

# Regulation and Evolution of Compliance in Common Pool Resources

Anastasios Xepapadeas<sup>1</sup>

University of Crete, Department of Economics  
University Campus, 74100 Rethymno, Greece  
xepapad@econ.soc.uoc.gr

## Abstract

The paper jointly models the evolution of compliance with regulation and the evolution of a CPR stock, by combining replicator dynamics describing compliance with harvesting rules, with resource stock dynamics. This evolutionary approach suggests that coexistence, in long run equilibrium, of both cooperative and non-cooperative rules under regulation is possible. Stock effects on profits and a certain structure of auditing probabilities could imply the emergence of a limit cycle in areas of low stock levels, as an equilibrium outcome for compliance and the biomass stock. It might be easier for the regulator to obtain full compliance under precommitment to fixed auditing probabilities.

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# 1 Introduction

Common pool resources (CPR) can be described as stocks of natural capital that generate flows of useful goods and services to humans<sup>2</sup> and share two main characteristics:

1. It is costly to exclude individuals from benefiting from the flows of goods and services associated with the resource stocks.
2. Once a resource unit is harvested from the CPR by an individual, this unit is not available to other individuals. This is the subtractability property.

Design of institutions to exclude potential beneficiaries from harvesting the resource is not easy, thus many CPR have open access characteristics.<sup>3</sup> As is well known in the analysis of open access resources, a negative appropriation externality stems from the fact that individual harvesting ignores the impact of individual harvesting on the resource stock. In harvesting a CPR, individual appropriators could, in the absence of appropriate institutions, engage in “scramble competition” to appropriate the resource before someone else does and ignore the impact of their actions on the resource stock. For example, in a fishery, individual harvesting reduces stocks and increases unit harvesting costs for all appropriators. In groundwater management, individual pumping reduces the water head and increases unit pumping costs for all individuals. The non-cooperative outcome obtained when each appropriator maximizes individual benefits without taking into account the negative appropriation externality is Pareto inferior to a cooperative outcome where total benefits are maximized and in this way the externality is internalized.<sup>4</sup> This non-cooperative outcome can be associated with historical resource overexploitation and collapses of stocks.<sup>5</sup>

The overexploitation of a CPR leads to the need for a regulatory framework.<sup>6</sup> In a fishery, probably the most well-studied case, at a theoretical level, optimal regulation can be designed by comparing the non-cooperative

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<sup>2</sup>See, for example, Ostrom, Gardner and Walker (1993).

<sup>3</sup>A CPR is typically associated with a fixed number of potential beneficiaries or users, while for an open access resource this restriction does apply.

<sup>4</sup>There is extensive literature on this issue. See, for example, Gordon (1954), Harding (1968) for the “tragedy of the commons,” Smith (1968), Negri (1989), Clark (1990) and Ostrom (1993).

<sup>5</sup>See Jackson et al. (2001). Also, FAO estimates that currently 71 - 78 percent of fish stocks are fully exploited, overexploited or recovering from depletion.

<sup>6</sup>In the absence of regulation, and given that the appropriation externality appears as stock effects in harvesting costs, the appropriators’ effort or harvesting will be higher, the

fishing effort with the corresponding cooperative effort and then using instruments to achieve the cooperative outcome. In practice, such instruments include limits on entry, gear restrictions, area closures, seasonal restrictions, individual transferable quotas (ITQ), total allowable catch (TAC), quotas for important species, minimum landing size, minimum mesh size, by-catch rules, and landing fees.<sup>7</sup> A typical property of the economic instruments is that they can sustain decentralized regulation. That is, once they are properly enforced and monitored, the individual appropriators follow the cooperative behavior dictated by the regulation, and the system converges to the desired socially-optimal steady state.

Of course it is not realistic to assume that all agents will follow regulation, especially if the number of agents is large. In fishery management there is a tendency to support the idea that regulation has difficulties in protecting fisheries from overexploitation. This opinion is supported by real evidence regarding quota busting, data fouling and in general noncompliance behavior.<sup>8</sup> In particular, typical violations of regulations involve illegal catches or landings, misreporting landings, violation of by-catches rules, discards of fish, fishing without a licence, landing of protected stocks, or misreported catch areas.<sup>9</sup>

The behavior of a fisher regarding compliance or noncompliance can be modeled by following Becker's (1968) general approach, under which a fisher will decide to comply or not by comparing expected benefits from noncompliance, including any expected penalty if audited, with the expected benefits from compliance. Compliance behavior in CPRs has also been modelled, following mainly Ostrom (1990), in the context of institution formation within the appropriators of the CPR, that allows the imposition of sanctions on noncompliers. Sethi and Somanathan (1996) consider the evolution of social norms for CPR and show that cooperative behavior guided by norms of restraint and punishment may be a stable outcome of an evolutionary process, against non-cooperative behavior.

In the present paper compliance or noncompliance, or equivalently the decision to follow the cooperative or the non-cooperative harvesting rule, is modelled by assuming that appropriators are expected to choose their

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less the individuals take into account the effects of their actions on total stocks. If stock effects are completely ignored, in the sense that the appropriators are myopic and treat the resource stock as a fixed parameter, then individual harvesting, at least in the short run, will be set at the maximum possible level relative to the cooperative rule.

<sup>7</sup>See, for example, Conrad and Clark (1987), Clark (1990), and Homans and Wilen (1997).

<sup>8</sup>See, for example, Nielsen and Mathiesen (2003).

<sup>9</sup>For example, Jensen and Vestergaard (2002), Eggert and Ellegard (2003).

harvesting rule in an evolutionary way by considering the evolution of their profits and by taking into account the probability of paying a fine if audited and found not to be in compliance with regulation. This type of rule can be associated with a process, noted by Ostrom (1990), which indicates that *"the most one can say is that individuals ... are engaged in a trial-and-error effort to learn more about the results of their actions so that they can evaluate benefits and costs more effectively over time"*. Profits in general are affected by the deviation between harvesting levels with or without compliance, by stock effects on unit costs, since these effects are eventually most likely to be realized in a dynamic context, by the size of the probabilistic fine and by the probability of been audited. If following the non-cooperative strategy implies profit reduction relative to the average profits of the appropriators' group, the appropriator will choose the cooperative strategy and vice-versa. Since a CPR with a fixed large number of appropriators and two possible strategies is examined, this evolutionary assumption implies that a replicator dynamics framework should be adopted to describe the evolution of appropriator shares that follow cooperative or non-cooperative strategies.<sup>10</sup> The steady-state equilibrium resource level and harvesting rule will be the outcome of this evolutionary process. Thus the evolution of harvesting rules could in principle lead to full adoption of a single rule (cooperative or non-cooperative), or equivalently full compliance or not, but also coexistence of both rules in equilibrium, that is partial compliance. Once the mechanism resulting in no compliance or partial compliance is characterized, regulation could be adjusted in order to steer the system towards the adoption of the cooperative rule, or full compliance.

Therefore the contribution of this paper lies in that it models jointly the evolution of compliance to regulation and the evolution of the CPR stock in the context of an evolutionary process emerging from combining replicator dynamics, which describe the adoption of harvesting rules, with resource stock dynamics. This evolutionary approach characterizes the emergence of steady-state equilibrium harvesting rules or compliance levels under regulation, and the corresponding behavior of the steady-state equilibrium resource stock. Thus the present paper does not seek to model the evolution of institutions or social norms in CPR harvesting, but rather to model the outcome of regulation. This outcome is analyzed in terms of compliance levels and resource stock, when decisions to comply or not are taken in an evolutionary way, based on the evolution of profits associated with different compliance decisions among appropriators, over a sufficiently long time period.

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<sup>10</sup>For the use of the replicator dynamic methodology coupled with stock dynamics in a CPR problem, see also Sethi and Somanathan (1996).

This evolutionary approach suggests that coexistence of both cooperative and non-cooperative rules under regulation is possible. It is shown that stock effects on profits and a certain structure of auditing probabilities could imply the emergence of a limit cycle in areas of low stock levels, as an equilibrium outcome for the level of compliance and the biomass stock. Given the observed fluctuations in the biomass of fisheries, and regulatory failures, the evolutionary mechanism developed in this paper could be regarded as explaining such periodic fluctuations in stocks and levels of compliance.<sup>11</sup> It is also shown that it is possible to modify regulation, by modifying penalties for regulatory violations, in order to attain full compliance equilibria and take the system out of low stock traps, and that it might be easier for the regulator to obtain the full compliance if there is precommitment to fixed auditing probabilities.

## 2 Harvesting Rules

We start by briefly characterizing competitive (that is, non-cooperative) and socially-optimal (that is, cooperative) harvesting rules for a CPR fishery with  $i = 1, \dots, n$  appropriators.<sup>12</sup> Let resource dynamics be described by

$$\dot{S} = F(S) - H, \quad H = \sum_{i=1}^n h_i \quad (1)$$

where  $h_i$  denotes harvesting by harvester or appropriator  $i$  at time  $t$ ,  $H$  denotes total harvesting at time  $t$ , and  $F(S)$  is the biomass growth function with the usual inverted ‘‘U’’ properties,  $F(0) = F(S^{\max}) = 0$ ,  $F'(S^0) = 0$ ,  $F''(S) < 0$  for  $0 \leq S \leq S^{\max}$ . As usual  $S^{\max}$  denotes carrying capacity and  $S^0$  the biomass level corresponding to maximum sustainable yield. Assuming general nonlinear stock effects and that individual harvesters face a fixed market price (for example, the world price) for the harvested resource, the appropriator’s profit flow is determined as

$$\pi_i = ph_i - c_i(h_i, S) \quad (2)$$

The cost function is strictly convex and increasing in harvesting and decreasing in  $S$  due to stock effects. In a non-cooperative equilibrium each harvester maximizes profits by considering the biomass stock as a fixed parameter. Thus non-cooperative harvesting at each point in time is determined

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<sup>11</sup>This of course does not diminish the importance of environmental factors in biomass fluctuations.

