological uncertainty may be below or above that of the benchmark model with no uncertainty. On the other hand, when stock measurement is uncertain, expected harvest never exceeds the benchmark level. We also demonstrate that the harvesting profit, or rent, under uncertainty may be above that of the benchmark situation of complete information. In other words, less information may be beneficial for the fishermen.

KEY WORDS: Fishing, uncertainty, unregulated exploitation, profitability.

1. Introduction. Complete information is usually assumed in harvesting models of marine and terrestrial resources. In reality, however, complete information never exists. Fish and wildlife populations frequently fluctuate unpredictably in numbers (e.g., Lande et al. [2003]), and particularly in fisheries, severe measurement problems are

*Corresponding author: Anne B. Johannesen; Department of Economics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway, anne.borge@svt.ntnu.no
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present (e.g., Gulland [1986], Hilborn and Walters [1992]). In addition, future prices and costs are uncertain (see, e.g., Andersen [1982]). In this paper, however, economic uncertainty is left aside and only ecological uncertainty[1] and measurement problems are considered. In his fundamental paper, Reed [1979] modeled a stochastic biological process in which environmental shocks occur between previous fishing period and current recruitment. He considered a regulator that harvests sequentially and aims to maximize expected present-value profit. When assuming that harvest is chosen *after* uncertainty has been resolved, he found a "bang-bang" constant escapement harvest to be optimal. In contrast to Reed [1979], Clark and Kirkwood [1986] assumed that the regulator chooses a harvest policy *before* uncertainty is resolved. In this context, they showed that the optimal solution is a nonconstant escapement policy that may be above or below that of Reed's model.

Both Reed [1979] and Clark and Kirkwood [1986] assumed that the harvesters always take the quota set by the regulator and hence ignored any possible information asymmetry between regulator and harvesters. Weitzman [2002], on the other hand, assumed that the regulator makes a decision and sets the quota *before* uncertainty is resolved, whereas the fishermen choose their harvesting effort *after* the resource stock has been observed. Therefore, ecological information asymmetry is present between the regulator and the harvesters. In this setting, Weitzman analyzed the performance of a landing tax versus a quota and found the landing tax to be most efficient. However, as the individual harvesters know more than the regulator and adjust their effort and harvest accordingly, this result is not a big surprise. The efficiency of landing fees versus quota control was further examined by Hannesson and Kennedy [2005].

As far as we can see, there is really no distinction between uncertainty in the biological processes, that is, ecological uncertainty and stock error measurement, in these papers. Recruitment occurs after the end of the fishing period, and the stochastic process is connected to the realization of the relationship between recruitment and escapement (i.e., fish remaining alive at the end of the fishing period). The stochastic process is modeled by multiplying the recruitment function, assumed to be known exactly, by a random factor. However, whereas Reed and Weitzman interpreted the stochastic process as ecological uncertainty, Clark and Kirkwood assumed that it might reflect stock measurement errors as well. Hence, although their interpretations differ, the papers are similar in the technical modeling of the stochastic process. Sethi et al. [2005] extended Reed's and Clark and Kirkwood's models by distinguishing between ecological uncertainty and measurement error within a social planner framework.[2] They modelled both stochastic processes as multiplicative to the escapement–recruitment function and found that uncertainty had a significant optimal escapement impact only when measurement error is high. The present paper also distinguishes between ecological uncertainty and measurement error. In contrast to the social planner model of Sethi et al., however, we analyze the effects of uncertainty within the framework of an *unregulated* fishery in which it is allowed for a positive rent.

In an unregulated fishery, the so-called open-access fishery has for many years served as the benchmark (e.g., Gordon [1954], Homans and Wilen [1997]). Within such an exploitation regime, uncertainty has no rent effect as profitability, at least in the long term, as per definition, equalizes zero. However, in an unregulated fishery allowing for a positive rent, introduction of uncertainty generally affects profitability and the catch of the fishermen. In what follows, such an unregulated fishery is examined. Contextually, the sort of resource management we have in mind is a local in-shore fishery in a typical developing country setting. It may fit to the FAO ([2007], pp. 7–8) definition of a small-scale fishery "broadly characterized as a dynamic sector employing labour intensive harvesting…to exploit marine and inland water fishery resources…(where the)…activities…are often targeted on supplying fish and fishery products to local and domestic markets, and for subsistence consumption…." In such a small-scaled fishery, it is assumed that the number of fishermen (or vessels) flowing into (and out of) the fishery caused by changing profitability opportunities is small, or even negligible. This may be due to a possible license system that restricts the entrance of new fishermen. We abstract from any further regulations, or enforcement, which typically is the case in such small-scale fisheries (see, e.g., Pomroy et al. [2009] with examples from Vietnam). The exploitation scheme may vary because of circumstances (e.g., Bromley [1991] for a general discussion), but here we focus on a situation in which the fishermen lack any long-term view on the resource utilization. Within this framework, it is assumed that they aim to do it as "as good as possible," approximated by short term, or myopic, profit maximization. The exploitation hence takes place within the management setting described by, among others, Baland and Platteau [1996] as an *unregulated local common property* regime. It fits to the notion of a local common because the number of exploiters is fixed, and it fits to the notion of unregulated exploitation because it lacks any long-term view on the resource utilization. It may also be quite similar to Ostrom's [1990] notion of a small-scale local common-pool resource but in which economic, cultural, and economic changes, in short "modernization," may have changed the way in which the fishery resources are exploited. Unregulated resource management schemes such as the present one are studied in numerous papers (see, e.g., Brander and Taylor [1998]).

Within this institutional setting, we analyze how ecological uncertainty and measurement error affect harvest, stock growth, and profitability. We distinguish between the situations in which harvest takes place *after* the fishermen have observed the realization of the uncertainty and the situations in which harvest takes place *before* uncertainty is revealed. We deviate from the abovementioned escapement–recruitment models by assuming that harvest occurs after natural growth. By doing so, we allow for a conceptual distinction between ecological uncertainty and measurement error. A simple biomass model in which the individual harvesters employ a generalized Schaefer harvesting function is considered, and it is demonstrated that the effects of the two types of uncertainty depend crucially on the harvest scale properties.

