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A Bioeconomic Analysis of a Renewable Resource inthe Presence of Illegal, Unreported and Unregulated Fishing

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Abstract

In poor nations, where regulatory frameworks are often lacking, the problem of illicit, unreported, and unregulated (IUU) fishing is a major concern for fisheries. To examine how illegal, unregulated, and unregulated fishing affects marine fish stocks in Ghana, this research suggests a Gordon-Schaefer bioeconomic model that accounts for non-linear costs and non-constant catchability. We define and talk about the model's static equilibrium reference points. A transcritical bifurcation point where the model becomes structurally unstable is shown by bifurcation analysis applied to the revised Schaefer model. We use Pontryagin's maximal principle to study the model's required circumstances and find the sufficiency criteria that ensure the optimality system exists and is unique. The optimum control may be described in two ways: the border solution, which states that the resource should be harvested only when the marginal income of harvesting is more than the marginal revenue of stocking, and the interior solution, which states the opposite. The theoretical predictions are validated by numerical simulations using actual data on the Ghana sardinella. As a result of IUU fishing, resource biomass is overexploited to the point that it falls below 50% of its carrying capacity. As a result, fishermen stand to lose money and the fishery becomes unsustainable.

The following terms are used to describe various aspects of the Ghana sardinella fishery: bioeconomics, renewable resources, shadow pricing, transcritical bifurcation, optimum control, illegal, unreported, and uncontrolled fishing, catchability coefficient.

2010 Mathematics Subject Classification: 37N40; 49K15; 92B05.

1 Introduction

There are artisanal, semi-industrial, and industrial subsets within Ghana's marine fishing industry, all of which contribute significantly to the country's economy. The artisanal sector stands out among these sectors when considering the quantity of catches and the number of fishermen involved. There is little to no oversight in the artisanal fishing industry, which is characterised by unfettered access. Every fisherman believes, "If I don't catch the fish, someone else will or might!" because of the unhealthy competitiveness that this open access fishing creates. [1]. That is why it shouldn't come as a surprise that when fish populations are becoming low, individual fisherman would go to great lengths to beat the competition. Use of chemicals, undersized mesh gears, light (or attractants) while fishing, and explosives (such as dynamite) are all examples of such methods.

To back up this claim, Koranteng [2] states that using smaller-sized meshes to maximise capture is standard practice for fishermen working in an over-exploited

and poorly managed fishery. Pauly et al. [3] and Pauly [4] define Malthusian overfishing as "poor fishers, faced with declining catches and lacking any other alternative, initiate wholesale resource destruction in their effort to maintain their incomes." As a result, the situation becomes even more dire. Malthusian overfishing is characterised by the following, according to Pauly et al.: (i) the use of gears and mesh sizes that are not approved by the government; (ii) the use of gears that are not approved within the communities of fishermen; and (iii) the use of gears
the use of "gears" like dynamite or sodium cyanide, which damage both the fisher-folks and the marine ecosystem, and (iv) the destruction of the resource base [2, 5].

Among the few rules imposed by the government on the artisanal fishing industry is the requirement that every mesh must be at least 25 millimetres (or about an inch) in extended diagonal length. The fisherman have willfully disobeyed this restriction, making it useless. The fishermen's major point is that some species, including anchovies, are too small to be caught with a minimum size of 25 millimetres in extended diagonal length. The artisanal fishing industry suffers as a result of their persistence in using prohibited mesh sizes [6].

The conventional Gordon-Schaefer bioeconomic model's [7, 8] assumption of a constant catchability coefficient conflicts with technical features of fishing power's progression. While standardising fishing effort, it is seldom taken into account that improvements in fishing gear design, such as the use of synthetic fibres in conjunction with fish recognition technologies, contribute to enhanced accuracy in the application of fishing power [9, 10, 11]. Additionally, while climate change is certainly a contributing factor to the dwindling sardinella fishery, overfishing caused by fishers using prohibited mesh sizes and attractants is making matters worse. In order to test this assertion, the suggested model's catchability parameter is subjected to sensitivity analysis. Models assessing the impacts of illicit, unreported, and unregulated (IUU) fishing on marine ecosystems in poor nations are few and few between. According to Petrossian [12], the ecology suffers and people whose livelihoods are dependent on it are in danger because of IUU fishing. Illegal, unregulated, and unregulated (IUU) fishing is a major cause of marine species overexploitation and a barrier to ecosystem and biomass recovery [13]. In order to determine the potential effects of these IUU fishing methods on the catchability of sardinella, a bioeconomic model is created using a quadratic cost function of fishing effort. This is
A variant of the more common linear cost function, the quadratic cost function is often used in resource modelling. Look at the work of researchers like Dubey et al. [15] and Kar and Misra [14]. This study is also unique since it discusses the optimum fishing effort in connection to the shadow price and the net income per unit harvest, which is not done before. The optimum control model, which includes the biomass dynamics and the whole bioeconomic model, is described in Section 2. Using bifurcation analysis, Section 3 investigates the model's dynamical features. Section 4 depicts the existence and uniqueness of the optimality system in addition to describing the optimal controlpresents the simulations that were used to analyse the Ghana sardinella fishery, while Section 6 discusses the results and provides a summary.