<sup>12</sup>For detailed modeling see, for example, Smith (1968) and Clark (1990).

as

$$h_i^N : p - \frac{\partial c_i(h_i^N, S)}{\partial h_i} = 0 \quad (3)$$

Then the individual profit function under the non-cooperative harvesting rule is determined as

$$\pi_i^N(h_i^N, S), h_i^N = h_i^N(p, S) \quad (4)$$

It follows from the envelop theorem that the profit function is positively related to stock effects

$$\frac{\partial \pi_i^N(h_i^N, S)}{\partial S} > 0 \quad (5)$$

To define cooperative or socially-optimal harvesting, welfare from total harvest  $H$  is defined, assuming symmetry, as the sum of consumer and producer surplus or  $U(H) = S(H) - nc(h, S)$ , where  $S(H) = \int_0^{nh} P(u) du$  is the area under the demand curve  $p = P(H)$  and  $S'(H) = P(H) = p$ . The social planner's problem is defined as

$$\max_{\{h(t)\}} \int_0^\infty e^{-\delta t} [S(H) - nc(h, S)] dt, H = nh \text{ s. t. (1)} \quad (6)$$

The current value Hamiltonian for this problem is defined as

$$\mathcal{H} = S(H) - nc(h, S) + \mu [F(S) - H]$$

where the costate variable  $\mu$  is interpreted as the resource stock shadow value. The optimality conditions derived from the maximum principle can be written as:

$$\frac{\partial \mathcal{H}}{\partial h} = 0 \text{ or } \mu = p - \frac{\partial c(h, S)}{\partial h}, h^C = h^C(p, \mu, S) \quad (7)$$

$$\dot{\mu} = \left( \delta - \frac{\partial F}{\partial S} \right) \mu + n \frac{\partial c(h, S)}{\partial h} \quad (8)$$

along with (1) and the transversality condition at infinity. As is common in these problems, by differentiating (7) and substituting into (8), we determine the dynamic fishery system in the state - control space  $(S, h)$ . Assume that a steady-state equilibrium  $(S^*, H^*)$  exists, which has the usual saddle point property, then the policy function  $H_t^* = Q(S_t)$  is determined by the stable manifold converging to  $(S^*, H^*)$ . The policy function can be used by the regulator to design a socially-optimal quota system. The corresponding quota for each harvester is then  $h_t^C = H_t^*/n$ . This socially-optimal harvesting rule  $h^C$  is announced to the appropriators and they are expected to follow the

rule, harvesting  $h_t^C$  per period. Thus under optimal regulation the profit function for the appropriator becomes

$$\pi^C(h^C, S) \tag{9}$$

Therefore, the profit or payoff function for each appropriator under non-cooperative or cooperative (regulated) harvesting rules can be defined as

$$\pi^N(h^N, S), \pi^C(h^C, S) \tag{10}$$

respectively. The harvesting rules, or harvesting strategies, are divergent in the sense that for any given biomass stock  $S$ , and for  $\mu > 0$ , it holds that  $h^N > h^C$ . It should be noted that  $\pi^C(h^C, S) = ph^C - c^C(h^C, S)$ , thus stock effects could be realized even through the socially-optimal rule, in the sense that if stock is reduced, because say the majority of the appropriators do not follow the socially-optimal rule, then profits will fall, since the harvesters that follow  $h^C$  are trying to harvest this amount from lower stocks.

### 3 Replicator Dynamics and the Evolutionary Adoption of Harvesting Rules

Given the existence of two possible harvesting rules  $\{h^N, h^C\}$  for the fixed number of  $i = 1, \dots, n$  harvesters, we seek to model the evolution of the adoption of the harvesting rules and the interaction of this evolution with the evolution of the resource biomass.<sup>13</sup>

Let the state vector  $\mathbf{x}(t) = (x_N(t), x_C(t))$  denote the share of the total population of harvesters following non-cooperative or cooperative harvesting rules respectively at time  $t$ . If a regulator follows the cooperative harvesting rule, that is, s/he follows regulation, then the payoff will be  $\pi^C(h^C, S)$ . On the other hand a harvester can choose not to comply with regulation,<sup>14</sup> that is to follow the non-cooperative rule  $h^N$ . In this case, if audited (caught), s/he is liable for a fine.

A harvester's subjective probability of being audited can be defined in a general form by  $\phi(\mathbf{z})$ , where  $\mathbf{z}$  is a vector of parameters. It is assumed that

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<sup>13</sup>It should be noticed that what follows applies to any two distinct harvesting rules independent of how they have been defined. Non-cooperative and cooperative optimization is used in order to define these rules, since this approach relates more to the traditional regulation theory.

<sup>14</sup>Nielsen and Mathiesen (2003) report, regarding Danish fishers, that conflicts in the normal pattern of fishing and the pattern of fishing implied by regulation has a major impact on their compliance behavior.

this function is common for all harvesters. This probability can be further specified by making additional assumptions.

In the first case the regulator exercises fixed monitoring effort and makes a fixed number of inspections, say  $\bar{n}$  per period. In doing so the regulator announces this policy and thus precommits to a certain auditing probability which is known by the harvesters. The regulator sticks to the policy and the harvesters know this policy. In this case the audit probability is fixed, or<sup>15</sup>

$$\phi(\mathbf{z}) \equiv \bar{\phi} \quad (11)$$

An alternative assumption would be that the regulator exercises variable monitoring effort, which depends on global variables of the problem that the regulator can observe.<sup>16</sup> One such variable is the resource stock  $S$ , another variable is the share of violators  $v$  detected during an audit. The regulator increases the monitoring effort if the stock is reduced or the share of violators increases. This policy can be regarded as a type of no full commitment - or partial commitment - auditing policy on the regulator's part. The regulator might for example not audit individual harvesters if the stocks are sufficiently high, but the regulator might start inspecting if stocks fall below a certain level.<sup>17</sup> The harvesters are made aware of the results of the inspections, say through public announcements and/or private communications,<sup>18</sup> and perceive that if the stock is reduced or the share of violators increases, more effort will be exercised and thus the subjective probability of being audited increases. In this case the probability  $\phi$  can be specified as stock dependent auditing probability:

$$\phi(\mathbf{z}) \equiv \phi(S), \phi'(S) < 0, (\phi(S^*), \phi(0)) > 0 \quad (12)$$

If harvesters use the observed  $v$  as an estimate for their perceived  $x_N$ , that is they set  $v = x_N$ , a compliance dependent auditing probability is defined as:

$$\phi(\mathbf{z}) \equiv \phi(x_N), \phi'(x_N) > 0, \phi(1) > 0, \phi(0) = 0 \quad (13)$$

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<sup>15</sup>This is a common assumption in the enforcement literature in environmental economics (e.g. Malik, 1993; Garvie and Keeler, 1994; Segerson and Miceli, 1998; Stranlund and Dhana, 1999).

<sup>16</sup>In the enforcement literature, variable monitoring effort is usually related to firm specific variables (e.g. Malik, 1990; VanEgteren and Weber, 1996).

<sup>17</sup>Grieson and Singh (1990), Khalil (1997), and Franckx (2002) analyze no commitment frameworks. Franckx relates individual auditing to the level of ambient pollution which is a global state variable. An environmental regulator chooses which firm to inspect without observing firms' action but after observing ambient pollution.

<sup>18</sup>In their survey Nielsen and Mathiesen (2003) report that " *fishers observe the activities and movements of the enforcement agents and continuously report to their peers about it.*"



It is expected that the value of  $\phi(1)$  will be large but not unity since not every harvester is audited even if nobody complies, while  $\phi(0) = 0$ , since if everybody is complying the subjective probability of paying the fine is zero.

If (12) and (13) are taken together, a more general formulation for the subjective audit probability with joint dependence on compliance and stocks would be:

$$\phi(\mathbf{z}) \equiv \phi(x_N, S) \quad (14)$$

In this framework the payoff when the non-cooperative rule is followed, or equivalently the appropriator does not comply, is

$$\Pi^N(h^N, S) = \pi^N(h^N, S) - \phi(\mathbf{z})\mathcal{F} \quad (15)$$

where  $\mathcal{F} > 0$  is a fixed penalty.<sup>19</sup> Under these assumptions the average profit flow associated with the CPR is defined, using the fact that  $x_N + x_C = 1$ , as:

$$\bar{\pi} = x_N [\pi^N(h^N, S) - \phi(\mathbf{z})\mathcal{F}] + (1 - x_N) \pi^C(h^C, S) \quad (16)$$

Suppose that in every time period  $dt$  each appropriator, say  $i$ , following a certain strategy  $h^N$  or  $h^C$ , learns the profit, and consequently the harvesting strategy, of another randomly chosen appropriator, say  $j$ , with probability  $\alpha dt > 0$ .<sup>20</sup> The appropriator will change his/her strategy to the other strategy if s/he perceives that the other's profit is higher because s/he follows the other harvesting strategy. The higher the difference between the payoffs, the higher the probability that the appropriator will take it into account and change his/her harvesting rule. The probability that an appropriator  $i$  using non-cooperative strategy  $h^N$  will switch to  $h^C$ , after learning the profit of the  $j$  appropriator, is:

$$p_{NC}^t = \begin{cases} \beta (\pi^{tC} - \Pi^{tN}) & \text{for } \pi^{tC} > \Pi^{tN} \\ 0 & \text{for } \pi^{tC} \leq \Pi^{tN} \end{cases}$$

Following Gintis (2000) the expected proportion of the population following the non-cooperative harvesting rule is defined as

$$\begin{aligned} \mathcal{E}x_N^{t+dt} &= x_N^t + \alpha dt x_N^t \sum_{l=N,C} x_l^t \beta (\Pi^{tN} - \Pi^{tl}), \quad x_N^t + x_C^t = 1 \quad (17) \\ \Pi^{tN} &= \pi^{tN}(h^N, S) - \phi(\mathbf{z})\mathcal{F}, \quad \Pi^{tC} = \pi^{tC}(h^C, S) \end{aligned}$$

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<sup>19</sup>In an empirical study of Danish fishers, Nielsen and Mathiesen (2003) suggest that among the major factors affecting compliance in fisheries are: (i) the economic gains to be obtained from noncompliance, (ii) the risk of being detected and the severity of the sanction. In (15) factor (i) is captured by the term  $\pi^N(h^N, S)$ , while factor (ii) is captured by the term  $\phi(\mathbf{z})\mathcal{F}$ .

