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Regulation and Evolution of Harvesting Rules and Compliance in Common Pool Resources[1]

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RESUMEN

Este trabajo modeliza conjuntamente la evolución del acatamiento de la regulación y del stock de un recurso de libre acceso en el contexto de un proceso evolutivo que combina el mecanismo de "replicator dynamics", para describir la adopción de políticas de captura, con la dinámica del stock del recurso. Este enfoque evolutivo determina la aparición de políticas de captura de equilibrio en estado estacionario o niveles de acatamiento bajo la regulación, y el correspondiente comportamiento del stock de equilibrio del recurso en estado estacionario. Este enfoque evolutivo sugiere que es posible la coexistencia de estrategias cooperativas y no cooperativas en un contexto en que existe regulación. Se muestra que el efecto del stock sobre los beneficios, junto con una cierta estructura de las probabilidades de ser auditado, pueden implicar la aparición de un ciclo límite en zonas de bajos niveles de stock, como un resultado de equilibrio para el nivel de acatamiento y el stock de biomasa. También se muestra que es posible modificar la regulación modificando las penalizaciones asociadas al incumplimiento de la regulación, a fin de lograr equilibrios con acatamiento completo y salir del equilibrio con bajos niveles de stock. Asimismo se pone de manifiesto que podría ser más fácil para el regulador obtener el acatamiento completo si existe un compromiso de mantener unas probabilidades de supervisión prefijadas.

Palabras clave: Recursos de libre acceso, capturas, regulación, "replicator dynamics", acatamiento.

ABSTRACT

The present paper 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. 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. 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. It shown it might be easier for the regulator to obtain the full compliance if there is precommitment to fixed auditing probabilities.

Keywords: Common pool resources, harvesting, regulation, replicator dynamics, compliance

JEL Classification: Q20, Q22, C61

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[1] Paper presented at the centrA Workshop on Dynamics Economics and the Environment, Seville, Spain, July 2003.

Regulation and Evolution of Harvesting Rules and Compliance in Common Pool Resources*

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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[1] 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 substractability property.

Design of institutions to exclude potential beneficiaries from harvesting the resource is not easy, thus many CPR have open access characteristics.[2] 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,

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[*] Paper presented at the *Sevilla Workshop on Dynamic Economics and the Environment,* Sevilla, Spain, July 2003.

[1] See, for example, Ostrom, Gardner and Walker (1993).

[2] A CPR is typically associated with a fixed number of potential beneficiaries or users, while for an open access resource this restriction does apply.

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.[3] This non-cooperative outcome can be associated with historical resource overexploitation and collapses of stocks.[4]

The overexploitation of a CPR leads to the need for a regulatory framework.[5] In a fishery, probably the most well-studied case, at a theoretical level, optimal regulation can be designed by comparing the non-cooperative 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, landing fees.[6] 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

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[3] 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) andOstrom (1993).

[4] See Jackson et. al. (2001). Also, FAO estimates that currently 71 - 78 percent of fish stocks are fully exploited, overexploited or recovering from depletion.

[5] 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 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.

[6] See, for example, Conrad and Clark (1987) Clark (1990), and Homans and Wilen (1997).

evidence regarding quota busting, data fouling and in general noncompliance behavior.[7] In particular, typical violations of regulations involve illegal catch or landings, misreporting landings, violation of by-catches rules, discards of fish, fishing without licence, landing of protected stocks, misreported catch areas.[8]

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 been also modelled, following mainly Ostrom (1990), in the context of institution formation within the appropriators of the CPR that allows the imposition on sanctions to 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 con cooperative behavior.

In the present paper compliance or noncompliance, or equivalently the decision to follow the cooperative or the noncooperative harvesting rule, is modelled by assuming that appropriators are expected to choose their harvesting rule in an evolutionary way, by considering the evolution of their profits, taking into account the probability of paying a fine if audited and found not to comply 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 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.[9] The steady-state equilibrium resource level and harvesting rule will be the outcome of this evolutionary

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[7] See, for example, Nielsen and Mathiesen (2003).

[8] For example, Jensen and Vestergaard (2002), Eggert and Ellegard (2003).

[9] For the use of the replicator dynamic methodology coupled with stock dynamics in a CPR problem, see also Sethi and Somanathan (1996).

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.

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.[10] 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. It shown it might be more easy 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

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[10] This of course does not diminish the importance of environmental factors in biomass fluctuations.

$i = 1, ..., n$ appropriators.[11] Let resource dynamics be described by

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

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

$$\pi_i = p h_i - c_i(h_i, S) \tag{2}$$

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 as

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

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

$$\pi_i^N\left(h_i^N, S\right) \ , \ h_i^N = h_i^N(p, S) \tag{4}$$

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

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

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 $U(H) = S(Y) - nc(h, S)$, where $S(Y) = \int_0^{nh} P(u)\, du$ is the area under the demand curve $p = P(H)$ and $S'(H) = P(H) = p$. The social planner's problem is defined as

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

The current value Hamiltonian for this problem is defined as

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

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[11] For detailed modeling see, for example, Smith (1968) and Clark (1990).