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Otherwise, the harvests h^θ would be a value $h\vartheta$ greater than the harvests without any increase in catchability, h. Furthermore, x^θ would be less than x_{MSY} . For more information on a modified catchability, see Mackinson et al. [20].

1.1 The bioeconomic model

Incorporating economic parameters into the afore-mentioned biological model gives the static Gordon- Schaefer bioeconomic model. The net revenue is the difference of total sustainable revenue TR_S and total cost TC, where TC is taken to be a quadratic function of E. That is,

$$TC = c_1 E + \frac{c_2}{2} E^2,$$

where c_1 and c_2 are the cost components relating to the effort. As stated by Hanson and Ryan [21], the additional quadratic cost term $\frac{c_2}{2} E^2$ may be seen as a perturbation on the usual linear cost, c_1E. It may also be viewed as a technique to avoid complexities inherent in the characterization of singular controls. The assumption is that both c_1 and c_2 are strictly positive, thereby making the costs to be monotonically increasing and growing rapidly than the corresponding linear costs (see Figure 1). Clark and Munro [22] as well as Sancho and Mitchel [23] asserted that quadratic costs are more in tune with reality than linear costs. Furthermore, the employment of a quadratic costs leads to the derivation of an explicit optimal control [24]. This is in contrast to linear costs, which give rise to bang-bang or singular controls [19].

Operating under an open-access regime where there is little or no regulation of the resource, effort E tends to a level where the sustainable economic rent (or net revenue) π_S is zero. This gives rise to what is known as open access yield (OAY). It must be noted that the OAY is also known as bionomic equilibrium (BE). The sustainable net revenue is given by

$$\pi_S = ph^\theta_S - c_1E - \frac{c_2}{2}E^2 = pq(1+\vartheta)EK\left(1 - q(1+\vartheta)E\right) - c_1E - \frac{c_2}{2}E^2, \qquad (2.8)$$

where p is the price per unit harvest.

Setting Equation (2.8) to zero gives

$$E^\theta_{OAY} = \frac{2r\,[pq(1+\vartheta)K - c_1]}{2pq^2(1+\vartheta)^2K + rc_2}, \qquad (2.9)$$

where $pq(1+\vartheta)K > c_1$. Note that E^θ_{OAY} reduces to the standard Gordon-Schaefer reference point E_{OAY} when $\vartheta = 0$ and $c_2 = 0$.

The biomass level x^θ_{OAY}

$$x_{OAY} = K \quad \frac{\quad}{OAY}$$

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Therefore, the optimal control problem is to maximize the present value (or discounted value) of the net revenue, and can be expressed as:

$$\max_{E} J(E) = \int_0^\infty e^{-\delta t}\left(pq(1+\vartheta)x - c_1 - \frac{c_2}{2}E\right)E\,dt$$

$$\text{subject to} \quad \frac{dx}{dt} = rx\left(1-\frac{x}{K}\right) - q(1+\vartheta)Ex \qquad (2.15)$$

$$x(0) = x_0$$

$$0 \le E \le E_{max}.$$

For this study, the biological parameter values employed are r = 1.42/year, $q = 1.8\times10^{-6}$/trip/year and $K = 1\times10^{6}$ tonnes. The economic values are given by p = \$600/tonne and c_1 = \$195/trip/year [25]. In addition, the discount rate δ is assumed to be 0.15/year. Note that the currency is denominated in United States dollars.

The linear and quadratic costs are depicted in Fig. 1. The perturbation in the linear costs is such that when the effort is at the MSY level, the quadratic costs are 25% greater than the linear costs. Therefore, c_2 is computed as

$$c_2 = 2\left(\frac{0.25c_1}{E_{MSY}}\right) = \$2.47\times10^{-4}/\text{trip}^2/\text{year}.$$