<sup>20</sup>See Gintis (2000) for use of this approach in order to derive the replicator dynamic.

or using the definition of the average profit flow

$$\mathcal{E}x_N^{t+dt} = x_N^t + \alpha dt x_N^t \beta (\Pi^{tN} - \bar{\pi}^t) \quad (18)$$

For a large population,  $\mathcal{E}x_N^{t+dt}$  can be replaced by  $x_N^{t+dt}$ , subtracting  $x_N^t$  from both sides of (18), dividing by  $dt$  and taking the limit as  $dt \rightarrow 0$ , and setting without loss of generality  $\alpha\beta = 1$ , we obtain the replicator dynamic equation:<sup>21</sup>

$$\dot{x}_N^t = x_N^t (\Pi^{tN} - \bar{\pi}^t) \quad (19)$$

The replicator dynamic indicates that the share of harvesters following non-cooperative harvesting rules increases over time if non-cooperative profits increase relative to average profits and vice versa. The replicator dynamic can be written, using the payoff definitions and dropping  $t$ , as:

$$\dot{x}_N = (1 - x_N) x_N [\pi^N(h^N, S) - \pi^C(h^C, S) - \phi(\mathbf{z}) \mathcal{F}] \quad (20)$$

Replicator dynamics equation (20) describes the evolution of harvesters that violate regulation. Since the evolution of the resource biomass is affected by the harvesting rule choice, its evolution will be determined by

$$\dot{S} = F(S) - n [x_N h^N + (1 - x_N) h^C] \quad (21)$$

The dynamical system (20), (21) can be used to analyze the evolution of harvesting rules and resource stock towards an evolutionary equilibrium, that determines the share of appropriators following cooperative or non-cooperative harvesting rules, and the resource biomass. The equilibrium harvesting rule could be monomorphic if all harvesters are following the same rule, or polymorphic if both cooperative and non-cooperative rules coexist in equilibrium.<sup>22</sup> Two possible cases are examined. In the first profits are not affected by changes in the stocks, while in the second stock effects are present so that a reduction in the resource stock reduces individual profits.

## 4 Evolution of Harvesting Rules without Stock Effects

In analyzing the first case we assume that harvesting rules have been set at some point in time in the sense that harvesting quotas have been set by a

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<sup>21</sup>See also for example, Taylor and Jonkar (1978), Weibull (1995) and Samuelson (1997).

<sup>22</sup>It should be noted that in this setup the regulator does not optimize with respect to the choice of auditing probabilities or fines. Auditing probabilities and fines take arbitrary values and the regulator could change them if a specific compliance level, which is not attained by the current values of these parameters, is required.

regulator at the level  $h^C$ , in response to non-cooperative profit maximizing harvesting at the level  $h^N$ . Once these two rules are applied, stock effects are completely ignored and behavior regarding rule adoption is determined by the evolution equation (20). This assumption can be thought of as a situation in which the agents have been “hard wired” at the strategies  $h^N$  or  $h^C$ , with  $h^N > h^C$ , and stock effects are regarded as negligible,<sup>23</sup> thus  $\pi^N(h^N) - \pi^C(h^C) = \gamma > 0$ , independent of  $x_N$  and  $S$ . We examine the evolution of harvesting rules under fixed and variable auditing probabilities.

#### 4.1 Fixed auditing probability

Assume that the auditing probability is fixed as given in (11). Then the dynamic system (20), (21) becomes:

$$\dot{x}_N = (1 - x_N) x_N (\gamma - \bar{\phi}\mathcal{F}) \quad (22)$$

$$\dot{S} = F(S) - n [x_N h^N + (1 - x_N) h^C] \quad (23)$$

In this case the system (22), (23) has a hierarchical structure, so that the equilibrium of (22) can be determined first and then used to determine the equilibrium of (23).

Since  $x_N \in [0, 1]$ , it can easily be seen from (22) that there are two admissible equilibria,  $x_{1N}^* = 1$ ,  $x_{2N}^* = 0$ . Denote  $\delta = (\gamma - \bar{\phi}\mathcal{F})$ , by taking the derivative of (22) we obtain

$$\frac{d\dot{x}}{dx} = \delta(1 - 2x)$$

Evaluating it at  $x_{1N}^* = 1$ ,  $x_{2N}^* = 0$ , it follows that

$$\begin{aligned} \text{if } \delta > 0 \quad & x_{1N}^* = 1 \text{ is stable, } x_{2N}^* = 0, \text{ is unstable} \\ \text{if } \delta < 0 \quad & x_{1N}^* = 1 \text{ is unstable, } x_{2N}^* = 0, \text{ is stable} \end{aligned}$$

This result can be summarized in the following proposition

**Proposition 1** *Under precommitment to a fixed auditing probability  $\bar{\phi}$ , the evolutionary stable equilibrium harvesting rule is monomorphic. All harvesters violate regulation if  $\mathcal{F} < \gamma/\bar{\phi}$ . All harvesters follow regulation, that is, a full compliance equilibrium exists if the fine and the auditing probability are chosen such that  $\mathcal{F} > \gamma/\bar{\phi}$ .*

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<sup>23</sup>Stock effects could be absent if changes in  $S$  cause no change in the density of the stock (Smith 1968).

Thus the level of that fine can be seen as a bifurcation parameter. There is a critical level  $\mathcal{F}^{cr} = \gamma/\bar{\phi}$ , such that for fines larger than the critical level the steady-state equilibrium is characterized by full compliance, while for fines less than the critical level no one follows regulation in equilibrium. A similar role can be played by the auditing probability. In this case  $\bar{\phi}^{cr} = \gamma/F$ .<sup>24</sup>

If these equilibria are substituted into (23) the equilibrium biomass stock is defined as:

$$\begin{aligned} F(S_1^*) &= nh^N \text{ for } x_N^* = 1 \\ F(S_2^*) &= nh^C \text{ for } x_N^* = 0 \end{aligned}$$

The approach dynamics are shown in Figure 1a for  $\delta > 0$ , and in figure 1b for  $\delta < 0$  where the  $\dot{x}_N = 0$  corresponds to the two isoclines,  $x_{1N}^* = 1$ ,  $x_{2N}^* = 0$ . The  $\dot{S} = 0$  isocline is defined as  $x_N = x_N(S) = \frac{F(S)}{n(h^N - h^C)} - \frac{h^C}{h^N - h^C}$ . Let  $S_{msy} = \arg \max_S F(s)$ . In figures 1a and 1b it is assumed that  $x_N(S_{msy}) > 1$ , while in figure 1c it is assumed that  $x_N(S_{msy}) < 1$ , which implies that resource growth is weak.

[Figure 1]

In figure 1a,  $A$  is stable while  $B$  is unstable, with the reverse characterization in figure 1b. Figure 1d has been drawn under the assumption that  $x_{2N}^* = 0$  is the stable equilibrium. It should be noted that if initial conditions are such that trajectory  $Tr_1$  is relevant, then the monomorphic compliance equilibrium is attained. If however trajectory  $Tr_2$  is relevant, then the resource will collapse before equilibrium is reached. This result can be associated with the timing of introducing regulation, and indicates that if the resource is already at low levels and largely unregulated, that is, there is a high proportion of harvesters that do not follow regulation, then a very strict regulation might not help to prevent resource collapse while a laxer regulation might have helped if it had been applied when the resource stock was sufficiently large.

The results of this section indicate that without a sufficiently large fine, the cooperative harvesting rule is not sustainable as a long-run monomorphic evolutionary equilibrium. Resource extinction is possible even with stringent regulation if the resource growth is weak and it is applied to low stocks of a largely unregulated resource. The hypothesis that full compliance can be

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<sup>24</sup>Sutinen et al. (1990) suggest that the high level of noncompliance in the US groundfish fishery can be explained by low economic sanctions. In terms of our model this observation agrees with our result that full compliance can be attained by sufficiently high expected fines.

attained by sufficiently high expected fines is supported by ideas developed through empirical observation. Eggert and Ellerant (2003) claim that the decision of large scale industrial fishers in Sweden to comply is based mainly on economic considerations and less on moral obligation or peer pressure. They suggest that increased compliance can be obtained by "severe economic consequences of rule violation."

## 4.2 Compliance dependent auditing probability

In this case the auditing probability is given by (13). Then the dynamic system (20), (21) becomes:

$$\dot{x}_N = (1 - x_N) x_N [\gamma - \phi(x_N) \mathcal{F}] \quad (24)$$

$$\dot{S} = F(S) - n [x_N h^N + (1 - x_N) h^C] \quad (25)$$

The system (24), (25) has again a hierarchical structure but there is a possibility of a third equilibrium (24) in addition to  $x_{1N}^* = 1$ ,  $x_{2N}^* = 0$ . Using (13) we have for the function  $G(x_N) = \gamma - \phi(x_N) \mathcal{F}$ , that  $G(0) = \gamma > 0$ , while  $G(1) = \gamma - \phi(1) \mathcal{F}$ . If a combination of  $\gamma$  and  $\mathcal{F}$  exists such that  $G(1) < 0$ , or to put it differently, if  $\phi(1) > \frac{\gamma}{\mathcal{F}}$ , which is satisfied for a sufficiently large fine, then  $G(x_N)$  has a unique zero in the interior of  $[0, 1]$ , which is the third equilibrium  $x_{3N}^*$ .