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

$$\begin{aligned}\frac{\partial \mathcal{H}}{\partial h} &= 0 \text{ or } \mu = p - \frac{\partial c\,(h,S)}{\partial h}\; h^C = h^C\,(p,\mu,S) \qquad (7)\\ \dot{\mu} &= \left(\delta - \frac{\partial F}{\partial S}\right)\mu + n\frac{\partial c\,(h,S)}{\partial h} \qquad (8)\end{aligned}$$

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 regulation to design the 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

$$\pi^C\left(h^C,S\right) \qquad (9)$$

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

$$\pi^N\left(h^N,S\right)\;,\;\pi^C\left(h^C,S\right) \qquad (10)$$

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 $\pi^C\left(h^C,S\right) = ph^C - c^C\left(h^C,S\right)$, thus stock effects could be realized even through the socially-optimal rule, in the sense that if stock are 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 $\left\{h^N,h^C\right\}$ for the fixed number of $i = 1,...,n$ 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.[12]

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, he/she follows regulation, then the payoff will be $\pi^C\left(h^C, S\right)$. On the other hand a harvester can choose not to comply with regulation,[13] that is to follow the non-cooperative rule h^N. In this case, if audited (caught), he/she 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 this probability 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[14]

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

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.[15] 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 partiall 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

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[12] It should be noticed that what follows applies to any two distinct harvesting rules independent of how they have been defined. Noncooperative and cooperative optimization is used in order to define these rules, since this approach relates more to the traditional regulation theory.

[13] Nielsen and Mathiesen (2003) report about Danish fishers that conflicts in the normal pattern of fishing and the pattern of fishing implied by regulation has a major impact in their compliance behavior.

[14] 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).

[15] In the enforcement literature, variable monitoring effort is usually related to firm specific variables (e.g. Malik, 1990; VanEgteren and Weber, 1996).

level.[16] The harvesters are made aware of the results of the inspections, say through public announcements and/or private communications,[17] 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 ϕ can be specified as stock dependent auditing probability:

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

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

$$\phi(\mathbf{z}) \equiv \phi(x_N), \ \phi^{'}(S) > 0, \ \left(\phi(1), \phi(0)\right) > 0 \tag{13}$$

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:

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

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

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

where $\mathcal{F} > 0$ is a fixed penalty.[18] Under these assumptions the average profit flow associated with the CPR is defined, using the fact that $x_N + x_C = 1$, as:

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

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 $\alpha dt > 0$.[19] The appropriator will change his/her strategy to the other strategy if he/she perceives that the other's profit is higher because he/she follows

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[16] 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.

[17] In their survey Nielsen and Mathiesen (2003) report that " *fishers observe the activities and movements of the enforcement agents and continously report to their peers about it.*"

[18] In an empirical study of Danish fishers, Nielsen and Mathiesen (2003) sugest 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 $\pi^{N}\left(h^{N}, S\right)$, while factor (ii) is captured by the term $\phi(\mathbf{z})\mathcal{F}$.

[19] See Gintis (2000) for use of this approach in order to derive the replicator dynamic.

the other harvesting strategy. The higher the difference between the payoffs, the higher the probability that the appropriator will perceive it and change his/her harvesting rule. The probability of an appropriator i using noncooperative strategy h^N will switch to h^C, after learning the profit of the j appropriator, is:

$$p^t_{NC} = \begin{cases} \beta\left(\pi^{tC} - \Pi^{Nt}\right) & \text{for} \quad \pi^{tC} > \Pi^{tN} \\ 0 & \text{for} \quad \pi^{tC} \leq \Pi^{tN} \end{cases}$$

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

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

or using the definition of the average profit flow

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

For a large population, $\mathcal{E}x_N^{t+dt}$ can be replaced by x_N^{t+dt}, substracting x_N^t from both sides of (18), dividing by dt and taking the limit as $dt \to 0$, and setting without loss of generality $\alpha\beta = 1$, we obtain the replicator dynamic equation:[20]

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

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

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

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

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

The dynamical system (20), (21) can be used to analyze the evolution of harvesting rules and resource stock towards an evolutionary equilibrium,

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[20] See also for example, Taylor and Jonkar (1978), Weibull (1995) and Samuelson (1997).

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.[21] 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 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,[22] thus $\pi^N\left(h^N\right) - \pi^C\left(h^C\right) = \gamma > 0$, 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:

$$\begin{aligned} \dot{x}_N &= (1 - x_N)\, x_N \left(\gamma - \bar{\phi}\mathcal{F}\right) && (22) \\ \dot{S} &= F(S) - n\left[x_N h^N + (1 - x_N)\, h^C\right] && (23) \end{aligned}$$

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

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[21] 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.