The paper is structured as follows. In the next section, as a benchmark, the harvesting model is formulated without uncertainty. In Section 3, ecological uncertainty is introduced, and in Section 4, measurement errors are studied. Although these sections deal with stock growth and harvesting only, the economic consequences are analyzed in Section 5. Section 6 gives some numerical illustrations, and Section 7 summarizes the main findings.

2. Benchmark model. As a benchmark, just to fix ideas, we consider the simple situation without uncertainty. The biomass ("a fish is a fish") is assumed to be exploited instantaneously and simultaneously by n identical harvesters and in situations in which n is fixed (see above).[3] The population growth may hence be written as

$$X_{t+1} = X_t + F(X_t) - nh_t, \tag{1}$$

where X_t is the stock at time t, h_t is the individual harvest, and $F(X_t)$ is the natural growth function, assumed to be density-dependent in a standard manner (see below).

Harvest is governed by a generalized Schaefer function. When assuming that harvest takes place after natural growth (see above), the individual harvest function reads $h_t = qe_t^{\alpha}(X_t + F(X_t))^{\beta}$, with e_t as effort and q ("catchability" coefficient), α (input elasticity), and β (stock elasticity) as parameters. The case $\alpha = \beta = 1$ is frequently used in the literature and coincides with the standard Schaefer harvesting function. However, for many fish stocks, β may be substantial lower than 1 ("schooling stocks"), and there are good reasons to believe that the return on effort is decreasing so that α also is below 1. In what follows, these elasticities are constrained as $0 < \alpha < 1$ and $0 < \beta \leq 1$. For given and known harvest price and effort cost, p and c respectively, the current individual profit is $\pi_t = pqe_t^{\alpha}(X_t + F(X_t))^{\beta} - ce_t$. In this unregulated fishery, exploitation takes place in a myopic manner (Section 1); that is, individual profit is maximized while neglecting the stock effect (zero shadow price).[4] Maximization for a given stock $X_t > 0$ yields $e_t^* = \{(\alpha pq/c)(X_t + F(X_t))^{\beta}\}^{1/(1-\alpha)}$. When inserted into the harvest function, we find the (myopic) optimal harvest locus as $h_t^* = q(\alpha pq/c)^{\alpha/(1-\alpha)}(X_t + F(X_t))^{\beta/(1-\alpha)}$.[5,6]

In what follows, a distinction is made between the constant return to scale (c.r.s.) case $(\alpha + \beta) = 1$ and the increasing return to scale (i.r.s.) case $(\alpha + \beta) > 1$.[7] To work with tractable analytical expressions, the c.r.s. case is considered when $\alpha = \beta = 0.5$, and the i.r.s. case is considered when $\alpha = 0.5$ and $\beta = 1$ (but see Section 7 and the Appendix). In the c.r.s case, we obtain the linear individual harvesting locus:

$$h_t^* = a(X_t + F(X_t)), \tag{2}$$

where $a = pq^2/2c$. When next inserted into equation (1), the stock growth becomes

$$X_{t+1} = X_t + F(X_t) - na(X_t + F(X_t)). \tag{3}$$

This is a first-order nonlinear difference equation in which the dynamics generally depend on the parameterization of the model. However, typically, there will be no oscillations, and equilibrium will be approached monotonically.[8] The steady-state stock X^* is found through $F(X^*) = na(X^* + F(X^*))$, or $F(X^*) = (na/(1 - na))X^*$. Natural growth is given by the standard logistic function $F(X_t) = rX_t(1 - X_t/K)$, with r as the intrinsic growth rate and K as the carrying capacity. Therefore, the steady-state $X^* > 0$ will be unique.

The i.r.s. case ($\alpha = 0.5$, $\beta = 1$) yields $h_t^* = a(X_t + F(X_t))^2$. The population dynamics change accordingly compared with the c.r.s. case. So does the steady-state stock, which is now found through $F(X^*) = na(X^* + F(X^*))^2$. If $r < 1$ (which holds for most harvestable species), it can be shown that the right-hand side of this equilibrium condition slopes upward in the interval $[0, K]$. The steady-state $X^* > 0$ will then again be unique.

3. Ecological uncertainty. We now introduce uncertainty and start by analyzing a situation with uncertain recruitment, or natural growth. Lande et al. [2003] discusses the biological foundation of this type of uncertainty, and in which a crucial distinction goes between environmental uncertainty and population uncertainty. In our simple biomass framework, however, both these types are captured by the random variable θ_t, assumed to be independent and identically distributed (i.i.d.) over time, with unit mean, $E(\theta_t) = 1$, and finite support, $0 < \theta_{\text{low}} < \theta_t < \theta_{\text{high}} < \infty$. Therefore, the stock growth now writes:

$$X_{t+1} = X_t + \theta_t F(X_t) - nh_t. \tag{4}$$

As already indicated, two situations are studied. First, it is assumed that natural growth is known before the harvest decision. Second, harvesting takes place before natural growth uncertainty is resolved. In both cases, it is supposed that the stock level at the beginning of period t can be observed for sure; that is, all harvesters know X_t.[9]

3.1. Uncertainty resolved before harvesting. Assume that natural growth is known *before* the harvest decision, which may be seen as an analog to the Reed [1979] model. When θ_t is known and hence is *deterministic* to the harvesters, the individual harvester aims to maximize $\pi_t = pqe_t^{\alpha}(X_t + \theta_t F(X_t))^{\beta} - ce_t$. This yields $\tilde{e}_t = \{\alpha pq(X_t + \theta_t F(X_t))^{\beta}/c\}^{1/(1-\alpha)}$, which translates into the (myopic) optimal harvest locus $\tilde{h}_t = q(\alpha pq/c)^{\alpha/(1-\alpha)}(X_t + \theta_t F(X_t))^{\beta/(1-\alpha)}$. Therefore, not surprisingly, harvest is "high" in years with "good" natural growth conditions and above that of the harvest in the benchmark model and *vice versa*. In the c.r.s. case ($\alpha = \beta = 0.5$) we find $\tilde{h}_t = a(X_t + \theta_t F(X_t))$, and expected harvest is then just as in the benchmark model:

$$E[\tilde{h}_t] = a(X_t + F(X_t)). \tag{5}$$

In the i.r.s. case ($\alpha = 0.5$, $\beta = 1$), individual harvest becomes $\tilde{h}_t = a(X_t + \theta_t F(X_t))^2$ and, therefore, $E[\tilde{h}_t] = a\{X_t^2 + 2X_t F(X_t) + E[\theta_t^2]F(X_t)^2\}$. Because $E[\theta_t^2] = \mathrm{Var}[\theta_t] + 1$, expected harvest, for a given stock level, will be above that of the benchmark model. Moreover, the difference increases with more growth variation. This is stated as