The stability properties of the three equilibria can be characterized by evaluating the derivative

$$\frac{d\dot{x}_N}{dx_N} = (1 - 2x) [\gamma - \phi(x_N) \mathcal{F}] - x_N (1 - x_N) \phi'(x_N) \mathcal{F}$$

at each equilibrium point, or:

$$\frac{d\dot{x}_N}{dx_N} = \begin{cases} -[\gamma - \phi(1) \mathcal{F}] > 0 \text{ for } x_{1N}^* = 1 \\ [\gamma - \phi(0) \mathcal{F}] > 0 \text{ for } x_{2N}^* = 0 \\ -x_{3N}^* (1 - x_{3N}^*) \phi'(x_{3N}^*) \mathcal{F} < 0 \text{ for } x_{3N}^* \in (0, 1) \end{cases}$$

The result can be summarized as follows:

**Proposition 2** *When the auditing probability is compliance dependent and the fine is sufficiently large so that a polymorphic equilibrium exists in addition to the monomorphic equilibria of full compliance and no compliance, then the polymorphic equilibrium is evolutionary stable while the monomorphic equilibria are evolutionary unstable.*

The proposition implies that, for example, announcing after inspection that everybody is in compliance, does not provide a stable full compliance state, but creates tendencies for some harvesters not to comply. This is the result of having  $\phi(0) = 0$ . If the subjective probability of paying the fine is zero, then this creates an incentive not to comply and to deviate from the full compliance state.<sup>25</sup> If  $G(1) = \gamma - \phi(1)\mathcal{F} > 0$  because the fine is not sufficient, then there is not a third equilibrium in  $(0, 1)$  and the no compliance equilibrium is evolutionary stable. By taking the total derivative of  $\gamma - \phi(x_N)\mathcal{F} = 0$ , we obtain:

$$\frac{dx_{3N}^*}{d\mathcal{F}} = -\frac{\phi}{\phi'\mathcal{F}} < 0$$

Then for a sufficiently large fine the polymorphic equilibrium could be close to full compliance.<sup>26</sup>

Substituting the equilibria of (24) into (25) we obtain the steady state of the resource stock. The results are shown in figure 2, where there is polymorphic stable compliance equilibrium at point  $C$ , while points  $A$  and  $B$  are unstable monomorphic equilibria.

[Figure 2]

## 5 Stock Effects and the Evolution of Harvesting Rules

A more realistic representation of the CPR problems implies that we should allow for changes in the stock of the biomass to affect the appropriators' profits, through stock effects in the unit harvesting costs. We maintain, however, the assumption that there is no smooth dependence of the harvesting rule on the stock of the biomass. Thus the behavioral assumption regarding the appropriators is that although they realize changes in their profits and associate these changes with changes in the stock, they stick to their harvesting rule as long as by sticking to the rule their profits are not sufficiently below the profits of the harvester with which they randomly match. If individual profits are sufficiently below the profits of the other harvester, there is a switch of the harvesting rule, and the proportion of appropriators following the new rule starts to increase. Thus appropriators do not continuously adjust their harvesting rules to changes in stocks and their individual profits, unless profits

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<sup>25</sup>The same result holds if  $\phi(0)$  is small enough so that  $\gamma - \phi(0)\mathcal{F} > 0$ .

<sup>26</sup>However with  $\phi(0) = 0$  full compliance is not stable.

accruing from the specific harvesting rule fall sufficiently short of the profits of another randomly chosen harvester. In this case the evolutionary system can be defined as:

$$\dot{x}_N = (1 - x_N) x_N [\pi^N (h^N, S) - \pi^C (h^C, S) - \phi(\mathbf{z}) \mathcal{F}] \quad (26)$$

$$\dot{S} = F(S) - n [x_N h^N + (1 - x_N) h^C] \quad (27)$$

The evolutionary system (26) and (27) is analyzed under two alternative assumptions regarding the structure of the subjective auditing probability.

Under stock dependent probabilities (12),<sup>27</sup> the replicator dynamics (26) is written as

$$\dot{x}_N = (1 - x_N) x_N [\pi^N (h^N, S) - \pi^C (h^C, S) - \phi(S) \mathcal{F}] \quad (28)$$

The isocines corresponding to (26) are defined as  $x_{1N}^* = 1$ ,  $x_{2N}^* = 0$ , and, assuming that it exists, an  $S^*$  that satisfies

$$S^* : \psi(S^*) = \pi^N (h^N, S^*) - \pi^C (h^C, S^*) - \phi(S^*) \mathcal{F} = 0 \quad (29)$$

Differentiating totally (29) we obtain

$$\frac{dS^*}{d\mathcal{F}} = \frac{\phi(S^*)}{\left( \frac{\partial \pi^N}{\partial S} - \frac{\partial \pi^C}{\partial S} - \phi'(S^*) \mathcal{F} \right)}$$

We assume that  $\frac{\partial \pi^N}{\partial S} - \frac{\partial \pi^C}{\partial S} > 0$ , so that stock effects are relatively stronger under non-cooperative harvesting rules. Then  $\frac{\partial \psi(S)}{\partial S} > 0$  and  $\frac{dS^*}{d\mathcal{F}} > 0$ . The steady-state equilibria are shown in Figure 3. The fact that  $\frac{\partial \psi(S)}{\partial S} > 0$  implies that  $\dot{x}_N > 0$  to the right of  $S^*$ , while  $\dot{x}_N < 0$  to the left of  $S^*$ . Therefore the  $x_{1N}^* = 1$  is attracting for  $S > S^*$  and repelling for  $S < S^*$ .

[Figure 3]

Stock effects introduce one more steady state to the problem, point  $E$  in figure 3, in addition to the steady-state equilibria  $A, B, C$ , and  $D$ . Point  $A$  in figure 3a is locally stable, whereas points  $B, C$ , and  $D$  are locally unstable.

The critical point  $E$  that indicates polymorphic compliance, could, however, have different topological properties than the rest of the critical points. Point  $E$  in figure 4a is totally unstable, with the directions of the arrows in the four isosectors around  $E$  indicating that the flow of the vector field (26), (27) is pointing outwards around  $E$ . If a compact positively invariant region

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<sup>27</sup>Results are qualitatively similar if we consider fixed auditing probabilities.

$R$  containing  $E$  exists, such that the flow of the vector field points inwards on the boundary of  $R$ , then according to the Bendixon-Poincare theory, a limit cycle exists around  $E$  as shown by  $L$  in figure 3a.<sup>28</sup> The limit cycle might exist for relatively low resource levels, that is for  $S^* < S_{msy}$ . For  $S^* > S_{msy}$  the polymorphic equilibrium is stable but the approach path is characterized by oscillations. These results are summarized in the following proposition.

**Proposition 3** *Under stock dependent subjective auditing probability and appropriate values of the fine, a limit cycle indicating oscillating polymorphic compliance levels and resource stocks could exist for relatively low resource stock levels  $S^* < S_{msy}$ . Under the same conditions, for relatively high resource stock levels  $S^* > S_{msy}$ , a polymorphic compliance steady-state equilibrium exists. This steady state could be a stable focus with an approach path that spiral inwards towards  $S^*$ , a stable node without spiraling trajectories, or a saddle point with a one-dimensional stable manifold.*

*For Proof see Appendix.*

The intuition behind the existence of the limit cycle, with counterclockwise movement, goes as follows. For any given point to the southeast of the limit cycle  $L$ , the proportion of appropriators following non-cooperative harvesting increases faster than the resource stock. At some point towards the top of the cycle, stock starts declining but the proportion of appropriators following non-cooperative harvesting keeps growing, however at a slower rate. As stock effects become more severe and the auditing probability increases with the decline of the stock, the proportion of appropriators following non-cooperative harvesting is declining on the left side of the cycle. The reduction of the appropriators following non-cooperative harvesting causes stock recovery. However as stock recovers at the bottom of the cycle, stock effects become weaker and the auditing probability is declining, therefore the proportion of appropriators following non-cooperative harvesting starts growing again, and the cycle goes on.

These results indicate that for a relatively low fine level<sup>29</sup> such that  $S^* < S_{msy}$ , and appropriate initial conditions, the system could be trapped in a low stock area characterized by oscillations. If a large random shock shifts the system to the left of the region  $R$  in figure 3a, then the resource might collapse. On the other hand for initial conditions to the right of  $R$  the

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<sup>28</sup>See, for example, Sastry (1999, Ch. 2.3). Formally a region  $R \subset \mathbb{R}^2$  is said to be positively (negatively) invariant for the flow  $(\zeta_{1t}(x_N), \zeta_{2t}(S))$  if, for each  $(x_N, S) \in R$ ,  $(\zeta_{1t}(x_N), \zeta_{2t}(S)) \in R$  for all  $t \geq 0$  ( $t \leq 0$ ). A detailed discussion regarding the existence of a limit cycle is presented in the Appendix.

<sup>29</sup>Since  $\frac{dS^*}{dF} > 0$ , we expect that low fines result in  $S^* < S_{msy}$ .



system converges to the monomorphic no compliance equilibrium at  $A$ . What is worth noting is that this noncompliance equilibrium is characterized by a larger resource stock than the polymorphic equilibrium on the limit cycle. This is a result of the fact that to the right of  $R$  the proportion of appropriators following non-cooperative harvesting does not grow much faster than the resource stock, which is necessary for the generation of the limit cycle. Thus the resource is accumulated at a rate that allows the stock to move beyond the  $S_{msy}$ .