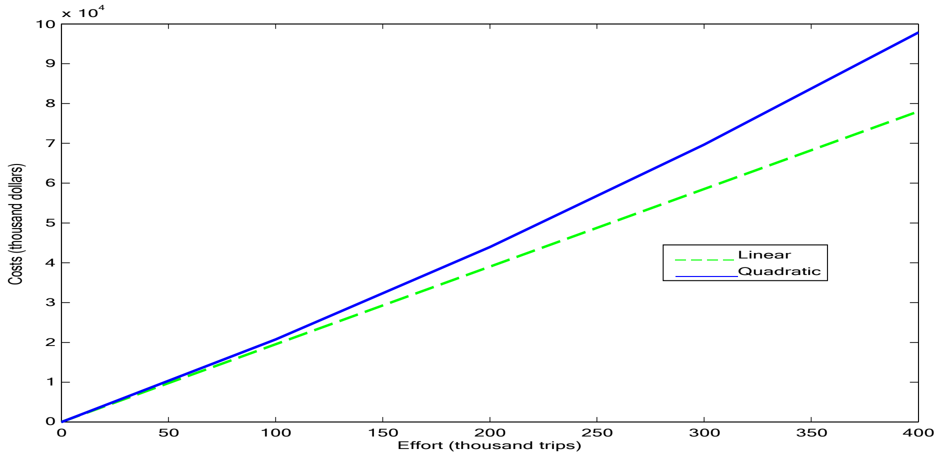


Fig. 1. Linear and quadratic costs

2 Bifurcation Analysis

When the parameter of a dynamical system is varied, it usually leads to a change in the number of equilibrium points or the stability properties of the system. This phenomenon is known as a bifurcation. The solution trajectories for the various scenarios depicting the effects of the variation in catchability on the fish stock are presented.

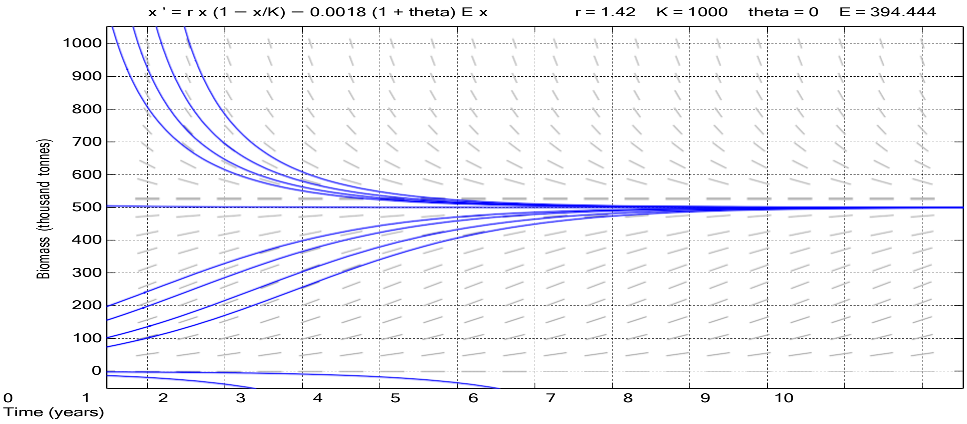


Fig. 2. Some solution trajectories when $E = 394,444$ and $\vartheta = 0$

The case where $E = E_{MSY} = 394,444$ trips with no variation in catchability, $\vartheta = 0$, is shown in Fig. 2. The system is structurally stable because there are two hyperbolic equilibrium points: 0 and $x_{eqm} = x_{MSY} = 500,000$ tonnes. For biomass levels $x_0 > x_{MSY}$ and $0 < x_0 < x_{MSY}$, the population asymptotically approaches x_{MSY}. Therefore, the zero stock size is unstable while x_{MSY} is stable. Furthermore, an effort rate of E_{MSY} leads to a stock size that is exactly half the carrying capacity.