[22] Stock effects could be absent if changes in S cause no change in the density of the stock (Smith 1968).

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 $\delta = \left(\gamma - \bar{\phi}\mathcal{F}\right)$, 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

$$\begin{array}{ll} \text{if } \delta > 0 & x_{1N}^* = 1 \text{ is stable, } x_{2N}^* = 0, \text{ is unstable} \\ \text{f } \delta > 0 & x_{1N}^* = 1 \text{ is unstable, } x_{2N}^* = 0, \text{ is stable} \end{array}$$

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 $\mathcal{F} > \gamma/\bar{\phi}$.*

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 none follows regulation in equilibrium. A similar role can be played by the auditing probability. In this case $\bar{\phi}^{cr} = \gamma/F$.[23]

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

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

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]

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[23] Sutinen et al (1990) suggestes 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.

In figure 1a, A is stable while B is unstable, with the reverse characterization in figure 1b. Figure 1c 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 result that full compliance can be attained by sufficiently high expected fines is supported by ideas developed through empirical observation. Sutinen et al. (1990) suggest that the high level of noncompliance in the US groundfish fishery can be explained by low economic sanctions. 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 (12). Then the dynamic system (20), (21) becomes:

$$\begin{aligned} \dot{x}_N &= (1-x_N)\,x_N\left[\gamma-\phi\left(x_N\right)\mathcal{F}\right] && (24)\\ \dot{S} &= F\left(S\right)-n\left[x_N h^N+\left(1-x_N\right)h^C\right] && (25) \end{aligned}$$

The system (24), (25) has again a hierachical structure but there is the possibility of three equilibria for (24). That is, $x_{1N}^{*}=1$, $x_{2N}^{*}=0$ as above but also more equilibria, provided that $\gamma-\phi\left(x_N\right)\mathcal{F}=0$ has solutions $x_N\in(0,1)$. Depending on the values of γ and $\mathcal{F}$ and the structure of $\phi\left(x_N\right)$ there could be one or more such equilibria.

The stability properties of these equilibria can be characterized in the following way. Since all admissible equilibria are in the compact and convex set $[0,1]$,the function $g(x_N) = (1-x_N)\, x_N [\gamma - \phi(x_N)\mathcal{F}]$ is continuous in x_N, and at $x_{1N}^* = 1$, $x_{2N}^* = 0$ the function $g(x_N)$ crosses the x_N axis, then if there are more crossings in $[0,1]$ there will be an alternating sequence of locally stable and locally unstable equilibria. In figure 2a $x_{1N}^* = 1$, $x_{2N}^* = 0$ are locally unstable while x_{3N}^* is locally stable. In figure 2b, $x_{1N}^* = 1$, $x_{2N}^* = 0$ are locally stable, x_{3N}^* is locally stable.

More formally the type of equilibrium 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. For example for three equilibria

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

If there are more than three equilibria, then in general there is an alternating sequence of locally stable and locally unstable equilibria, or vice versa. Ultimately.the number and the type of the equilibria depend on γ, ϕ and $\phi(x_N)$.

[Figure 2]

This result can be summarized as follows:

Proposition 2 *Assuming compliance dependent auditing probability there is a possibility of evolutionary stable polymorphic harvesting equilibria*

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, equilibria other than 0 and 1 can be eliminated by the regulator. In this case the stability properties are determined by the signs of $-[\gamma - \phi(1)\mathcal{F}]$ for $x_{1N}^* = 1$, and $[\gamma - \phi(0)\mathcal{F}]$ for $x_{2N}^* = 0$. For a sufficiently large fine and positive $\phi(0)$, the monomorphic full compliance equilibrium is evolutionary stable. As in the case of the fixed auditing probability the level of fine behaves as a bifurcation parameter.

Substituting the equilibria of (24) into (25) we obtain the steady state of the resource stock. The results are shown in Figure 3. In figure 3a there is polymorphic stable compliance equilibrium at point C, points A and B

are unstable monomorphic equilibria, while in figure 3b the compliance equilibrium is monomorphic (everybody either complies with regulation or not). This equilibrium depends on initial conditions. The stable monomorphic equilibria are A and B. Increasing the fine to eliminate a stable polymorphic equilibrium in terms of figure 3a implies that the $x_{3N}^{*}=0$ shifts down to the negative part of the x_N axis . Then the basin of attraction for the stable monomorphic full compliance equilibrium $x_{2N}^{*}=0$ is the whole $[0,1]$ space. As in the case of the fixed auditing probability if $x_N\left(S_{msy}\right)<1$, then for certain initial conditions indicating low stock and lax monitoring, the resource might collapse despite the introduction of stringent regulation.