For relatively high fines producing  $S^* > S_{msy}$  a polymorphic equilibrium could have different stability properties. For example at point  $E$  of figure 3b the approach path is spiraling inwards towards steady-state equilibrium. Furthermore, and since  $\frac{dS^*}{d\mathcal{F}} > 0$ , for a sufficiently high fine,  $S^*$  could be moved up to point  $B$  in figure 3b, which corresponds to the dashed line. In this case the monomorphic noncompliance equilibrium,  $x_{1N}^* = 1$ , is repelling for all relevant resource stocks. Oscillations in compliance and the resource stock have been eliminated and there is one stable full compliance equilibrium.

This analysis suggests that under stock effects in costs and auditing probabilities, the CPR could, for relatively low fines, exhibit periodic oscillations around a relatively low resource stock, given appropriate initial conditions or random shocks that could move initial values into the region  $R$ . By increasing the fine sufficiently, a full compliance monomorphic equilibrium can be attained.

The problem can be analyzed in terms of a more complicated subjective auditing probability structure with both compliance effects and stock effects. In this case  $\phi(\mathbf{z}) = \phi(x_N, S)$  and

$$\dot{x}_N = (1 - x_N) x_N [\pi^N(h^N, S) - \pi^C(h^C, S) - \phi(x_N, S) \mathcal{F}] \quad (30)$$

The evolutionary system is now given by (30) and (27). The analysis is basically a combination of the approaches followed above. There is a new isocline defined as

$$x_N = x_N(S) : \pi^N(h^N, S) - \pi^C(h^C, S) - \phi(x_N, S) \mathcal{F} = 0 \quad (31)$$

Under appropriate conditions on the functions and the fine, this isocline could generate two steady states like  $F$  and  $F_1$  in figure 2. These steady states are induced by the dashed line  $WW$ , which is the isocline corresponding to (31). The structure and the properties of the steady states can be analyzed using the same tools as above. Although the system is more complex, the properties of the steady states and the policy implications are in general similar to those derived above.

## 6 Concluding Remarks

The purpose of this paper was to examine the evolution of harvesting rules for a CPR which is subject to regulation. The two possible harvesting rules examined were: (i) a non-cooperative rule, which can be thought of as emerging from non-cooperative optimization, where the appropriators of the resource ignore the effects of their actions on the resource stock and the production set of the others, and (ii) a cooperative rule which can be thought of as emerging from social welfare optimization, and then used in the form of a quota for decentralized resource regulation. Appropriators are liable for a probabilistic fine if they violate regulation. The basic behavioral assumption is an evolutionary one, namely that the share of appropriators following a certain rule increases if by sticking to the rule, individual profits increase relative to average group profits. If individual profits are reduced relative to average group profits, then some appropriators are expected to switch to the alternative rule. We combine the evolutionary process of harvesting rule adoption with biomass dynamics to study the steady-state equilibrium harvesting rules, which is equivalent to studying compliance to regulation, and the corresponding steady-state resource stock.

Our results depend on the structure of the subjective auditing probability and whether stock effects on profits are realized or not. The equilibrium harvesting rule is homogeneous, indicating monomorphic full compliance to the cooperative harvesting rule or no compliance at all, when auditing probabilities are fixed and stock effects are not present. Without stock effects but with compliance dependent auditing probabilities and a sufficiently high fine, a polymorphic compliance steady state is evolutionary stable, with the monomorphic states being unstable, while under a low fine the no compliance state is evolutionary stable. In general when the subjective auditing probability depends on the level of compliance, and this probability tends to zero when compliance becomes full, then this full compliance state is never stable.

When stock effects are present there is the possibility that a mix of cooperative and non-cooperative behavior will be a steady-state equilibrium outcome. Since stock effects on profits act as a stimulant, the possibility of a limit cycle in a region of low biomass exists, when subjective auditing probabilities are stock dependent. In this case there are periodic oscillations where excess harvesting, lax regulation and low biomass levels are succeeded by reduced harvesting, more stringent regulation and recovery of stocks. In our model the mechanism driving periodic oscillations is the interaction between stock effects on profits, the stringency of regulation measured in terms of the movements of the subjective auditing probabilities as stocks change,

and evolutionary adoption of harvesting rules.

Combined stock and regulatory fluctuations, leading to eventual collapse, have been observed in fisheries. The Canadian cod fishery off the east coast of Newfoundland experienced its boom-bust phase in the mid-1950s. With the appearance of a new breed of factory-fishing, countries such as Germany (East and West), Great Britain, Spain, Portugal, Poland, the Soviet Union, Cuba and countries in east Asia had legally fished to within 12 miles of the eastern Canadian and New England (US) seaboard. Canada (and the US), concerned that stocks were being reduced to almost nothing, passed legislation in 1976 to extend their national jurisdictions over marine living resources out to 200 nautical miles. Catches naturally declined in the late 1970s and stocks started recovering after the departure of the foreign fleets. However national regulation did not set catch quotas at the late 1970s levels, and furthermore new technology in the form of factory-trawlers, or draggers as they became known, became the mainstay of Canada's Atlantic offshore fishing fleet. As a result the northern cod catch began a steady rise again, with a corresponding decline in stocks. By 1986 the stock decline was realized and by 1988 there were scientific opinions recommending that the total allowable catch be cut in half. Possibly because of delayed regulatory response, by 1992 the biomass estimate for northern cod was the lowest ever measured. The Canadian Minister of Fisheries and Oceans had no choice but to declare a ban on fishing northern cod. For the first time in 400 years the fishing of northern cod ceased in Newfoundland. The fisheries department issued a warning in 1995 that the entire northern cod population had declined to just 1,700 tonnes by the end of 1994, down from a 1990 biomass survey showing 400,000 tonnes (Greenpeace 2003).

The evolutionary framework developed in this paper can be regarded as providing some support for such observed fluctuations in the stocks and the stringency or effectiveness of regulation.

In terms of our model, oscillations can be eliminated and a full compliance steady state can be achieved by sufficiently high fines. If fines sufficiently high to take the CPR out of the trap of low stock oscillations and insufficient compliance are not feasible, because of say political reasons, then such fluctuations around a low stock will be persistent, and collapse might occur.

Comparing precommitment to auditing and partial commitment to auditing, it can be stated that a full compliance equilibrium can be achieved if the regulator is precommitted to announced fixed auditing probabilities. In this case there are combinations of fines/auditing probabilities that could attain the full compliance equilibrium. Thus if the regulator does not have the complete freedom to adjust fines due to political reasons the full compliance result can be achieved by increasing the auditing probability.

# Appendix

## Proof of Proposition 3 On the Existence of a Limit Cycle

We proceed in three steps.

1. First we show that point  $E$  in figure 3a is unstable. The linearization matrix around  $E$  is given by

$$J = \begin{bmatrix} 0 & \frac{\partial \pi^N}{\partial S} - \frac{\partial \pi^C}{\partial S} - \phi'(S^*) \mathcal{F} \\ -(h^N - h^C) & F'(S^*) \end{bmatrix}$$

with  $(h^N - h^C) > 0$ ,  $\frac{\partial \pi^N}{\partial S} - \frac{\partial \pi^C}{\partial S} - \phi'(S^*) F > 0$ ,  $F'(S^*) > 0$ . Thus  $tr(J) > 0$ ,  $Det(J) > 0$ . So there are two real positive characteristic roots and point  $E$  is unstable.

2. Then we show that a closed trajectory cannot be ruled out in a simply connected region,<sup>30</sup> like  $M$  in figure 3a, containing the isolated critical point  $E$ . This can be accomplished by using Bendixon's criterion (Sasstry 1999). It is clear that it is not possible to verify that the expression

$$div(\xi) := \frac{\partial \dot{x}_N}{\partial x_N} + \frac{\partial \dot{S}}{\partial S} = [(\pi^N(S) - \pi^C(S) - \phi(S) \mathcal{F}) (1 - 2x_N) + F'(S)] \quad (32)$$

does not change sign in a simply connected region containing  $E$ . Thus Bendixon's criterion implies that a closed trajectory cannot be ruled out in the region containing  $E$ .

3. Finally we construct the positively invariant set  $R$  where the flow of the vector field (26), (27) points inwards into  $R$  on the boundaries of  $R$  as shown in figure 3a. More precisely a trapping positively invariant region like the quadrilateral  $R$  can be constructed in the following way. The inwards pointing condition on the boundary of the  $R$  region means that  $(\eta_1, \eta_2)' \cdot (\dot{x}_N, \dot{S}) < 0$ <sup>31</sup> where  $(\eta_1, \eta_2)'$  is the outward pointing normal on the boundary of  $R$ . Region  $R$  is defined by segments of straight lines  $x_N = k_{1j} + k_{2j}S$ ,  $j = 1, 2, 3, 4$ . The outward pointing normals for the

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<sup>30</sup>A simply connected region is a region that can be (smoothly) contracted to a point. Thus a simply connected region cannot have more than one "blob" and that blob cannot have any holes in its interior. See for example Sasstry (1999, Ch. 2.3).

<sup>31</sup> $(\eta_1, \eta_2)'$  denotes a column vector.

lines  $k_{1j} + k_{2j}S$  are defined as  $(\eta_1, \eta_2)' \cdot (S, x_N) = 0$  or  $\eta_1 S + \eta_2 x_N = 0$   
or

$$-\frac{\eta_2}{\eta_1} = \frac{S}{x_N} = \frac{S}{k_{1j} + k_{2j}S}, \text{ thus } (\eta_1, \eta_2)' = \left( -\left(\frac{k_{1j}}{S} + k_{2j}\right), 1 \right), j = 1, \dots, 4$$

If real numbers  $(k_{1j}, k_{2j})$ ,  $j = 1, 2, 3, 4$  exist such that

$$\left( -\left(\frac{k_{1j}}{S} + k_{2j}\right) \right) \dot{x}_N + \dot{S} < 0, j = 1, 2, 3, 4 \quad (33)$$

then the vector field (26), (27) points inward on the boundary of the region  $R$ . Assume that a region  $R$  satisfies the above conditions. Then since  $E$  is unstable and it is the only critical point inside  $R$ , we can define a region like  $U$  around  $E$  where the flow of the vector field (26), (27) points outwards on the boundary of  $U$ . Then by the Bendixon-Poincare theorem a limit cycle  $L$ , exists in region  $R$ .