Result 1. *When harvesting takes place after natural growth uncertainty has been resolved, expected harvest is just as in the benchmark model when c.r.s. and above that in the benchmark model when i.r.s.*

The reason why there is no difference compared with the benchmark model when c.r.s. is that the stochastic term is linearly included in the optimal harvest function. On the other hand, in the i.r.s. case, the stochastic term is included in a convex manner. Therefore, Result 1 is simply because of Jensen's inequality, irrespective of the fact that there is no uncertainty involved in the harvest decision.[10]

When inserting $\tilde{h}_t$ into equation (4) in the c.r.s. case, the stock dynamics become

$$X_{t+1} = X_t + \theta_t F(X_t) - na(X_t + \theta_t F(X_t)). \tag{6}$$

The notion of steady state has now no obvious meaning, but the expected steady-state $E[X_{t+1} - X_t] = 0$ yields the biomass that the stock in the long-term will fluctuate around. Expected natural growth equals then expected harvest, that is, $F(\tilde{X}) = na(\tilde{X} + F(\tilde{X}))$, or $F(\tilde{X}) = [na/(1-na)]\tilde{X}$, which yields the same stock size as in the benchmark model, $\tilde{X} = X^*$. Therefore, a corollary of Result 1 is that expected steady state will be the same as in the benchmark model when c.r.s. On the other hand, it is easily recognized that the expected steady-state stock will differ from the benchmark model in the i.r.s. case.[11]

3.2. Harvesting before uncertainty is resolved. We next consider the situation in which harvest takes place *before* natural growth uncertainty has been resolved, which may be seen as an analog of the Clark and Kirkwood [1986] model. The goal of the individual fisherman is now to maximize expected profit $E[\pi_t] = E[pqe_t^\alpha(X_t + \theta_t F(X_t))^\beta - ce_t] = pqe_t^\alpha E[(X_t + \theta_t F(X_t))^\beta] - ce_t$. In the Appendix, it is demonstrated that expected harvest in the c.r.s. case ($\alpha = \beta = 0.5$) yields

$$E[\hat{h}_t] = a\left\{(X_t + F(X_t)) - \mathrm{Var}\left[(X_t + \theta_t F(X_t))^{0.5}\right]\right\}, \qquad (7)$$

which is lower than in the benchmark model. Moreover, the difference increases with the variation in the growth fluctuation. In the i.r.s. case ($\beta = 1$ and $\alpha = 0.5$), the harvest becomes just as in the benchmark model (see the Appendix). This is stated as

Result 2. *When harvest takes place before uncertainty is resolved, expected harvest for given resource abundance is lower than in the benchmark model when c.r.s. and equal to that in the benchmark model when i.r.s.*

Result 2 contrasts Result 1. Because uncertainty is unresolved when the harvesting decision is made, an i.r.s. fishery (with $\beta = 1$) is now characterized by optimal harvest as a linear function of the random variable. On the other hand, in an c.r.s. case (with $\beta = 0.5$), the harvesting function is concave in the random variable. Again, the result stems from Jensen's inequality and has a parallel with the standard theory for decisions under uncertainty (see above). Therefore, on average, unresolved uncertainty before harvesting works as if c.r.s. fisheries, in contrast to i.r.s. fisheries, take precaution when determining the harvesting effort. As a corollary to Result 1 and Result 2, we may also state:

Result 3. *Both when c.r.s. and when i.r.s., expected harvest for a given resource abundance is lower when harvesting takes place before natural growth uncertainty has been resolved than when harvest occurs after uncertainty has been resolved.*

When c.r.s., the population dynamics are

(8)
$$X_{t+1} = X_t + \theta_t F(X_t) - naE\left[(X_t + \theta_t F(X_t))^{0.5}\right](X_t + \theta_t F(X_t))^{0.5},$$

with expected steady-state $\hat{X}$ determined by $F(\hat{X}) = na\{(\hat{X} + F(\hat{X})) - \mathrm{Var}[(\hat{X} + \theta_t F(\hat{X}))^{0.5}]\}$, or $F(\hat{X}) = [na/(1-na)]\hat{X} - na\mathrm{Var}[(\hat{X} + \theta_t F(\hat{X}))^{0.5}]$. Therefore, expected steady state is higher than when harvest takes place after uncertainty has been resolved. This is the obvious corollary of Result 3. Not surprisingly, we find expected steady state in the i.r.s. case to be just as in the benchmark model.

4. Uncertain stock observations (measurement error). So far, the assumption has been that the stock size can be observed for sure. For large mammals, this assumption is not unrealistic, but it often lacks realism for fish stocks (again, see, e.g., Gulland [1986], Hilborn and Walters [1992]). Uncertain stock observations, or measurement errors, are now analyzed while ignoring any natural growth uncertainty. Contingent upon the time of measurement, it is modeled in two ways. First, it is assumed that the exploiters assess the species abundance just before harvesting and hence after natural growth. Second, the stock is measured before natural growth. All the time, any measurement or monitoring costs, and the fact that such costs may improve the accuracy of the stock assessment, are neglected. In both cases, the measurement error ϕ_t is captured by an i.i.d. random variable with $E[\phi_t] = 1$ and finite support, $0 < \phi_{\text{low}} < \phi_t < \phi_{\text{high}} < \infty$.