[Figure 3]

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 below the profits of the harvester with which they randomly mach. 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 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:

$$\begin{aligned}\dot{x}_N &= \left(1-x_N\right)x_N[\pi^N\left(h^N,S\right)-\pi^C\left(h^C,S\right)-\phi\left(\mathbf{z}\right)\mathcal{F}] &\quad (26)\\ \dot{S} &= F\left(S\right)-n\left[x_N h^N+\left(1-x_N\right)h^C\right] &\quad (27)\end{aligned}$$

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),[24] the replicator dynamics (26) is written as

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

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

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

Differentiating totally (29) we obtain

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

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 4. 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 4]

Stock effects introduce one more steady state to the problem, point E in figure 4, in addition to the steady-state equilibria A, B, C, and D. Point A 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 critical points. Point E 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 R exists, such that the flow of the vector field points inwards on the boundary of R, then according to the Bendixon-Poincare theory,[25] a limit cycle exists around E as shown by L in figure 4a. The limit cycle might exist for relatively low resource levels , that is for $F'\left(S^*\right) < 0$ or $S^* < S_{msy}$. For $S^* > S_{msy}$ then the polymorphic equilibrium is stable but the approach path is characterized by oscillations. These results are summarized in the following proposition.

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[24] Results are qualitatively similar if we consider fixed auditing probabilities.

[25] 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 $(\zeta_{1t}\left(x_N\right), \zeta_{2t}(S))$ if, for each $(x_N, S) \in R$, $(\zeta_{1t}\left(x_N\right), \zeta_{2t}(S)) \in R$ for all $t \geq 0\,(t \leq 0)$. A detailed discussion regarding the existence of a limit cycle is presented in the Appendix.

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[26] 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 4a, then the resource might collapse. On the other hand for initial conditions to the right of R the 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

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

4b 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 4b, 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

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

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 isocine defined as

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

Under appropriate conditions on the functions and the fine, this isocine could generate two steady states like F and G in figure 3a. These steady states are induced by the dashed line WW, which is the isocine 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. Still without stock effects but with compliance dependent auditing probabilities a polymorphic compliance steady state could be achieved. In general a sufficiently high fine can be chosen such that the cooperative rule is followed by everybody in equilibrium.

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) seaboards. 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 1970's and stocks started recovering after the departure of the foreign fleets.

However national regulation did not set catch quotas at the late 1970's 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. Thus the northern cod catch began a steady rise again as a result, 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 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 4a is unstable. The linearization matrix around E is given by

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

   with $\left(h^N - h^C\right) > 0$, $\frac{\partial \pi^N}{\partial S} - \frac{\partial \pi^C}{\partial S} - \phi'(S^*)F > 0$, $F'(S^*) > 0$. 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,[27], like M in figure 4a, containing the isolated critical point E. This can be accomplished by using Bendixson's criterion (Sastry 1999). It is clear that it is not possible to verify that the expression

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

   does not change sign in a simply connected region containing E. Thus Bendixson'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 4a. 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 $(\eta_1, \eta_2)' \cdot \left(\dot{x}_N, \dot{S}\right) < 0$[28] where $(\eta_1, \eta_2)'$ is the outward pointing normal on the boundary of R. Region R is defined by segments of straight lines $x_N = k_{1l} + k_{2j}S$, $j = 1, 2, 3, 4$. The outward pointing normals for the

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[27] A simply connected region is a region that can be (smoothly) contracted to a point. Thus a simply connected region cannot have more that one "blob" and that blob cannot have any holes in its interior. See for example Sastry (1999, Ch. 2.3).

[28] $(\eta_1, \eta_2)'$ denotes a column vector.

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

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

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

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

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) point outwards on the boundary of U. Then by the Bendixon-Poincare theorem a limit cycle 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