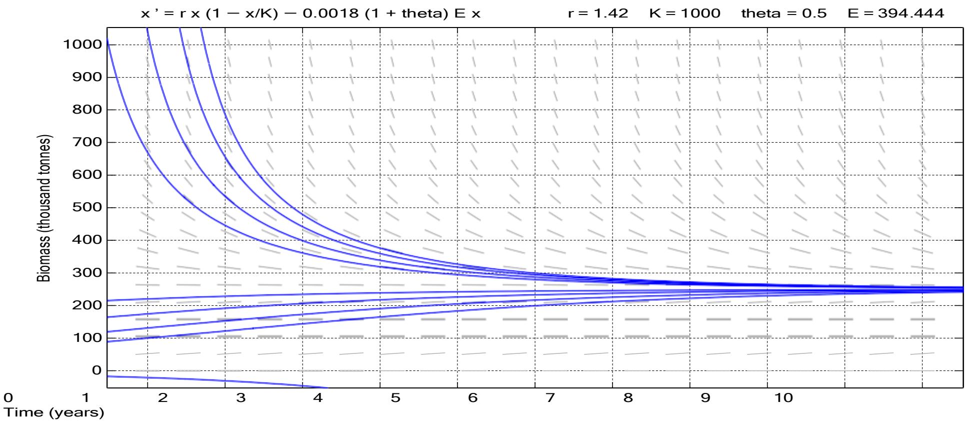


Fig. 3. Some solution trajectories when $E = 394,444$ and $\vartheta = 0.5$

Solution trajectories depicting a variation in catchability, $\vartheta = 0.5$, are presented in Fig. 3. There are two hyperbolic equilibrium points: 0, which is unstable and $x^{\theta} = 250,000$ tonnes, which is stable. For $x_0 > x^{\theta}$ and $0 < x_0 < x^{\theta}$, the population asymptotically approaches x^{θ}. This implies that an increase in catchability of 50% is equivalent to fishing at an effort rate E^{θ} that is one and a half times the effort rate at E_{MSY}. This induces a long-term decline in fish stocks to a level that is 50% of x_{MSY}. Note that, even though the effort rate $E = E^{\theta} = 394,444$ trips is greater than $E^{\theta}_{MSY} = 262,963$ trips, this model is structurally stable as the effort rate is still less than both the bifurcation points of the modified and standard models, 525, 926 trips and 788, 889 trips, respectively.

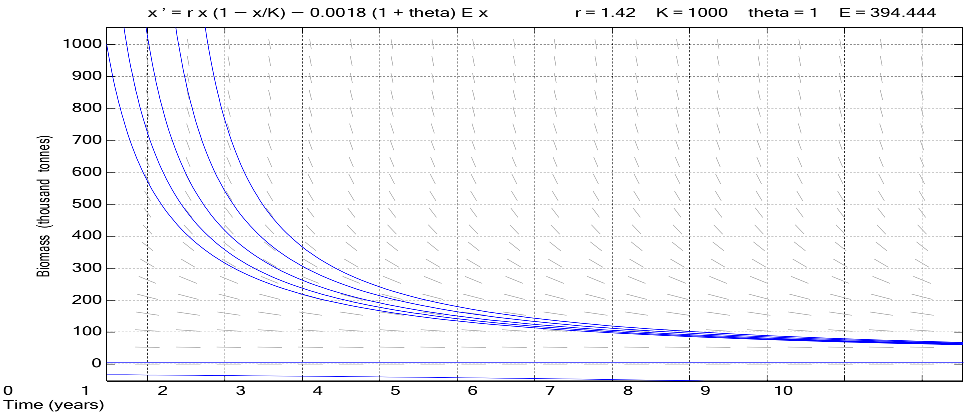


Fig. 4. Some solution trajectories when $E = 394, 444$ **and** $\vartheta = 1$

Fig. 4. portrays an extreme scenario where the catchability is doubled ($\vartheta = 1$). This implies that an increase in catchability of 100% is equivalent to fishing at an effort rate that is twice the effort rate at E_{MSY} (see Equation (2.7)). Fishing at two times of E_{MSY} corresponds to the bifurcation point of the standard model. Thus, for any $x_0 > 0$ the population approaches the nonhyperbolic equilibrium population, 0. Therefore at the bifurcation point ($2 \times E_{MSY}$), the single equilibrium biomass level 0 is semi-stable (making the system structurally unstable). Hence, for any initial biomass level, the long-term population of fish stock is towards extinction. It is instructive to note that when $\vartheta = 1$, $E^{\theta} = 394, 444$ trips exactly equal the bifurcation point of the modified model. However, to ensure sustainability of the resource ($x_{MSY} = x^{\theta}_{MSY}$ = 500, 000 tonnes) in the modified model, E^{θ}_{MSY} must be set 197, 222 trips (assuming zero costs and zero discounting).

3 Analysis of Optimal Control Problem

The sufficiency conditions are investigated and discussed in this section. In particular, the existence of an optimal control is determined. Also, the characterization of the optimal control and the existence and uniqueness of the optimality system are investigated.

3.1 Existence of optimal control

The stated goal is to maximize the present-value of the net revenue. Therefore, an optimal control E^* is sought that maximizes the objective functional over the Lebesgue measurable control set

$$U = \{E \mid 0 \leq E(t) \leq E_{max},\ \ t \in [0, \infty)\}.$$

In the course of solving an optimal control problem, there is the need to investigate and verify necessary and sufficient conditions that ensure optimality of the problem. A sufficiency condition for the existence of an optimal control to Problem (2.15) is given in Theorem 4.1 [26, 27].

Theorem 4.1. *Given the control problem* (2.15)*, there exists an optimal control* E^* *that maximizes the objective functional* $J(E)$ *over the control set* U *if the following conditions are satisfied:*

(i) The class of all initial conditions with a control E in the admissible control set together with the state system is nonempty.

(ii) The control set U is closed and convex.

(iii) The right hand side of the state system is bounded above by a linear function involving the state and control variables.

(iv) The integrand of the objective functional is concave on U.

(v) There exist constants $w_1, w_2 > 0$ and $\eta > 1$ such that the integrand $f(t, x, E)$ of the objective functional satisfies
$f(t, x, E) \le w_1 - w_2|E|^{\eta}$.

Proof. To prove the theorem, the given conditions are established as follows:

Regarding the first condition, the Picard-Lindelof existence theorem [28] guarantees the existence and uniqueness of a solution to a state equation with bounded coefficients.