### Polymorphic Compliance Equilibrium for $S^* > S_{msy}$

We consider the linearization matrix  $J$  with  $F'(S^*) < 0$ , since  $S^* > S_{msy}$ .  
Then

$$\begin{aligned} tr(J) &= F'(S^*) < 0, \\ Det(J) &= F'(S^*) + (h^N - h^C) \left[ \frac{\partial \pi^N}{\partial S} - \frac{\partial \pi^C}{\partial S} - \phi'(S^*) \mathcal{F} \right]. \end{aligned}$$

Let  $\delta = [tr(J)]^2 - 4[Det(J)]$ . From standard stability analysis of dynamical systems in two dimensions we have:

- If  $\delta < 0$ , or  $F'(S^*) [F'(S^*) - 4] < 4(h^N - h^C) \left[ \frac{\partial \pi^N}{\partial S} - \frac{\partial \pi^C}{\partial S} - \phi'(S^*) \mathcal{F} \right]$ , then the steady state is a stable focus.
- If  $Det(J) > 0$ ,  $\delta > 0$ , then the steady state is a stable node with non linear trajectory paths.
- If  $Det(J) < 0$ , then the steady state is a saddle point.

■

## References

- [1] Clark, C. (1990), *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*, Second Edition, Wiley: New York.
- [2] Gintis, H. (2000), *Game Theory Evolving*, Princeton University Press, Princeton.
- [3] Conrad, J. (1999), *Resource Economics*, Cambridge University Press, Cambridge.
- [4] Conrad, J. and C. Clark (1987), *Natural Resource Economics*, Cambridge University Press, Cambridge.
- [5] Eggert, H. and A. Ellegard (2003), Compliance and fisher influence in Swedish commercial fisheries regulations - A case for co-management, [www.beijer.kva.se/conference2003/Eggert\\_Ellegard.pdf](http://www.beijer.kva.se/conference2003/Eggert_Ellegard.pdf)
- [6] Franckx, L. (2002), The use of ambient inspections in environmental monitoring and enforcement when the inspection agency cannot commit itself to announced inspection probabilities, *Journal of Environmental Economics and Management*, 43, 1, 71-92.
- [7] Gordon, H. S. (1954), The economic theory of common property resource: The fishery, *Journal of Political Economy*, 62, 124-142.
- [8] Greenpeace (2003), *Canadian Atlantic Fisheries Collapse*, <http://archive.greenpeace.org/%7Ecomms/cbio/cancod.html>.
- [9] Grieson, R. E., and N. Singh (1990), "Regulating externalities through testing," *Journal of Public Economics*, 41, 369-387.
- [10] Garvie, D., and A. Keeler (1994), "Incomplete enforcement with endogenous regulatory choice", *Journal of Public Economics*, 55, 141-162.
- [11] Hardin, G. (1968), "The tragedy of the commons," *Science*, 162, 1243-1247.
- [12] Jackson, J. et al. (2001), "Historical overfishing and the recent collapse of coastal ecosystems", *Science*, 293, 629-637.
- [13] Jensen F., and N. Vestergaard (2002), "Moral hazard problems in fisheries regulation: The case of illegal landings and discard," *Resource and Energy Economics*, 24, 281-300.

- [14] Khalil, F. (1997), "Auditing without commitment," *The RAND Journal of Economics*, 28(4), 629-640.
- [15] Malik, A. (1990), Markets for pollution control when firms are non-compliant, *Journal of Environmental Economics and Management*, 18(3), 97-106.
- [16] Malik, A. (1993), Self-reporting and the design of policies for regulating stochastic pollution, *Journal of Environmental Economics and Management*, 24(3), 241-257.
- [17] Nielsen J. R. and C. Mathiesen (2003), Important Factors Influencing Rule Compliance in Fisheries - Lessons from Denmark, *Marine Policy* 27, 409-416.
- [18] Negri, D. H. (1989), The common property aquifer as a differential game, *Water Resources Research*, 25, 9-15.
- [19] Ostrom, E. (1990), *Governing the Commons - The Evolution of Institutions for Collective Action*, Cambridge University Press, Cambridge.
- [20] Ostrom, E., R. Gardner and J. Walker (1993), *Rules, Games and Common-Pool Resources*, The University of Michigan Press, Michigan.
- [21] Samuelson, L. (1997), *Evolutionary Games and Equilibrium Selection*, The MIT Press Cambridge, Massachusetts.
- [22] Sastry, S. (1999), *Nonlinear Systems: Analysis, Stability and Control*, Springer, New York.
- [23] Segerson, K. and T. Miceli (1998), Voluntary environmental agreements: Good or bad news for environmental regulation?, *Journal of Environmental Economics and Management*, 36(2), 109-130.
- [24] Sethi, R. and E. Somanathan (1996), "The evolution of social norms in common property resource use," *American Economic Review*, 86, 766-788.
- [25] Smith, V. (1968), Economics of production from natural resources, *The American Economic Review*, 58, 409-431.
- [26] Stranlund, J. K., and K.K. Dhada (1999), Endogenous monitoring and enforcement of a transferable emission permits system, *Journal of Environmental Economics and Management*, 38(3), 267-282.

- [27] Sutinen, J., A. Rieser and J. R. Gauvin (1990), "Measuring and explaining noncompliance in federally managed fisheries, *Ocean Development and International Law*, 21, 335-372.
- [28] Taylor, P. and L. Jonkar (1978), Evolutionary stable strategies and game dynamics, *Mathematical Biosciences*, 40, 145-56.
- [29] van Egteren, H and M. Weber (1996), Market permits, market power and cheating, *Journal of Environmental Economics and Management*, 30(2), 161-173.
- [30] Weibull, J. (1995), *Evolutionary Game Theory*, The MIT Press, Cambridge, Massachusetts.