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

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

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

■

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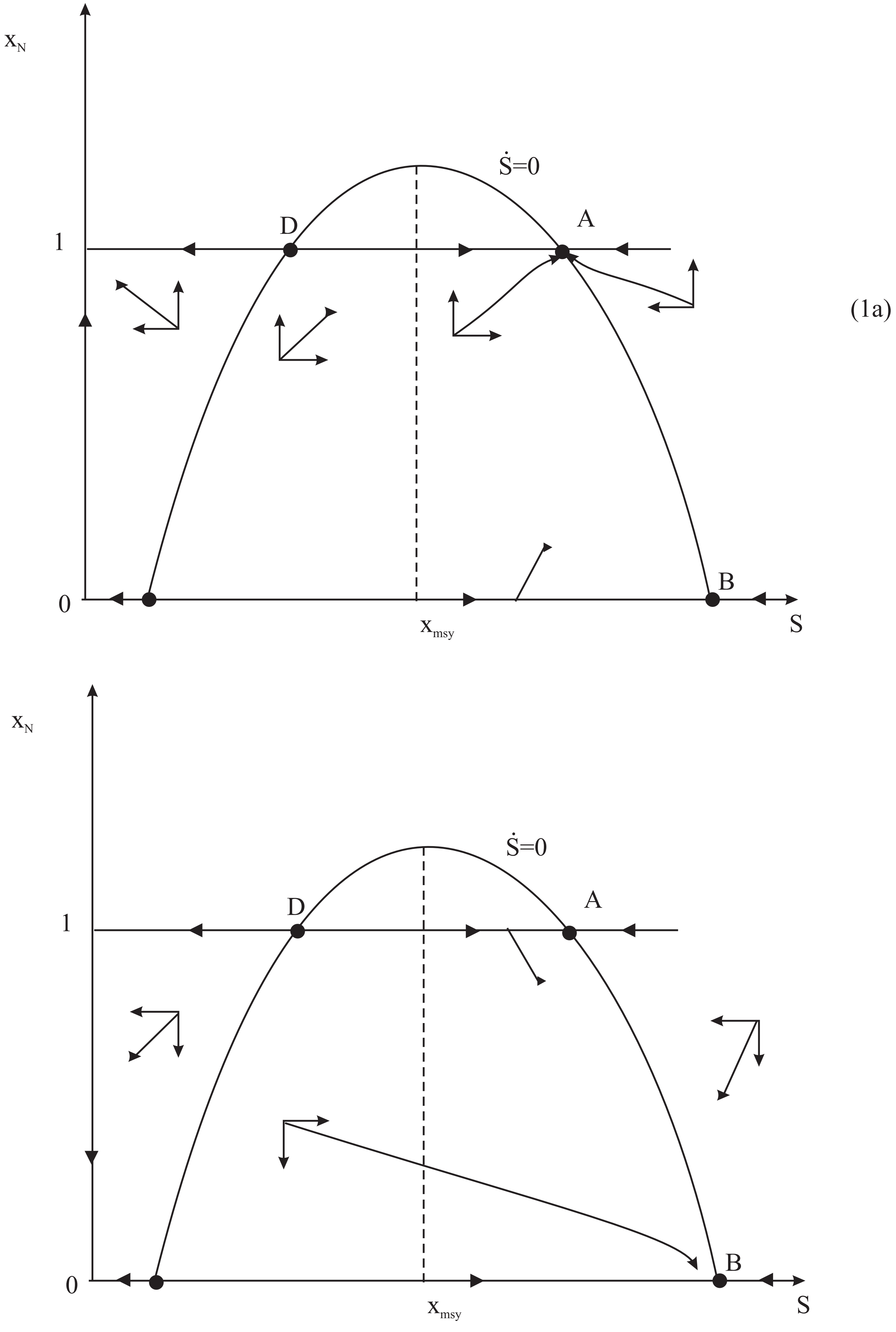