4.1. Stock measured after natural growth. When the stock is measured after natural growth and hence just before fishing, the exploiters consider the harvestable stock as $\phi_t(X_t + F(X_t))$. Therefore, the goal of the individual exploiter is now to maximize $E[\pi_t] = E[pqe_t^\alpha(\phi_t(X_t + F(X_t)))^\beta - ce_t] = pqe_t^\alpha E[\phi_t^\beta](X_t + F(X_t))^\beta - ce_t$. In the c.r.s. case ($\alpha = \beta = 0.5$), we find expected harvest as (again, see the Appendix)

$$E[\bar{h}_t] = a(X_t + F(X_t))\big(1 - \mathrm{Var}\big[\phi_t^{0.5}\big]\big). \tag{9}$$

Therefore, expected harvest is lower than in the benchmark model, and the discrepancy increases with the measurement error variation. In the i.r.s. case, the result is (the Appendix) $E[\bar{h}_t] = a(X_t + F(X_t))^2$. These outcomes are stated as

Result 4. *With measurement error and stock measurement after natural growth, expected harvest for given resource abundance is below (equal to) that of the benchmark model in the c.r.s. (i.r.s.) case.*

Again, the result is related to Jensen's inequality as the random variable is included in a concave and linear way in the optimal harvest function in the c.r.s. (with $\beta = 0.5$) and the i.r.s. fishery (with $\beta = 1$), respectively. Therefore, on average, measurement error just before harvesting works as if c.r.s. fisheries take precaution when determining the harvesting effort. This was also the case in the presence of ecological uncertainty.

In the c.r.s. case, the stock dynamics becomes

$$X_{t+1} = X_t + F(X_t) - naE\big[\phi_t^{0.5}\big](X_t + F(X_t))\phi_t^{0.5}, \tag{10}$$

with expected steady-state $\bar{X}$ determined by $F(\bar{X}) = na(1 - \mathrm{Var}[\phi_t^{0.5}])(\bar{X} + F(\bar{X}))$. The location of the steady state compared with the benchmark model is generally ambiguous.[12] In the i.r.s. case, however, we find the expected steady-state stock level to be just as in the benchmark model.

4.2. Stock measured before natural growth. Finally, we briefly look at the case in which the stock is measured before natural growth. The exploiters consider the harvestable stock now as $\phi_t X_t + F(\phi_t X_t)$, and the goal of the individual harvester is to maximize $E[\pi_t] = E[pqe_t^{\alpha}(\phi_t X_t + F(\phi_t X_t))^{\beta} - ce_t] = pqe_t^{\alpha}E[(\phi_t X_t + F(\phi_t X_t))^{\beta}] - ce_t$. The optimal (myopic) expected harvest in the c.r.s.

case now becomes (see the Appendix)

$$(11) \quad E[\bar{\bar{h}}_t] = a\left\{X_t + E\left[F(\phi_t X_t)\right] - \mathrm{Var}\left[(\phi_t X_t + F(\phi_t X_t))^{0.5}\right]\right\}.$$

The variance term pulls in the direction of a smaller expected harvest than in the benchmark model. When natural growth is given by the standard logistic growth function, the expectation term pulls in the same direction.[13] Hence, expected harvest for a given resource abundance is lower than in the benchmark model.

In the i.r.s. case, we find $E[\bar{\bar{h}}_t] = a\{X_t + E[F(\phi_t X_t)]\}^2$. Because $E[F(\phi_t\ X_t)] < E[F(X_t)]$ (see footnote 13), expected harvest is again below that of the benchmark model of $h_t^* = a(X_t + F(X_t))^2$. Therefore, measurement error taking place before natural growth works as if the harvesters take precaution in the harvesting decision, even in the i.r.s. case. This is stated as

Result 5. *Under measurement error with stock measured just prior to natural growth, expected harvest for a given resource abundance is lower than the benchmark model both when c.r.s. and i.r.s.*

The population dynamics and steady state can again be computed, and we now find that the expected steady-state stock becomes higher than in the benchmark model in the c.r.s. case as well as in the i.r.s. case.

5. Economic gain, or loss, of information.

So far, only harvest and stock evolvement have been considered. We now proceed to analyze the various economic outcomes. The uncertain natural growth cases are the only cases considered as these well enough illustrate the ambiguous profitability effect of information. In this section, the steady-state profit, or equilibrium rent, is analyzed, whereas Section 6 includes some dynamics.

The benchmark model is studied first. The optimal effort e_t^* (Section 2) inserted into the individual profit function yields $\pi_t^* = pq\{(\alpha pq/c)(X_t + F(X_t))^\beta\}^{\alpha/(1-\alpha)}(X_t + F(X_t))^\beta - c\{(\alpha pq/c)(X_t + F(X_t))^\beta\}^{1/(1-\alpha)}$. With c.r.s. ($\alpha = \beta = 0.5$), this expression reduces to $\pi_t^* = b(X_t + F(X_t))$, where $b = pa/2$, and $a = pq^2/2c$ (Section 2). Therefore, the steady-state profit, or equilibrium rent, is $\Pi^* =$

$nb(X^* + F(X^*))$. Because $F(X^*) = na(X^* + F(X^*))$ determines X^* (Section 2), the rent may also be expressed as

$$\Pi^* = (p/2)F(X^*). \tag{12}$$

When i.r.s. ($\alpha = 0.5$ and $\beta = 1$), we find $\Pi^* = nb(X^* + F(X^*))^2$. Because $F(X^*) = na(X^* + F(X^*))^2$, equation (13) holds now as well. Therefore, when biomass grows according to a single peaked growth function such as the logistic one, the steady-state rent will be at its maximum when $X^* = X^{msy}$. Many harvesters (n is large) and a high catchability coefficient (q is high) pull in the direction of $X^* < X^{msy}$, whereas a high cost–price ratio (c/p is high) pulls in the opposite direction.[14]

Ecological uncertainty is then considered. When harvesting takes place with c.r.s. ($\alpha = \beta = 0.5$) *after* ecological uncertainty has been resolved, it can be confirmed that individual profit and expected equilibrium rent read $\tilde{\pi}_t = b(X_t + \theta_t F(X_t))$ and $E[\tilde{\Pi}] = nb(\tilde{X} + F(\tilde{X}))$, respectively. Because $\tilde{X}$ is found through $F(\tilde{X}) = na(\tilde{X} + F(\tilde{X}))$ (Section 3), we may also write:

$$E[\tilde{\Pi}] = (p/2)F(\tilde{X}). \tag{13}$$

As $\tilde{X} = X^*$ (Section 3), the steady-state expected economic rent is hence just as in the benchmark model. Therefore, harvesting under stochastic ecology when c.r.s. yields, on average, the same equilibrium rent as in the deterministic case.