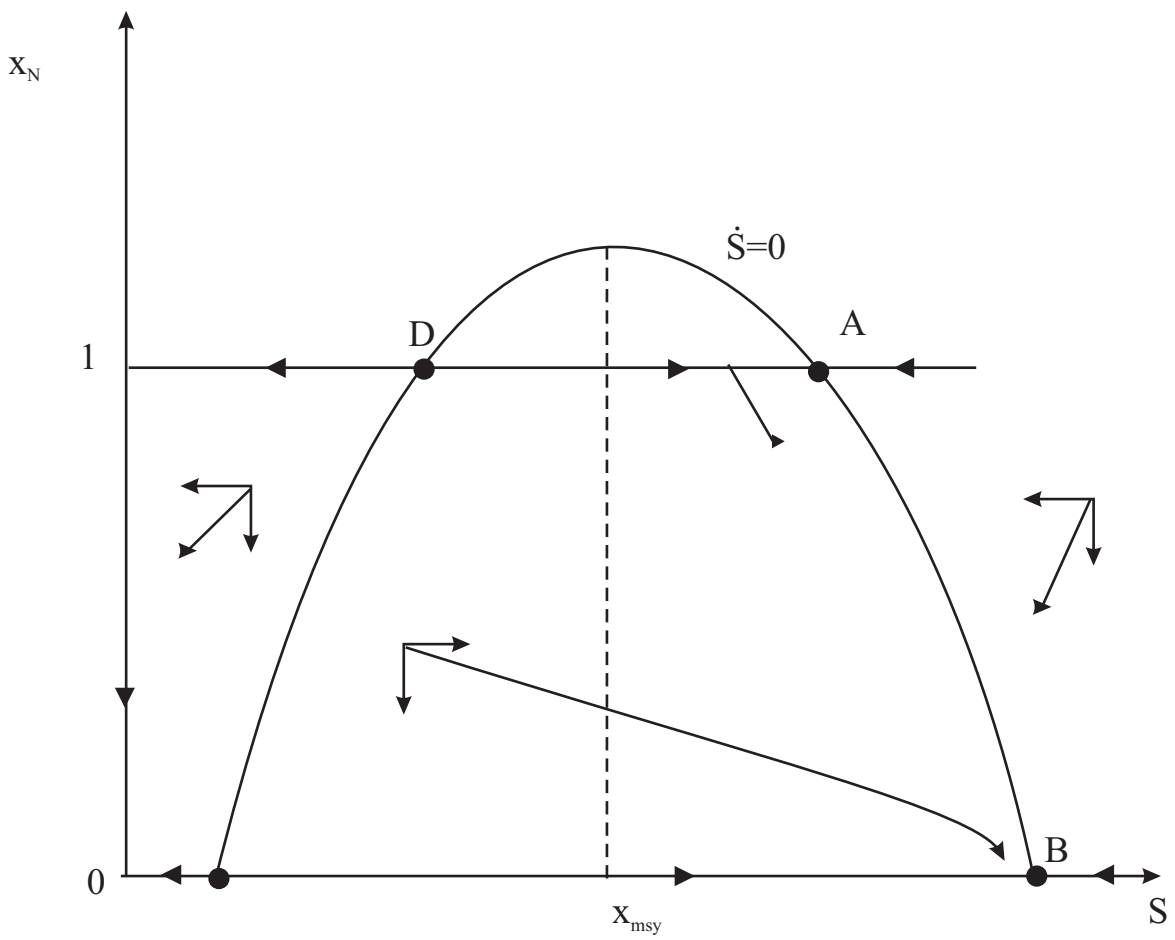
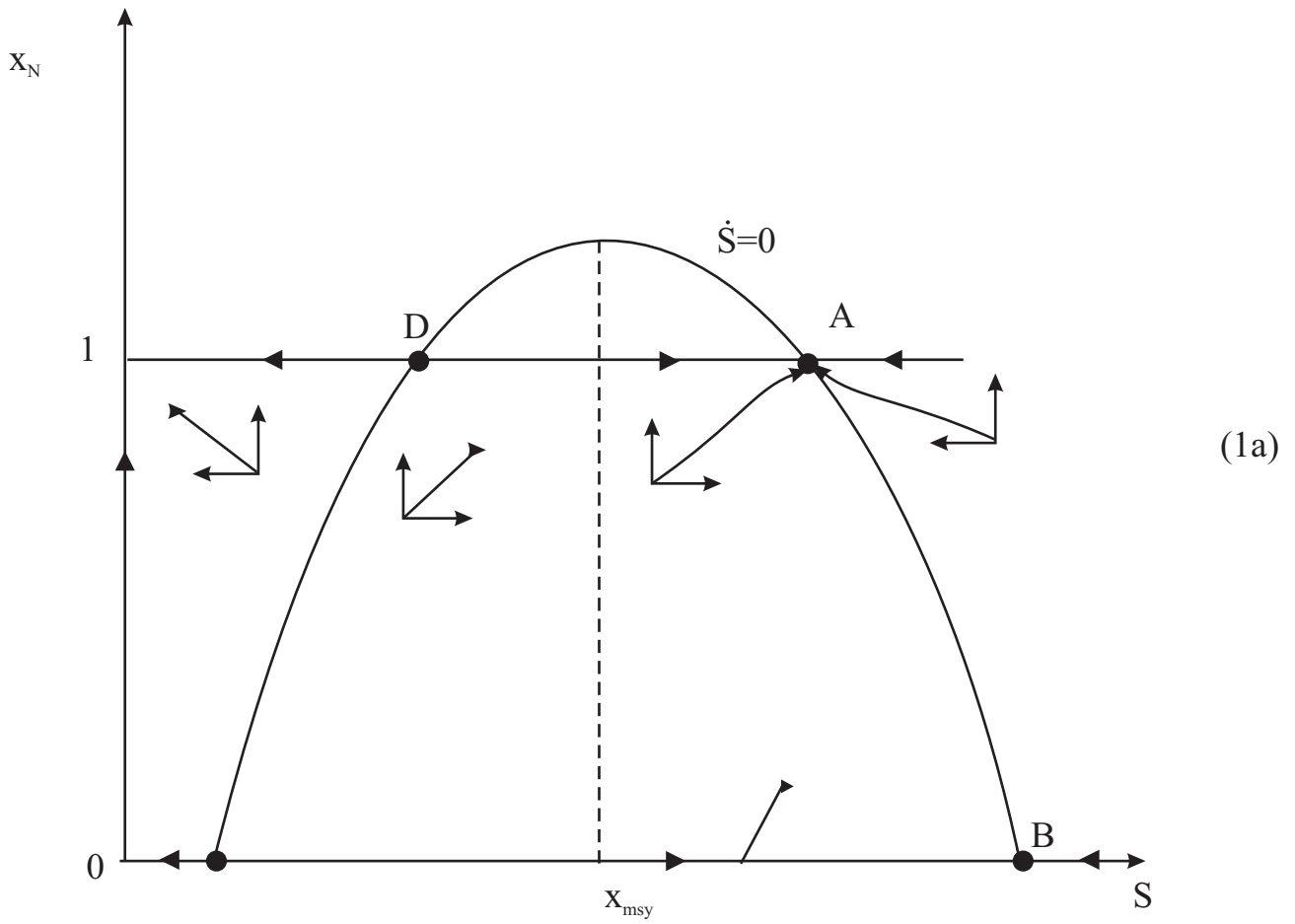


Figure 1

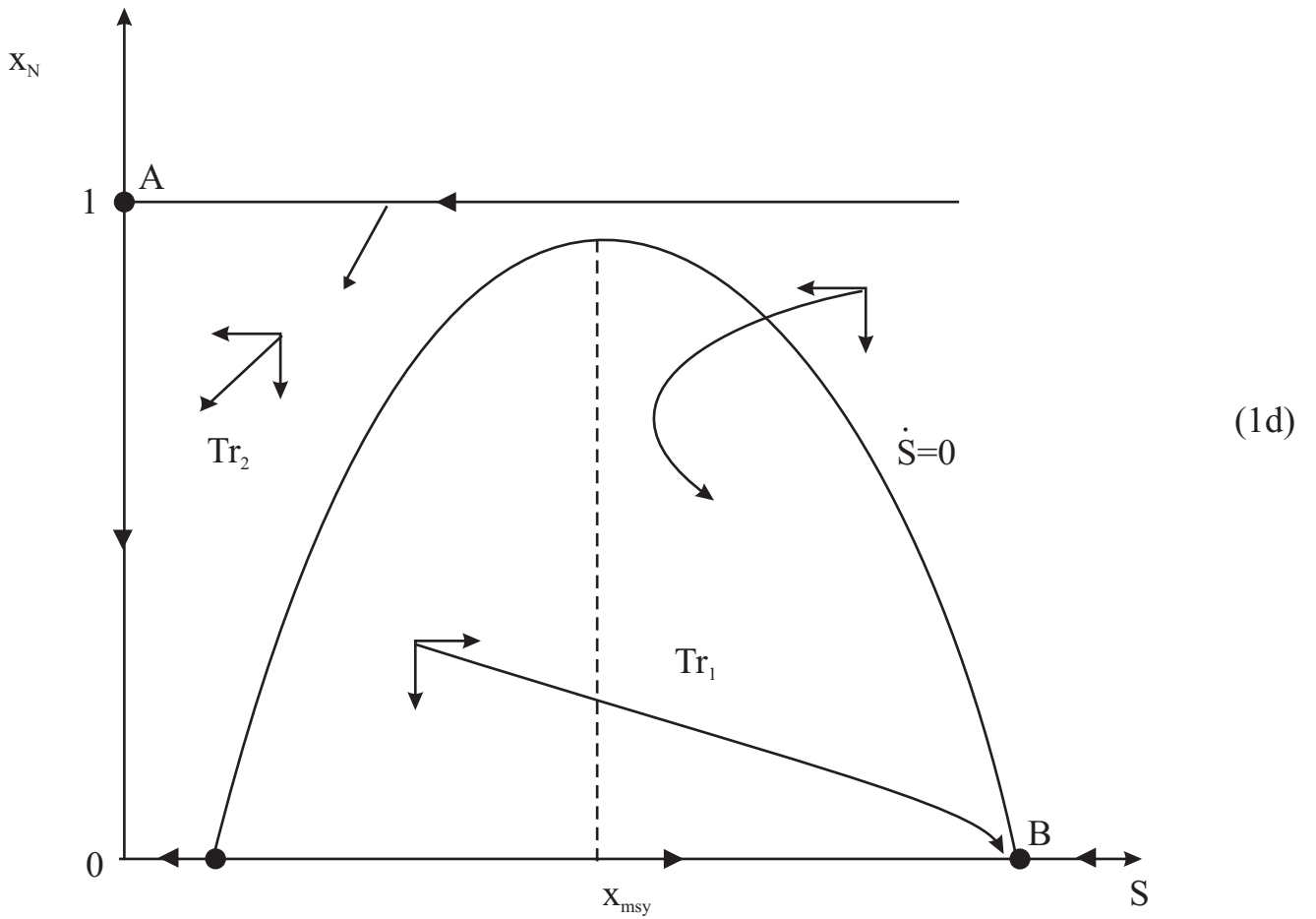
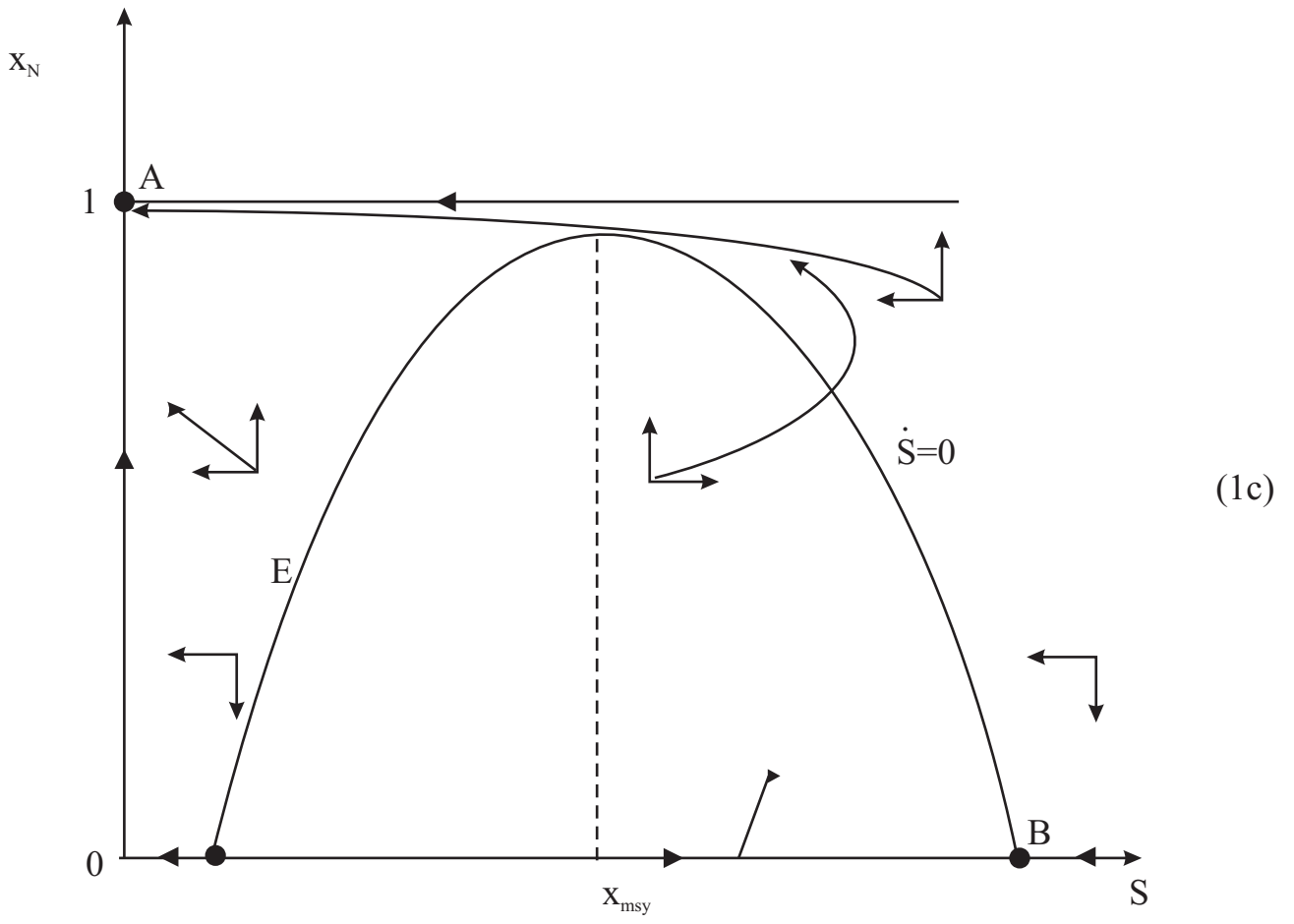