By definition, the control set U is closed and convex. This verifies condition 2. For verification of condition 3, the comparison theory of differential equations is applied to determine the boundedness of the solution to the state equation. Since

$$x' = rx\left(1 - \frac{x}{K}\right) - q(1+\vartheta)Ex \le rx\left(1 - \frac{x}{K}\right)$$

for $0 \le t < \infty$ and $x_0 > 0$, then

$$x' \le rx\left(1 - \frac{x}{K}\right) = rx - \frac{rx^2}{K}$$

For $x' \ge 0$,

$$0 \le \frac{rx^2}{K} \le rx.$$

$0 \leq x(t) \leq K.$

Additionally, the right hand side of the state equation can be expressed as

$$S(t, x, E) = rx\left(1 - \frac{x}{K}\right) - q(1 + \vartheta)Ex \leq rx \leq rK.$$

Hence the bound on the right hand side can be written as

$$S(t, x, E) \leq rK.$$

To prove that the integrand of the objective functional is concave on U, let $f(t, x, E) = e^{-\delta t}L(t, x, E) = e^{-\delta t}pq(1 + \vartheta)xE - c_1 E - \frac{c_2}{2}E^2$. Then $f(t, x, E) \leq L(t, x, E)$, since $e^{-\delta t} > 0$ for $t \geq 0$.

Using the convex property of E, for $0 \leq m \leq 1$ and $E_1, E_2 \in U$, it implies that

$$mE_1^2 + (1 - m)E_2^2 \geq [mE_1 + (1 - m)E_2]^2.$$

Therefore, the objective is to show that, for $0 \leq m \leq 1$,

$$mf(t, x, E_1) + (1 - m)f(t, x, E_2) \leq f(t, x, mE_1 + (1 - m)E_2),$$

or

$$mL(t, x, E_1) + (1 - m)L(t, x, E_2) \leq L(t, x, mE_1 + (1 - m)E.$$

This proof starts by observing that the difference of $mL(t, x, E_1)+(1-m)L(t, x, E_2)$ and $L(t, x, mE_1 + (1 - m)E_2)$ is given by

$$mL(t, x, E_1) + (1 - m)L(t, x, E_2) - L(t, x, mE_1 + (1 - m)E_2)$$
$$= mpq(1 + \vartheta)xE$$

and $\eta = 2$.

2

□

To show that the objective functional is convergent as $t \to \infty$, let $w_1 - w_2E^2 = G$. Then

$$\int_0^\infty e^{-\delta t}\left(pq(1 + \vartheta)x - c_1 - \frac{c_2}{2}E\right)E\,dt \leq \int_0^\infty e^{-\delta t}G\,dt = \frac{G}{\delta}.$$

3.2 Characterization of optimal control

In this section, the optimal control is characterized – obtaining an explicit formulation for the optimal control level – as well as determining the optimality system. Having established the existence of an optimal control to Problem (2.15), the necessary conditions for the control are derived using Pontryagin's maximum principle [29].

Theorem 4.2. *Given an optimal control E^* and a solution to the corresponding state equation, there exists an adjoint variable λ satisfying*

$$\lambda' = \left(\delta - r + \frac{2rx}{K}\right)\lambda - (p - \lambda)q(1 + \vartheta)E, \tag{4.1}$$

The uniqueness of the optimal control is investigated, since Theorem 4.1 establishes the existence of the control. Given the a priori boundedness of the state and adjoint equations together with the state equation being continuously differentiable, the mean value theorem ensures that the Lipschitz condition is satisfied by the state equation with respect to the state variable. This guarantees the uniqueness of the optimality system for small time intervals as result of the opposite time orientations of the state and adjoint equations. Furthermore, the uniqueness of the solutions of the optimality system guarantees uniqueness of the optimal control [32, 33, 34].

5 Simulations

Simulations are carried out using the Forward-Backward Sweep method outlined in Lenhart and Workman [32]. As the name of the method indicates, the state equation is solved forward in time while the adjoint equation is solved backward in time in order to achieve convergence.

In the standard Gordon-Schaefer model (where $\vartheta = 0$ and $c_2 = 0$) the optimum sustainable yield (OSY) is found to be 351, 328 trips per annum [19]. Therefore to ensure sustainability of the resource, the annual effort rate of the quadratic model should be less than 351, 328 trips (since the higher fishing costs in the quadratic model have the tendency to reduce effort rate). To ensure the sustainability of the quadratic model, the sustainable yield (SY) must be pegged at 315, 000 trips per annum.