Figure 1

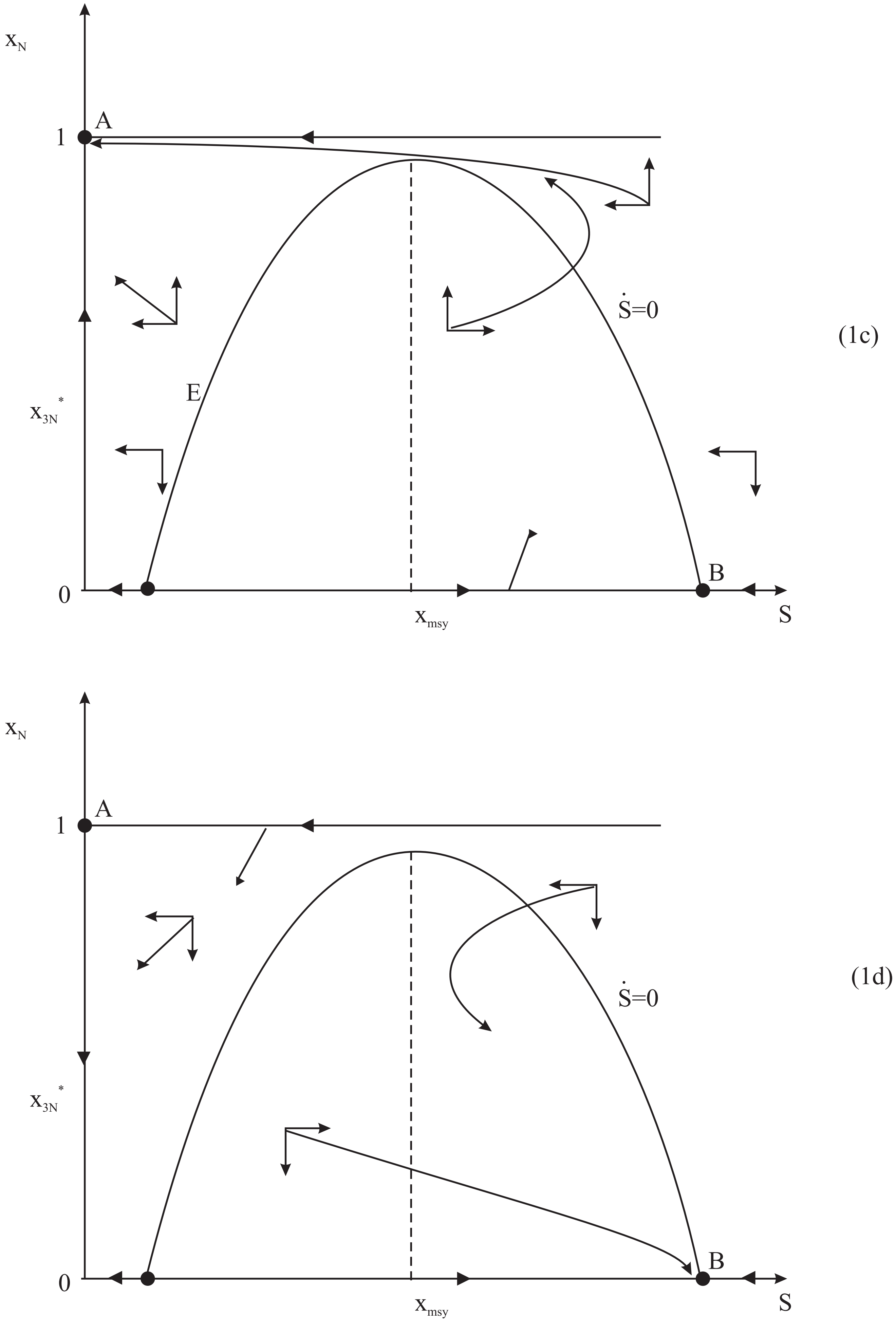


Figure 1

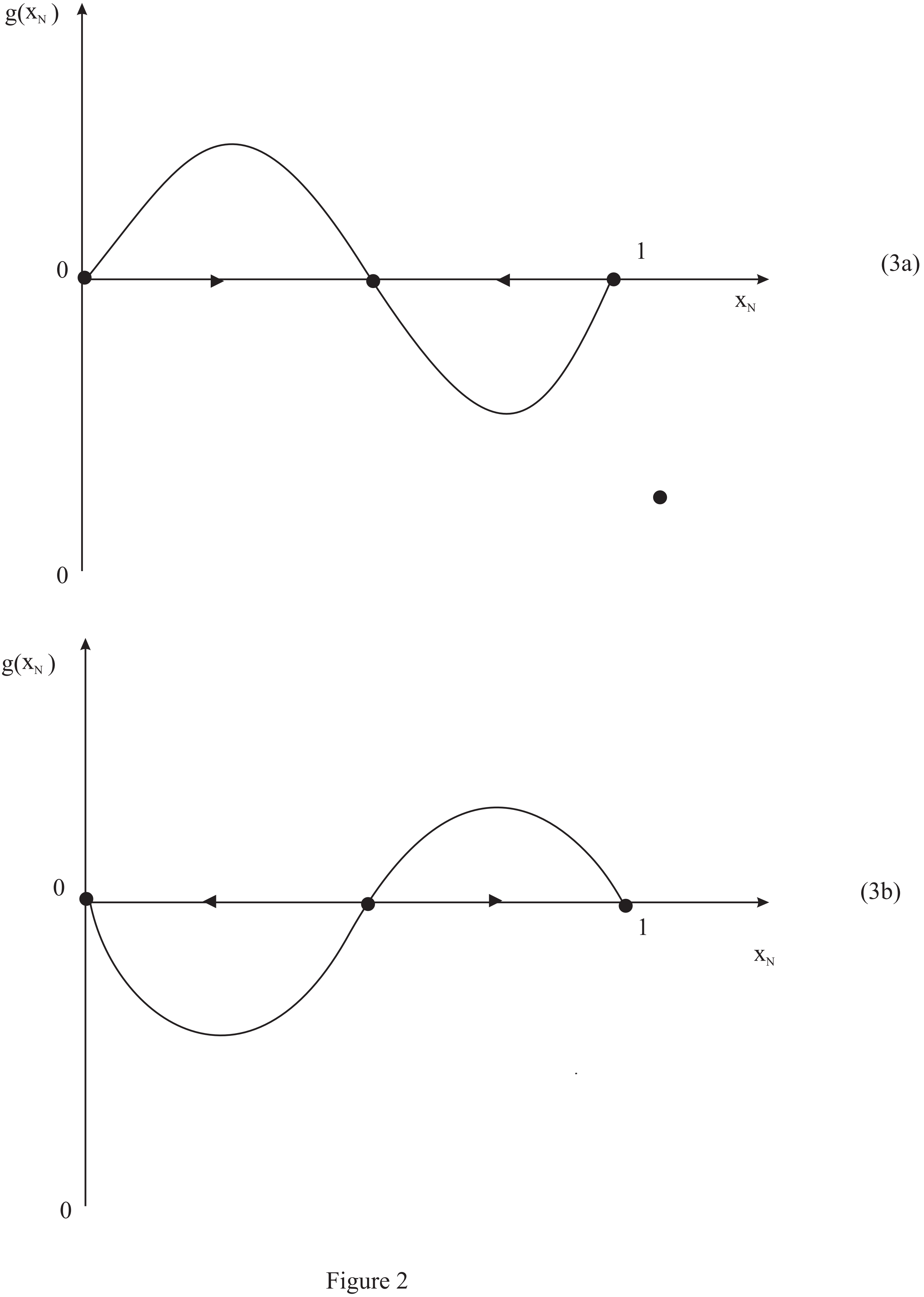