The i.r.s. case ($\alpha = 0.5$ and $\beta = 1$) gives $\tilde{\pi}_t = b(X_t + \theta_t F(X_t))^2$ and $E[\tilde{\Pi}] = nbE[(\tilde{X} + \theta_t F(\tilde{X}))^2]$. Because $F(\tilde{X}) = naE[(\tilde{X} + \theta_t F(\tilde{X}))^2]$ (Section 3), equation (14) holds now as well. As $X^* > \tilde{X}$ when i.r.s., $E[\tilde{\Pi}]$ will generally differ from the benchmark rent Π^*. Therefore, if the stock is heavily exploited and $X^* \leq X^{msy}$, we find $\Pi^* > E[\tilde{\Pi}]$. On the contrary, if the stock is moderately, or little, exploited (because of a high cost–price ratio, few harvesters, or both), the opposite conclusion may be drawn. This is stated as

Result 6. *When harvesting takes place after ecological uncertainty is resolved, there is no economic gain from deterministic ecological* *conditions when c.r.s. In the i.r.s. case, the gain is positive (negative) when* $X^* \leq X^{msy} (\tilde{X} \geq X^{msy})$.

When harvest takes place *before* natural growth uncertainty has been resolved, the individual optimal (myopic) effort (see the Appendix) inserted into the profit expression yields $\hat{\pi}_t = pq\{(\alpha pq/c) E[(X_t + \theta_t F(X_t))^\beta]\}^{\alpha/(1-\alpha)}(X_t + \theta_t F(X_t))^\beta - c\{(\alpha pq/c)E[(X_t + \theta_t F (X_t))^\beta]\}^{1/(1-\alpha)}$. When c.r.s. ($\alpha = \beta = 0.5$), we may also now write (see the Appendix):

$$(14) \qquad E\left[\hat{\Pi}\right] = (p/2)F(\hat{X}).$$

The i.r.s. case ($\alpha = 0.5$ and $\beta = 1$) yields $\hat{\pi}_t = bE[X_t + \theta_t F(X_t)]\{2(X_t + \theta_t F(X_t)) - E[X_t + \theta_t F(X_t)]\}$, and equation (15) still holds.

In the c.r.s. case, we have $\hat{X} > X^*$ (Section 3). Therefore, $E[\hat{\Pi}] > \Pi^*$ when $\hat{X} \leq X^{msy}$. In the i.r.s. case, on the other hand, the outcome is $E[\hat{\Pi}] = \Pi^*$ because $\hat{X} = X^*$. We may therefore state:

Result 7. *When harvesting takes place before ecological uncertainty is resolved, there is no economic gain from information when i.r.s. In the c.r.s. case, the gain is positive (negative) when* $X^* \geq X^{msy}$ $(\hat{X} \leq X^{msy})$.

The fact that more information may reduce profitability is obviously a counterintuitive result. However, it is readily explained by the myopic nature of the harvesting. The various steady states, as well as the transition paths, are therefore of a second-best type, and hence the exploiters may be better off with less information. This possible outcome follows the classic externality paper by Lipsey and Lancaster [1956]. It should be noted that the same results prevail with just one harvester ($n = 1$) while still (somewhat unrealistic) having myopic resource utilization. Therefore, Results 6 and 7 are due to the myopic nature of the exploitation.

6. Numerical illustration. The theoretical reasoning when we have ecological uncertainty is now illustrated numerically. The natural growth function, assumed to be of the logistic type (Section 2), is given

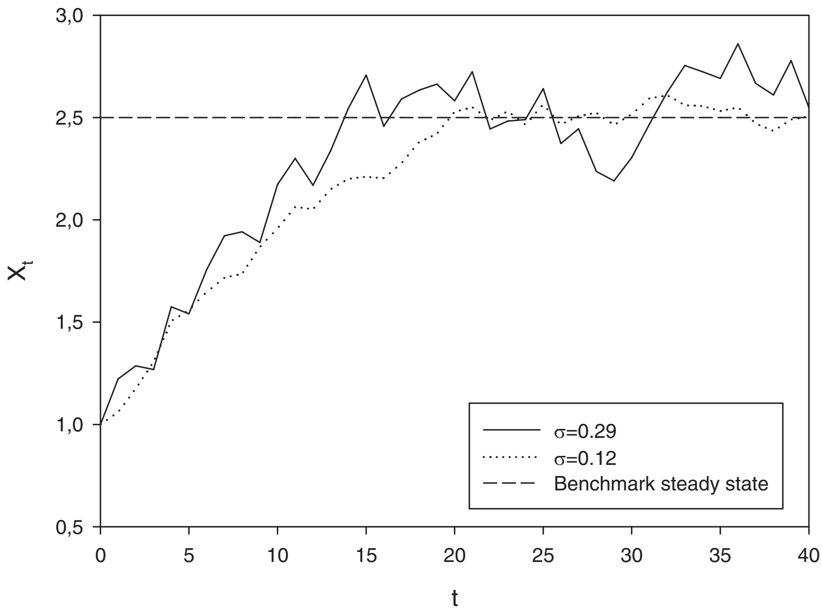

FIGURE 1. Stock expansion paths. Harvesting before ecological uncertainty is resolved. The c.r.s. case, $na = 0.2$.

with parameter values $r = 0.5$ and $K = 5$ (in, say, 1,000 tonnes). All the time, we use $p = 160$ (in, say, Euro per tonne) as the harvest price, whereas the value of na is changed throughout (which may happen through q, c or n, or all). The stochastic density function is specified just as in Clark and Kirkwood [1986] and reads $f(\theta_t) = 1/2\gamma$ for $\theta_{\text{low}} = 1 - \gamma \leq \theta_t \leq 1 + \gamma = \theta_{\text{high}}$ and zero elsewhere. This distribution has unit mean and $\text{Var}[\theta_t] = \sigma^2 = \gamma^2/3$.

First, under the assumption of c.r.s. ($\alpha = \beta = 0.5$) and harvesting taking place *before* ecological uncertainty is resolved, Figure 1 demonstrates two stock expansion paths with different variations $\text{Var}[\theta_t]$. As a corollary of Result 2, both paths will fluctuate around a steady state above that of the benchmark value, as given by $F(X^*) = na(X^* + F(X^*))$, or $X^* = 2.5$, for the given parameter values. Larger variation pulls in the direction of a higher expected steady-state value.