The model is subjected to numerical simulations with the maximum fishing effort initially set at the SY level, E_{SY} and the results illustrated graphically. Also considered is the case of E^{θ}_{MEY} with no variation in catchability. That is, let E^{0}_{MEY}
= 296, 380 trips (see Equation (2.12)). Firstly, simulations are carried out with a fixed initial

5.1 Long-run dynamics of model

The long-run scenario, as shown in Fig. 5, depicts fishing at a maximum effort rate of 315, 000 trips (SY effort rate) and an initial biomass level of 550, 000 tonnes. From an initial value of \$346.35, the shadow price steadily decreases and after a few years sharply declines to zero. However, the net revenue of \$346.35 is almost constant for the entire horizon. The fact that the shadow price is lower than the net revenue for the majority of the horizon indicates that the marginal revenue of harvest exceeds the marginal revenue of stock. It is therefore in the fishermen's best interest to apply the maximum available effort in harvesting.

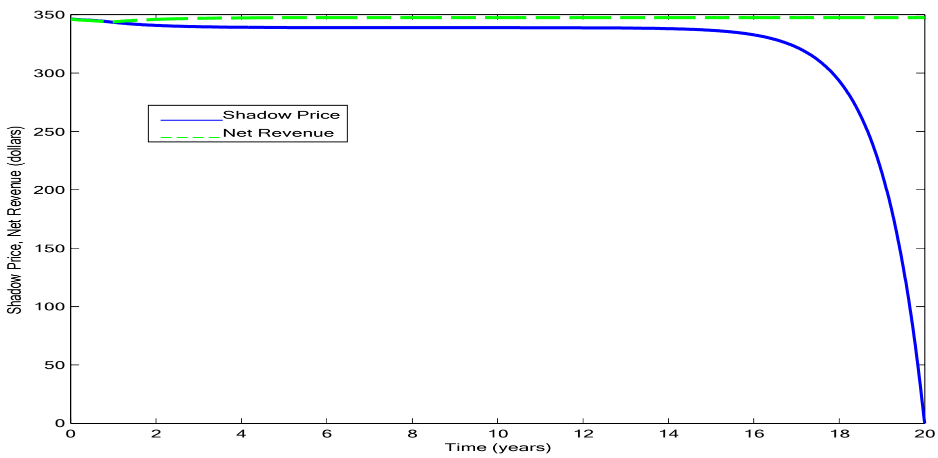


Fig. 5. Shadow price and net revenue for $x_0 = 550,000$, $\vartheta = 0$ and $E_{max} = 315,000$

In Fig. 6, it is observed that when the maximum effort rate E_{max} is set at the MEY and SY levels, the optimal effort rates settle down at their respective equilibrium levels. Starting at about 245, 827 trips, the effort rate for E^{0}_{MEY} increases rapidly and stabilizes at a final value of around

296*,* 310 trips. Meanwhile, the effort rate for E_{SY} starts much lower at 227*,* 634 trips and converges to 314*,* 923 trips. Similarly, the biomass levels for MEY and SY increase and converge to the equilibrium values of 624*,* 491 tonnes and 600*,* 899 tonnes respectively. The total net revenues corresponding to the effort levels at MEY and SY are computed as $806*,* 620*,* 000 and $809*,* 690*,* 000, respectively.

Fig. 10. shows that the initial shadow price, $346.14, is significantly lower than the net revenue,
$509.41 making it worthwhile to harvest at the maximum effort rate. After some years, the shadow price and the net revenue attain the same value of $469.25. Subsequently, the shadow price plummets to zero while the net revenue ends at $462.60. Thus, the optimal control alternates between the interior and boundary controls. This shows that it is not optimal to exert the maximum effort at the middle portion of the horizon.

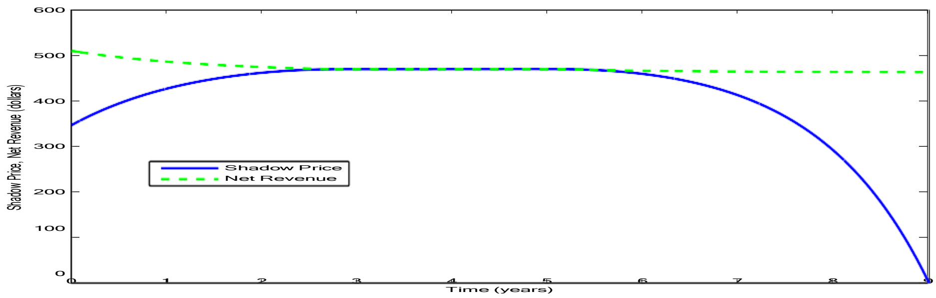
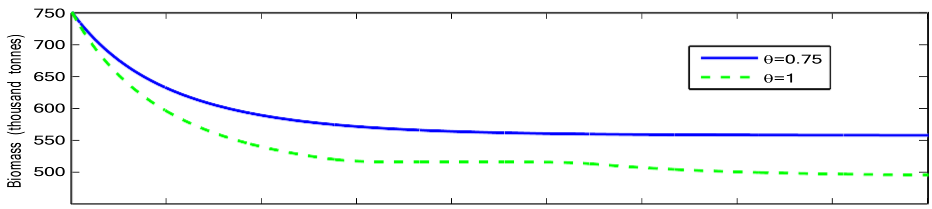