Figure 1

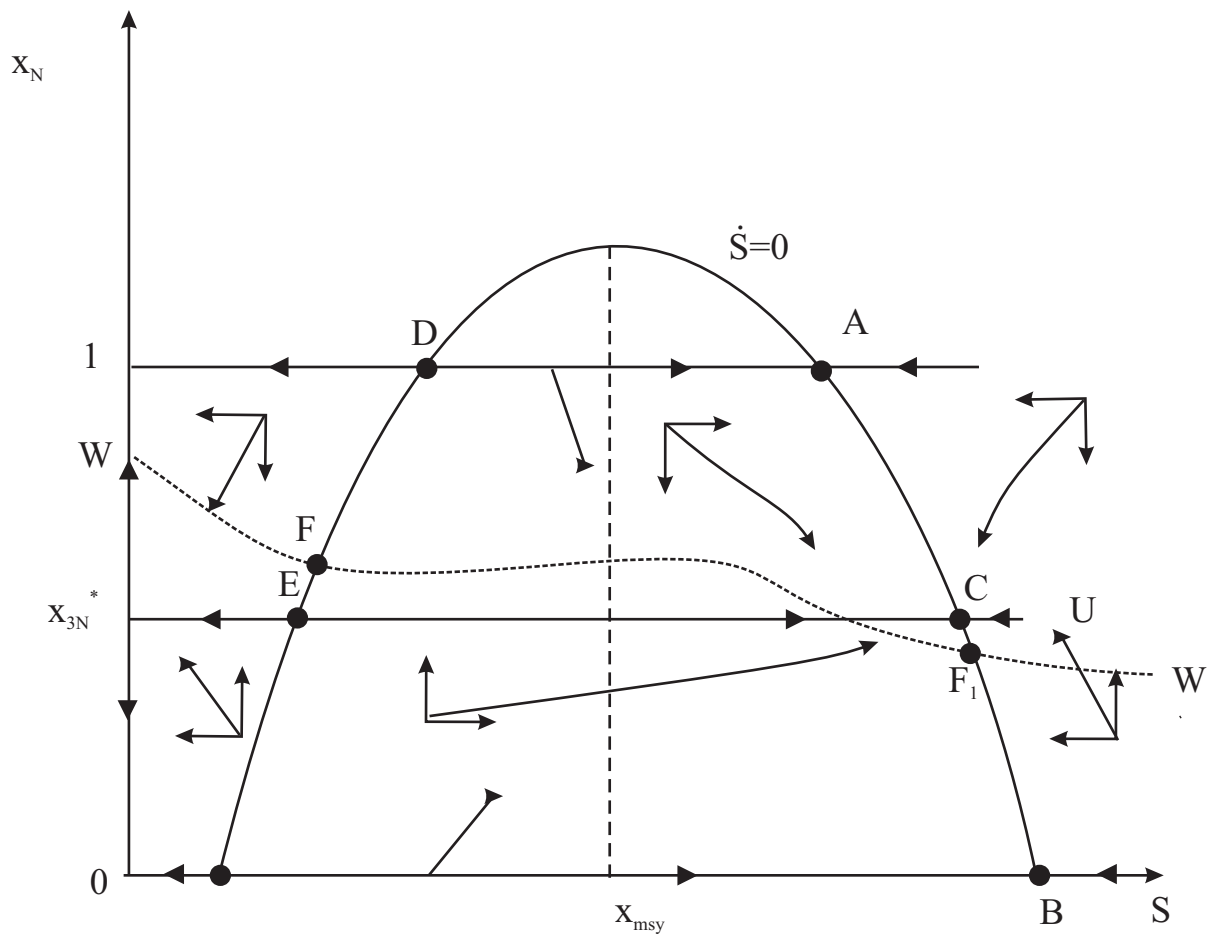
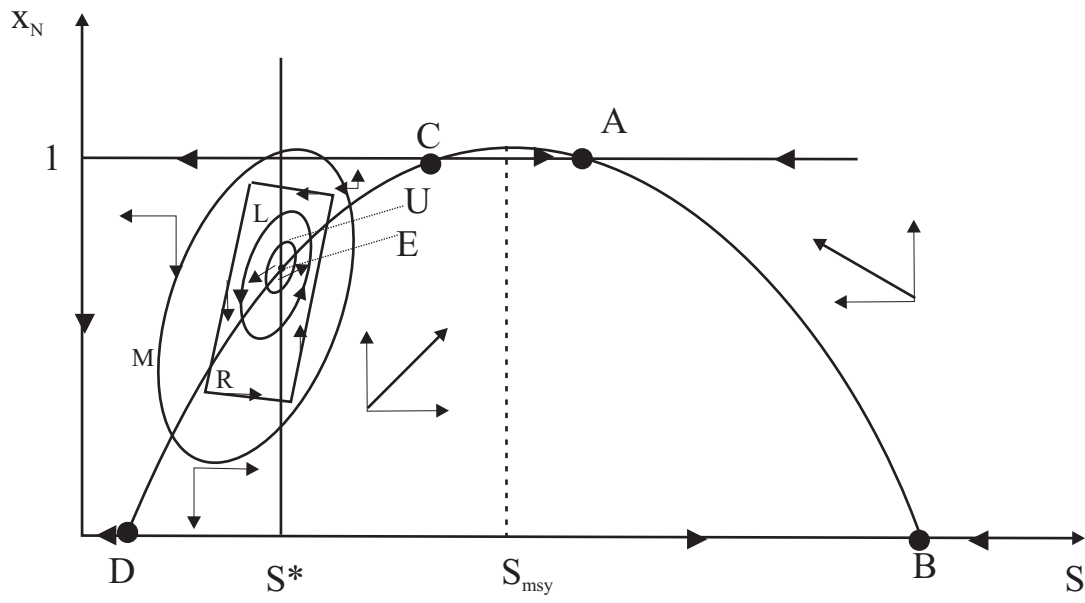
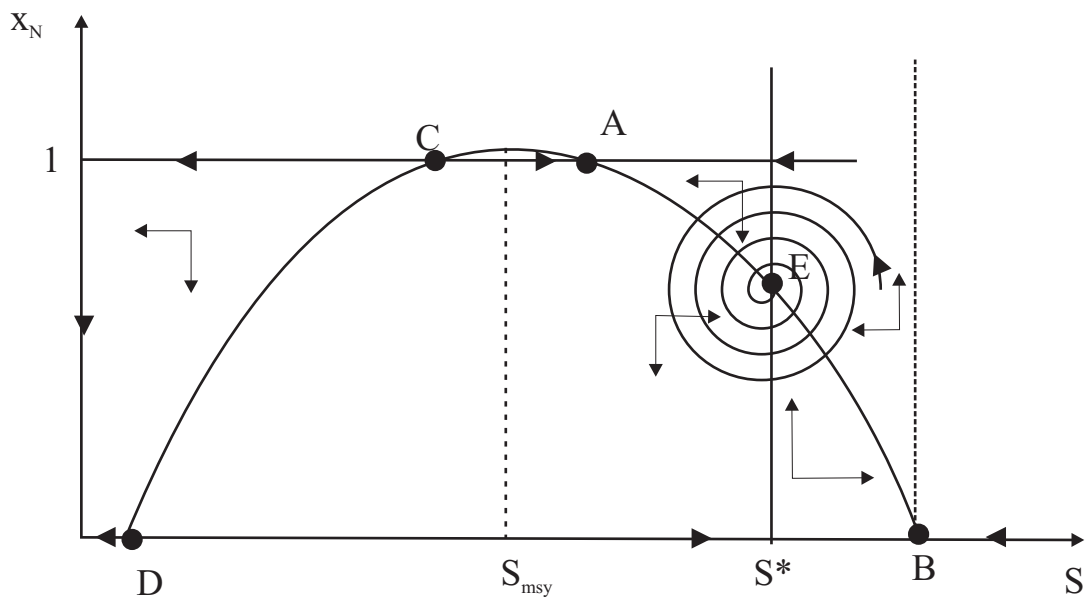


Figure 2.



(3a)



(3b)

Figure 3