TABLE 1. Steady-state stock, harvesting, and profit. Harvesting after ecological uncertainty is resolved. The i.r.s. case.

na	σ	$\tilde{X}$	$E[\tilde{h}]$	$E[\tilde{\Pi}]$
0.05	0[a]	2.883	0.610	48.8
	0.12	2.882	0.610	48.8
	0.29	2.872	0.611	48.8
	0.58	2.836	0.614	49.1
0.10	0[a]	1.828	0.580	46.4
	0.12	1.825	0.579	46.3
	0.29	1.808	0.577	46.2
	0.58	1.747	0.568	45.4
0.20	0[a]	1.018	0.405	32.4
	0.12	1.015	0.404	32.3
	0.29	1.000	0.400	32.0
	0.58	0.947	0.384	30.7
0.30	0[a]	0.701	0.301	24.1
	0.12	0.699	0.301	24.1
	0.29	0.686	0.296	23.7
	0.58	0.645	0.281	22.5

[a] Benchmark model.

Next, Table 1 illustrates how steady-state expected harvest, resource abundance, and profit vary with the exploitation pressure na and growth variation when harvesting occurs *after* ecological uncertainty is resolved. The expected values coincide with the benchmark model in the c.r.s. case (not shown in the table), whereas the steady-state stock will be below that of the benchmark model when i.r.s. ($\alpha = 0.5$, $\beta = 1$), which is a corollary of Result 1. It is also seen that expected profitability is above that of the benchmark model for a low harvest pressure and is lower for a high pressure. This confirms Result 6. However, the differences are small, but they increase somewhat with the amount of growth variation.

TABLE 2. Steady-state stock, harvesting and profit. Harvesting before ecological uncertainty is resolved. The c.r.s. case.

na	σ	$\hat{X}$	$E[\hat{h}]$	$E[\hat{\Pi}]$
0.10	0[a]	3.889	0.432	34.6
	0.12	3.889	0.432	34.6
	0.29	3.890	0.432	34.5
	0.58	3.892	0.431	34.4
0.15	0[a]	3.235	0.571	45.7
	0.12	3.236	0.571	45.7
	0.29	3.238	0.570	45.6
	0.58	3.247	0.569	45.2
0.20	0[a]	2.500	0.625	50.0
	0.12	2.501	0.625	50.0
	0.29	2.507	0.625	49.9
	0.58	2.530	0.624	49.5
0.30	0[a]	0.714	0.306	24.5
	0.12	0.720	0.308	24.6
	0.29	0.748	0.318	25.4
	0.58	0.848	0.352	28.2

[a] Benchmark model.

Finally, Table 2 demonstrates the situation when harvest takes place *before* ecological uncertainty is resolved. The expected values coincide with the benchmark model in the i.r.s. case (not shown in the table), whereas the steady-state stock is higher when c.r.s. (Result 2). It is also seen that expected profitability is above that of the benchmark model for a high harvest pressure and is the opposite for a low pressure. This confirms Result 7. Furthermore, the main impression is that natural growth variation has a small and modest effect on stock size and profitability. The exception seems to be the combination of high exploitation pressure and substantial natural growth variation.

7. Concluding remarks. The resource management scheme considered in this paper falls in the category of a small-scale in-shore fishery in a developing country setting. The exploitation takes place within what Baland and Platteau [1996] refer to as an unregulated common property regime and in which the fishermen exploit the resource stock in a *myopic* profit-maximizing way; that is, the fish stock is considered as exogeneous under the harvest decision. The number of harvesters is assumed fixed because of a possible license system that restricts the entrance of new fishermen. The effects of uncertainty are analyzed under different assumptions about when uncertainty is resolved (under ecological uncertainty) and the timing of measurement (under measurement error). Under measurement error, we find the average harvest, for a given resource abundance, to be lower than that of the benchmark model (no uncertainty). The same result applies for ecological uncertainty when harvesting takes place after uncertainty is resolved. However, if harvesting takes place before ecological uncertainty is resolved, expected harvest is above, or equal to, that of the benchmark model.

The model has been analyzed under two scale specifications of the harvest function. The c.r.s. case is studied when the resource stock elasticity β is 0.5, whereas it equals 1 in the i.r.s. case. For tractability, the effort elasticity α is, all the time, assumed to be 0.5. However, it can be demonstrated that several of the derived results apply to all $0 < \alpha < 1$ (see the Appendix). Under measurement error, exceptions include c.r.s. cases in which α differs from 0.5. Under ecological uncertainty when harvesting takes place after uncertainty is resolved, exceptions include the i.r.s. case in which α differs from 0.5. Second, in the c.r.s. case with $(\alpha + \beta) = 1$, and in which harvest takes place before uncertainty is resolved, we cannot conclude expected harvest to be below that of the benchmark model for α and β values different from 0.5.

In most instances, both types of uncertainty work as a precautionary role as the expected steady-state stock level is above that of what we find in the absence of uncertainty. However, the economic effect of uncertainty is unclear. When natural growth is governed by the standard logistic growth function, it is demonstrated that the economic gain, or loss, of information depends on whether expected steady-state stock is above, or below, the maximum sustainable yield (msy) level. When harvesting takes place after ecological uncertainty is resolved, there is no economic gain from deterministic conditions when c.r.s. with $\alpha = 0.5$ and $\beta = 0.5$. It can be demonstrated (the Appendix) that this result applies to all stock and effort elasticity values $(\alpha + \beta) = 1$. When harvesting takes place before ecological uncertainty is resolved with c.r.s., there is a positive economic gain from information when the stock level is above the maximum sustainable yield, whereas the gain in information is negative when the resource is heavily exploited. Under i.r.s. with $\alpha = 0.5$ and $\beta = 1$, we find no economic gain from information. In the Appendix, it is shown that this result holds for all $0 < \alpha < 1$. The fact that more information may reduce profitability is strange, but this finding is embedded in the very nature of the myopic structure of the harvest, which implies that the solution concepts are of the second-best type (Lipsey and Lancaster [1956]). The analysis is also illustrated numerically, and the effect of biological uncertainty seems to be small when the harvesting pressure is small and modest. These results are in line with the findings of Sethi et al. [2005].