Fig. 10. Shadow price and net revenue for $x_0 = 750,000$**,** $E_{max} = 200,000$**,** $\vartheta = 1$ **and** $T = 9$

In Fig. 11, the optimal effort rates follow the same trajectory of almost 200*,* 000 trips for bothcatchability levels throughout the nine-year horizon, except for a brief period where it is almost convex and attaining a minimum value of 190*,* 748 trips for $\vartheta = 1$. The biomass decreases for the catchability levels $\vartheta = 0.75$ and $\vartheta = 1$ to 556*,* 672 tonnes and 494*,* 515 tonnes, respectively. It is noteworthy that when $\vartheta = 1$, the iterates failed to converge beyond a time horizon of nine years. The total net revenues for $\vartheta = 0.75$ and $\vartheta = 1$ are $889*,* 200*,* 000 and $941*,* 440*,* 000, respectively. Therefore, a 33% increment in the catchability results in a revenue increase of 6%, and a decrease in final biomass level of 11% (with no equilibrium or sustainable level achieved for $\vartheta = 1$).



6 Concluding Remarks

Using the modified Gordon-Schaefer model, this study sought to identify the most effective fishing effort tactics for sardinella. The model for the dynamics of the fish biomass was a modified Schaefer equation, and it was subjected to bifurcation analysis with a modification in the catchability coefficient. Also, the classic Gordon-Schaefer model's goal functional was changed. A more practical cost alternative, quadratic costs, was examined in place of the model's linear costs. The MSY, MEY, and OAY were established as the reference points under this revised paradigm. The points of reference for the modified model revert to the conventional Gordon-Schaefer model when the coefficient of the quadratic cost component is zero and the percentage of variance in catchability is zero, as was realised. Both the presence of an ideal control and its characterization by means of Pontryagin's maximal principle were established. The model's Lipschitz property ensures that the optimality system is unique. The updated model underwent numerical simulations in which the quadratic costs were seen as deviations from the standard linear costs. To model the impact of illegal, unregulated, and unregulated fishing (IUU) on fish populations, a sensitivity analysis was run on the catchability coefficient. This study focused on the usage of under-sized mesh gears in particular. Findings from this research highlight the role of illegal, unregulated, and unregulated fishing in the Ghanaian sardinella fishery's near-collapse. In the long term, the modelling findings demonstrate that IUU fishing has a devastating impact on fish biomass while generating very little additional cash. The effects on the quantity of fish stocks are almost disastrous at greater levels of enhanced catchability due to the illicit methods. In other words, there is a limited amount of time and very little gain for the fishermen financially when fish populations are depleted to below 50% of the ecosystem's carrying capacity. Hence, fisheries management should firmly enforce all restrictions regarding the use of under-sized mesh gears and other IUU fishing practices to guarantee the resource's long-term survival.

References

Environmental economics and policy: a primer (Stavins, 2012). Reached on May 1, 2019.
This resource is accessible at: https://scholar.harvard.edu/stavins/classes....

Second, Koranteng KA. Influences from the natural world on the movement of

Ghana's demersal fish stocks. Publish by the University of Warwick in 1998. (Doctoral dissertation, unpublished) Pauly, D., Silvetre, G., & Smith, IR. (2008). A condensed overview of tropical fisheries management on development, explosives, and fishing. The article is published in 1989 in the journal Natural Resource Modelling and has sections 307–329.
Pauly D. On fish sex and scientists' gender: essays in fisheries research (book collection). Series 14 of Fish and Fisheries published by Chapman & Hall in 1994.
Fifthly, Koranteng KA. The sardine fishery in Ghana. Delivered as a paper at the 1994 DUSRU Workshop in Accra, Ghana, on the dynamics and uses of Sardinella resources from upwelling off Ghana and Côte d'Ivoire. Retrieved on July 12, 2017. https://fishcomghana.com/wp-content/uploads/2017/03/The-Ghanaian-Fishery-for- Sardinellas.pdf
[6] Akpalu W. Adherence to Ghana's artisanal marine fisheries' mesh size standards. The Beijer Research Seminar in Durban, South Africa, in 2002 included this paper. Retrieved on September 13, 2017. Akpalu34.pdf may be accessed at: https://www.oceandocs.org/bitstream/handle/1834/878/.
A shared property resource: the fisheries (Gordon HS, 2007). Political economy (1954) 62(2): 124-142.
[8] Schaefer MB. Population dynamics and their relevance to commercial marine fisheries management. Publication: Bulletin of the Inter-American Tropical Fish Commission, 1954;1(2):25-56.
Is equilibrium thinking still relevant in the face of regime transitions and paradigm shifts? [9] Caddy JF. Journal of Fish Research, 1996, 25(4), 219–230. Will new paradigms apply to fisheries management in the twenty-first century? [10] Caddy JF. Published in 1999, Rev. Fish. Biol. Fish. 9:1-43.
O. Defeo and J. F. Caddy [11]. A dynamic approach to yield-mortality models is being evaluated. Published in the International Journal of Marine Science, volume 58, pages 253-1260,2001.
[12]Petrossian GA. A situational approach to preventing illicit, unreported, and unregulated (IUU) fishing. Conserv. Biol., 2015. April 29, 2021. Accessible at: http://dx.doi.org/10.1016/j.biocon.2014.09.005. *
Agnew et al. [13] (includes Pearce, Beddington, Pramod, Peatman, Watson, and Beddington, Jr.). Assessing the scope of illicit fishing on a global scale. Public Library of Science Open Access Journal. 2009;4(2):1-8.
Karak TK and Misra S. In this resource-based, stage-structured fishing paradigm, adults are harvested at the right time. Applied Mathematics, 2010;5(1):42-58.
Referenced in [15] Dubey, Patra, and Sahani. Using taxes as a control variable, we model the dynamics of a renewable resource that is being harvested. Application of Mathematics, 2014, 2, 592–621.
Regarding reference 16, the authors are Hilborn and Walters. Evaluation of fish stocks quantitatively: options, dynamics, and unpredictability. Chapman and Hall, New York, 1992.
[17] Clark CW editors Mathematical Bioeconomics: The Mathematical