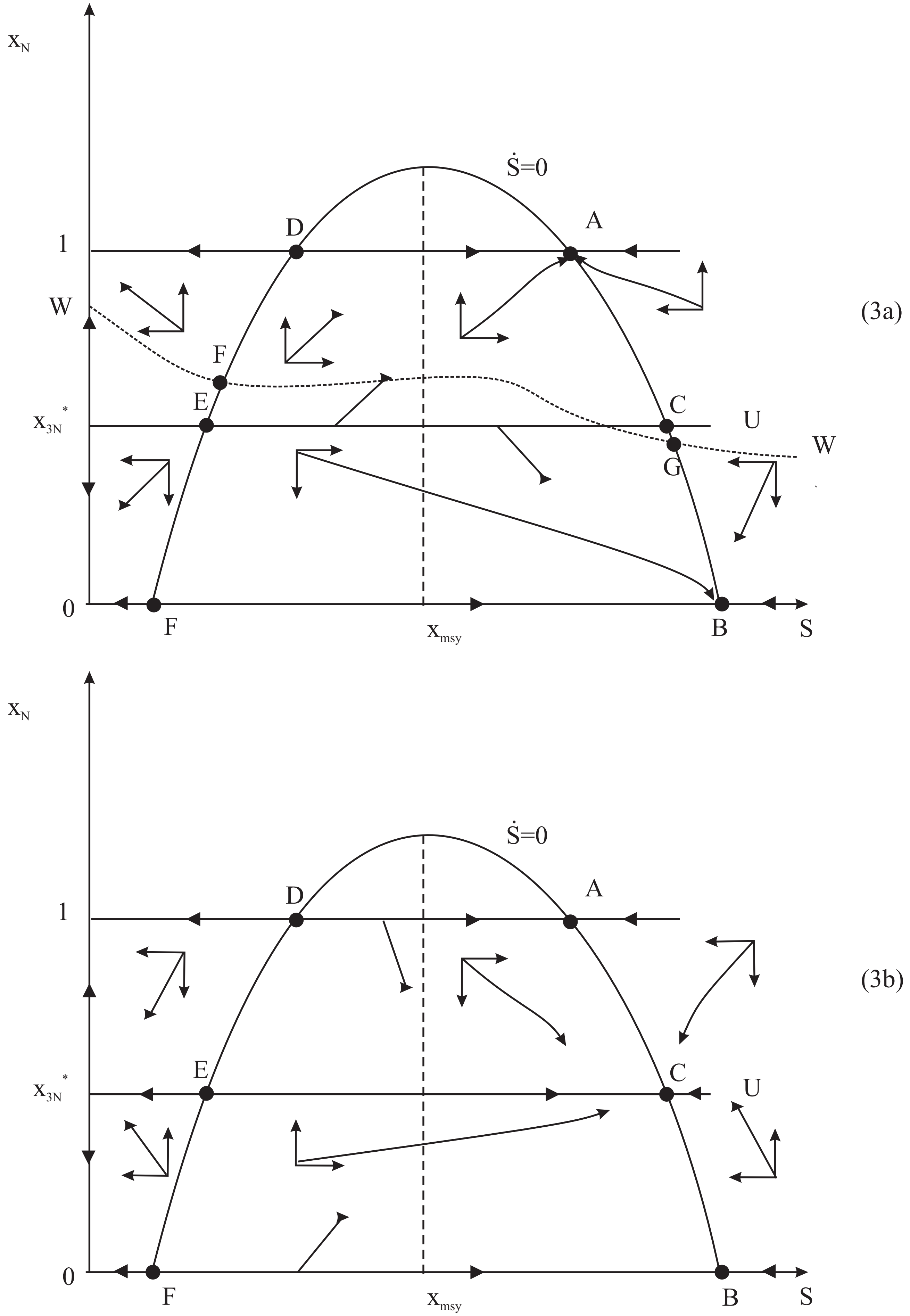
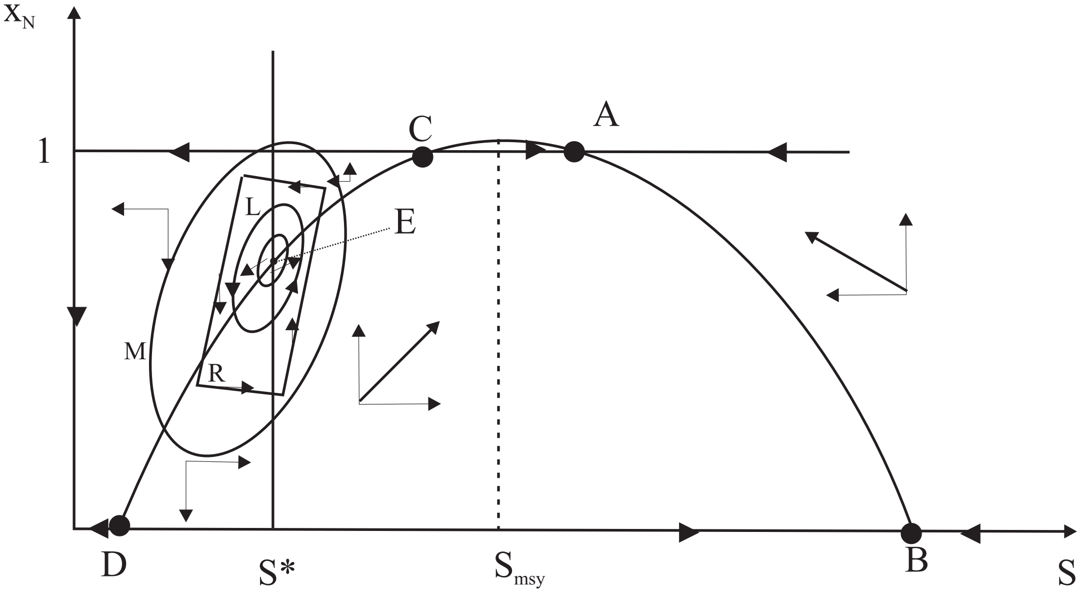