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Appendix

A.1. Ecological uncertainty. When harvesting takes place before uncertainty is resolved, the (myopic) optimal effort and harvest become $\hat{e}_t = \{(\alpha pq/c)E[(X_t + \theta_t F(X_t))^{\beta}]\}^{1/(1-\alpha)}$ and $\hat{h}_t = q(\alpha pq/c)^{\alpha/(1-\alpha)}\{E[(X_t + \theta_t F(X_t))^{\beta}]\}^{\alpha/(1-\alpha)}(X_t + \theta_t F(X_t))^{\beta}$, respectively. In the c.r.s. case ($\alpha = \beta = 0.5$), this yields $\hat{h}_t = aE[(X_t + \theta_t F(X_t))^{0.5}](X_t + \theta_t F(X_t))^{0.5}$. Expected harvest is $E[\hat{h}_t] = aE[(X_t + \theta_t F(X_t))^{0.5}]^2$, which may also be written as in main-text equation (7). In the i.r.s. case ($\beta = 1$ and $\alpha = 0.5$), the harvest becomes $\hat{h}_t = aE[X_t + \theta_t F(X_t)](X_t + \theta_t F(X_t))$. Expected harvest is therefore just as in the benchmark model, $E[\hat{h}_t] = a(X_t + F(X_t))^2$.

A.2. Uncertain stock observations. When the stock is measured after natural growth and hence just before harvesting, the (myopic) optimal effort becomes $\bar{e}_t = \{(\alpha pq/c)E[\phi_t^{\beta}](X_t + F(X_t))^{\beta}\}^{1/(1-\alpha)}$, whereas the harvest reads $\bar{h}_t =$

$q(\alpha pq/c)^{\alpha/(1-\alpha)}\{E[\phi_t^\beta]\}^{\alpha/(1-\alpha)}(X_t + F(X_t))^{\beta/(1-\alpha)}\phi_t^\beta$. Accordingly, in the c.r.s. case ($\alpha = \beta = 0.5$), we find $\bar{h}_t = aE[\phi_t^{0.5}](X_t + F(X_t))\phi_t^{0.5}$, and main-text equation (9) yields expected harvest. In the i.r.s. case ($\beta = 1$ and $\alpha = 0.5$), the result is $\bar{h}_t = a(X_t + F(X_t))^2\phi_t$.

When the stock is measured before natural growth, maximization yields $\bar{\bar{e}}_t = \{(\alpha pq/c)E[(\phi_t X_t + F(\phi_t X_t))^\beta]\}^{1/(1-\alpha)}$ and $\bar{\bar{h}}_t = q(\alpha pq/c)^{\alpha/(1-\alpha)}\{E[(\phi_t X_t + F(\phi_t X_t))^\beta]\}^{\alpha/(1-\alpha)}(\phi_t X_t + F(\phi_t X_t))^\beta$. When c.r.s. ($\alpha = \beta = 0.5$), we find $\bar{\bar{h}}_t = aE[(\phi_t X_t + F(\phi_t X_t))^{0.5}](\phi_t X_t + F(\phi_t X_t))^{0.5}$, and equation (11) yields expected harvest. In the i.r.s. case ($\beta = 1$ and $\alpha = 0.5$), the harvest reads $\bar{\bar{h}}_t = aE[\phi_t X_t + F(\phi_t X_t)](\phi_t X_t + F(\phi_t X_t))$.

A.3. Economic gain, or loss, of information. When harvest takes place before natural growth with c.r.s. ($\alpha = \beta = 0.5$), we find $\hat{\pi}_t = bE[(X_t + \theta_t F(X_t))^{0.5}]\{2(X_t + \theta_t F(X_t))^{0.5} - E[(X_t + \theta_t F(X_t))^{0.5}]\}$, $E[\hat{\pi}_t] = b\{X_t + F(X_t) - \mathrm{Var}[(X_t + \theta_t F(X_t))^{0.5}]\}$ and $E[\hat{\prod}] = nb\{\hat{X} + F(\hat{X}) - \mathrm{Var}[(\hat{X} + \theta_t F(\hat{X}))^{0.5}]\}$. Because $\hat{X}$ is defined by $F(\hat{X}) = na\{\hat{X} + F(\hat{X}) - \mathrm{Var}[(\hat{X} + \theta_t F(\hat{X}))^{0.5}]\}$ (Section 3), equation (14) yields expected profit.

In the i.r.s. case ($\beta = 1$ and $\alpha = 0.5$), we find $E[\hat{\prod}] = nb(\hat{X} + F(\hat{X}))^2$. Because $F(\hat{X}) = na(\hat{X} + F(\hat{X}))^2$ (Section 3), equation (15) still holds.

A.4. Generalizations: ecological uncertainty. When harvesting takes place after uncertainty is resolved, we have $\tilde{h}_t = q(\alpha pq/c)^{\alpha/(1-\alpha)}(X_t + \theta_t F(X_t))$ in the general c.r.s. case with $(\alpha + \beta) = 1$. Expected harvest is $E[\tilde{h}_t] = q(\alpha pq/c)^{\alpha/(1-\alpha)}(X_t + F(X_t))$, which equals the benchmark harvest. Therefore, Result 1 holds for all α and β values consistent with c.r.s.

When harvesting takes place before uncertainty is resolved, expected harvest is generally given as $E[\hat{h}_t] = q(\alpha pq/c)^{\alpha/(1-\alpha)}$ $\{E[(X_t + \theta_t F(X_t))^\beta]\}^{1/(1-\alpha)}$. When $\beta = 1$, it simplifies to $E[\hat{h}_t] = q(\alpha pq/c)^{1/(1-\alpha)}\{X_t + F(X_t)\}^{1/(1-\alpha)}$, which equals the optimal harvest in the benchmark model. Therefore, Result 2 holds for all $0 < \alpha < 1$ and $\beta = 1$.

A.5. Generalizations: measurement error. When the stock is measured after natural growth, the optimal harvest reads $\bar{h}_t = q(\alpha pq/c)^{\alpha/(1-\alpha)}(X_t + F(X_t))^{\alpha/(1-\alpha)}((X_t + \phi_t F(X_t))$ when $\beta = 1$. Therefore, expected harvest equals $E[\bar{h}_t] = q(\alpha pq/c)^{\alpha/(1-\alpha)}(X_t + F(X_t))^{1/(1-\alpha)}$ for all $0 < \alpha < 1$ with $\beta = 1$. This is just as in the benchmark model. Hence, Result 4 holds when i.r.s. for all $0 < \alpha < 1$ and $\beta = 1$.