Foundations of Conservation, Third Edition. Wiley, 2010. It is published in Hoboken.
Hasanbulli M, Rogovchenko SP, and Rogovchenko YV collaborated on this study. Effects of periodic yield harvesting on the dynamics of a single species in an environment that is unstable. "J. Appl. Math." 2013; 1–12.
[19] Ibrahim M. Optimal control applications to Ghanaian maritime artisanal fishing. The article "Commun. Math. Biol. Neurosci. 2019;22:1-27" provides further information.
*Mackinson, S., Sumaila, U., & Pitcher, T.J. (2021). Bioeconomics and catchability: how fish populations decline and how fishermen react to it. Reference: Fish. Res. 1997;31(1-2):11-17.
[21] Optimal harvesting considering both price and population dynamics, by Hanson FB and Ryan D. The Mathematical and Biophysical Journal, Volume 148, Issue 2, pages 129–146, 1998.
[22] Munro GR, and Clark CW. A streamlined look at fishing economics and contemporary capital theory. This article is from the Journal of Environmental Economics and Management, volume 2, pages 92–106, published in 1975.
To optimise economics in managed fisheries, see [23] Sancho NGF and Mitchell C. Science and Mathematics 27(1-2): 1–7, 1975.
According to [24] Elmojtaba IM, Al-Sawah A, and Al-Moqbali M. In a predator-prey model with harvesting and changing carrying capacity, optimal control analysis is performed. Publication: Commun. Math. Biol. Neurosci. 2020;12:1-19.
[25] TheAlder, Quaatey, Bailey, Jacquet, Khan, Armah, and Jacquet all contributed to this work. Achieving social and economic goals in the sardinella fishery in Ghana. Included in the edited volume by Nanang DM and Nunifu TK. Governance, policy, and economics of Ghana's natural resources. Nova Science Publishers, Hauppauge, 2011. Ebook.
[26] inRishel RW and Fleming WH. Control systems that are both deterministic and stochastic. Springer Verlag, New York, 1995.
Florian KR, Panetta JC [27]. Optimal control used to cancer treatment targeting certain cell cycles. (2000) SIAM Journal of Applied Mathematics, 60(3), 1059–1072.
[28] Lukes DL. From classical to controlled differential equations. Academic Press; 1982, New York.
In a study conducted by Pontryagin LS, Boltyanskii VG, Gamkrelize RV, and Mishchenko EF, 29. Optimal control theory in mathematics. Wiley, New York, 1962.
The third edition of Royden's Real Analysis was published in 1988 by Macmillan Publishing in New York.
[31] Muhammad A. A sustainable harvesting strategy for sardinella in Ghana's fishery: an application of optimum control. Academic institution in Ghana's Cape Coast; 2018. (Doctoral dissertation, unpublished)
"Optimal control applied to biological models" (Lenhart S, Workman JT, 32) referenced. Chapman & Hall, 2007 (New York).
[33]Ibrahim M. A fishery's optimal management using critical depensation and compensation models. Practical Mathematics and Computer Science

2020; 14:67-479.
on page 34Treatment of HIV/AIDS and screening of unaware infectives: the impact of optimum control (Okosun KO, Makinde OD, Takaidza I.). Article published in 2013 in the journal "Appl. Math. Model" with the DOI #37:3802-3820.