Figure 2

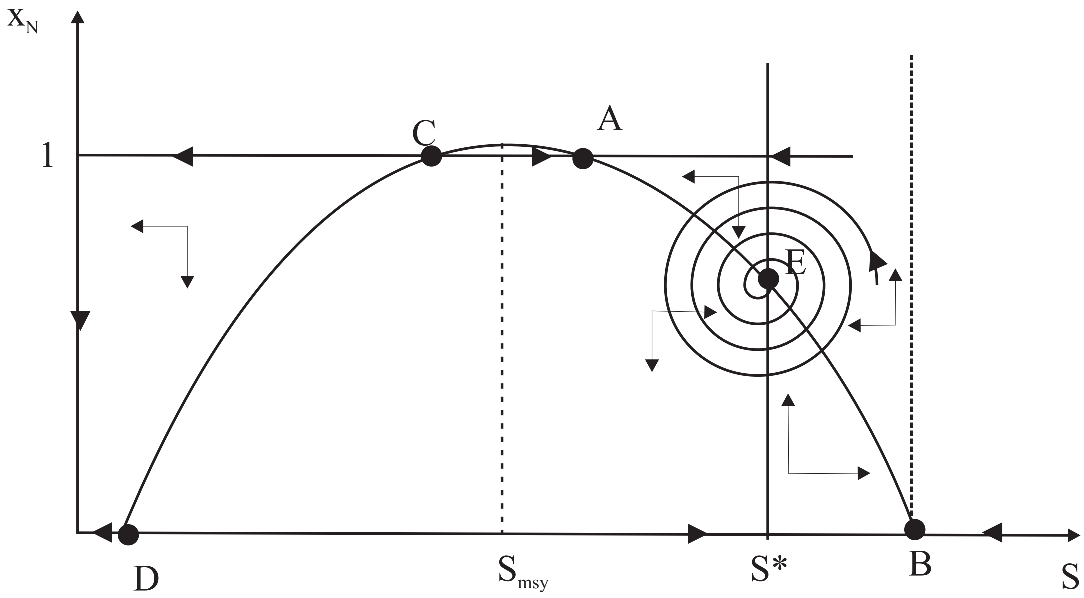


x_N
$\dot{S}=0$
D
A
1
W
(3a)
F
E
C
x_{3N}^*
U
W
G
0
F
x_{msy}
B
S
x_N
$\dot{S}=0$
D
A
1
(3b)
E
C
x_{3N}^*
U
0
F
x_{msy}
B
S

Figure 3.



(4a)



(4b)

Figure 4

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