When the stock is measured before natural growth, the optimal harvest generally reads $\bar{\bar{h}}_t = q(\alpha pq/c)^{\alpha/(1-\alpha)}\{E[(\phi_t X_t + F(\phi_t X_t))^\beta]\}^{\alpha/(1-\alpha)}(\phi_t X_t + F(\phi_t X_t))^\beta$ (see above). With $\beta = 1$, expected harvest equalizes $E[\bar{\bar{h}}_t] = q(\alpha pq/c)^{\alpha/(1-\alpha)}\{X_t + E[F(\phi_t X_t)]\}^{1/(1-\alpha)}$. Therefore, when using footnote 13, Result 5 holds for all $0 < \alpha < 1$ and $\beta = 1$.

A.6. Generalizations: profitability. When harvesting takes place after uncertainty is resolved, we have seen that Result 1 holds for all α andβ values consistent with c.r.s. Therefore, Result 6 holds as well for all α andβ values consistent with c.r.s. When harvesting takes place before uncertainty is resolved, Result 2 holds for all $0 < \alpha < 1$ and $\beta = 1$. Consequently, Result 7 holds when i.r.s. for $0 < \alpha < 1$ and $\beta = 1$.

ENDNOTES

1. The terms *risk* and *uncertainty* are often used to characterize various situations of incomplete information. Risk is usually taken to mean a situation in which the probability distribution is known. Uncertainty, on the other side, means a situation in which the probability distribution is *not* known. The first of these situations is considered here. Nevertheless, we use the term *uncertainty*.

2. Sethi et al. [2005] introduce harvest implementation uncertainty as well.

3. Instantaneous fishing is somewhat easier to analyze than continuous fishing over a given fishing season (because of a simpler cost function). As long as, say, ecological uncertainty is resolved either before the fishing season starts (as in Reed [1979]) or after the season ends (as in Clark and Kirkwood [1986]), uncertainty influences exploitation in the same principal manner under instantaneous and continuous fishing.

4. One of the referees has suggested that a utility maximization approach is more suitable than profit maximization when analyzing a small-scale fishery and in which the marginal utility of the catch should decrease with the amount harvested. We agree on this when considering a subsistence fishery, but here we are basically

thinking of a fishery supplying products to a market (cf. Section 1). The profit-maximizing approach, however, easily fits into a framework in which the marginal utility of the catch declines. To see this, the individual utility function may be specified as $U_t = Ah_t^{\eta} - we_t$. The marginal disutility of effort is then fixed by w, whereas A is a scaling parameter. With $\eta < 1$, and inserting for $h_t = qe_t^{\alpha}(X_t + F(X_t))^{\beta}$, it is recognized that maximization of U_t boils down to the same problem as the main-text maximization of π_t.

5. Because of the lack of any strategic interaction among the exploiters, the number of fishermen does not influence the individual effort use at a given point of time. However, n influences the effort use *indirectly* through previous years' harvesting. In renewable harvesting models, strategic interaction is usually channeled through the resource stock, resulting in reciprocal cost externalities. Under myopic harvesting in which the stock is treated as exogenous by the exploiters (as here), this type of strategic interaction is hence ruled out. There may also be strategic interactions through various markets in which the product market for fish may be of particular relevance. However, this possibility is not explored in this paper as the harvest price is assumed to be fixed and given.

6. Hence, irrespective of the price–cost ratio and other parameter values, harvest will always take place as long as the stock size is positive. This is due to the fact that the marginal profit, when $X_t > 0$, always will be positive for a small effort use (because $\alpha < 1$).

7. Scale properties are usually studied within a framework in which the firm chooses the amount of the various production factors. Therefore, the present model is different as the fish abundance is *exogenous* for each harvester. The notions of c.r.s. and i.r.s. should be seen in this light. See also the discussion in Reed [1979].

8. There are two reasons for this: first, the intrinsic growth rate of commercial species such as fish and large mammals is relatively small, and second, harvesting stabilizes. See the classical May [1975] paper. When working with the standard logistic natural growth function (main text below), it is straightforward to show that (local) stability demands $na/(1 - na) < r < (2 + na)/(1 - na)$. A higher n (or a) increases the right-hand side of this inequality, meaning that harvesting works in a stabilizing manner. It is also recognized that the left-hand side of this inequality is the condition for not depleting the resource.

9. Conceptually, we may think that a fishing authority measures the stock after harvest and announces the stock.

10. This result may also be seen in light of, say, the standard production theory model of the firm under product price uncertainty. The finding here is that expected production should be identical to the no uncertainty case when the stochastic term is embodied in a linear way in the profit function ("risk neutrality"). On the other hand, when embodied in a convex function, the result is typically higher production under uncertainty ("risk lover").

11. The difference depends on whether the expected steady state is located above or below the maximum sustainable yield (i.e., whether $\tilde{X} < X^{msy}$ or the opposite holds). If the stock is above steady state, then higher expected harvesting in the i.r.s. case means a lower expected steady-state stock compared with the benchmark model.

12. The location of the solution in relation to the maximum sustainable yield stock is again crucial (cf. footnote 11).

13. We find $E[F(\phi_t X_t)] = E[r\phi_t X_t(1 - \phi_t X_t/K)] = rX_t(1 - X_t(1 + \mathrm{Var}[\phi_t])/K)$. Uncertain stock observation hence works as if the carrying capacity becomes smaller and $E[F(\phi_t X_t)] < E[F(X_t)]$.

14. *Ceteris paribus*, we may hence find that many harvesters can produce a higher equilibrium rent than few harvesters, suggesting that the cost–price ratio is high. Such an outcome contrasts standard harvesting theory, in which the equilibrium rent decreases steadily with the number of exploiters and equals zero when the number of exploiters approaches infinity (see, e.g., Mesterton-Gibbons [1993]). In our myopic harvesting model, however, the zero-profit condition coincides with the stock depletion condition. In the c.r.s. case, the positive rent condition is hence $F'(0) > (1 - na)/na$. With logistic growth (Section 2), this may be written as $(r/a)(1 + r) > n$.

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