Fish Biodiversity of Digha Fishery in Eastern India: An Empirical Analysis

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Abstract*:* *The problem of water pollution is linked up with loss of biodiversity and impacts on fish harvested. This twin problem has been addressed simultaneously and modelled in an aggregated Gordon-Schaefer model for the Digha fishery. An economic biodiversity index and an environmental quality variable have been included which modifies the aggregated Gordon-Schaefer model. For estimating the parameters of the model, the Schnute method has been used. Since the Digha Fishermen and Trader's Association regulates fishing activities and acts as a profit-maximising unit within a larger competitive fish market, this paper focuses on the dynamics of the profit-maximising regime and explores the dynamic maximum economic yield and net present-value of fishery profit that is maximized here. Small perturbations in discount rate and intrinsic growth rate have been done as part of sensitivity analysis and their impact on optimal profit has been examined. This has been done under different biodiversity scenarios. It is found that in Digha fishery there exists a trade-off between economic biodiversity conservation and profit maximization. Policy measures have to be so designed as to minimize the level of conflict between them.*

JEL Classification: Q22,Q28, Q53 andQ57

Key Words: Ecological biodiversity, economic biodiversity, fish biodiversity, Gordon-Schaefer model, maximum sustainable yield, optimal harvest, open access, Digha estuary, Schnute method, sensitivity analysis.

1. Introduction

Fisheries are a major world industry exploiting natural resources for food. Globally, fishery products directly provide approximately 14 kg of food per person and approximately 28% of global fishery products are used for animal feed and other products that do not contribute directly to human food. Yet, the condition of coastal ecosystems, from the standpoint of fish production, is poor. Many marine fisheries are in decline and globally it has reached a plateau of about 84 million metric tons. Yields of 35% of the most important commercial fish stocks went down between 1950 and 1994 (Grainger and Garcia, 1996). As of 1999, FAO reported that 75% of all fish stocks for which information is available are in urgent need of better management- 28% being currently overharvested, and 47% are being fished at their biological limit and therefore vulnerable to depletion if fishing intensity increased further (Garcia and DeLeiva, 2000). The improved management of fisheries, which are either already depleted from past overfishing or in imminent danger of depletion, could realize substantial long-term benefits. Robinson (1980) estimated that possibly some 10-15 million tones of additional fish could be landed as a result of improved management.

Declining marine fishery catches has been the subject of much recent attention in the technical literature (Botsford et al., 1997). For example, Atlantic halibut once commonly found off New England are now rare. Some fisheries have been subject to severe curtailment and closure: in North America, most notably cod off Newfoundland, groundfish off New England, and some salmon species in the Pacific Northwest. Atlantic salmon and American shad have largely disappeared from many rivers of the eastern United States (Merrett and Haedrich, 1997).

The concept of sustainable yield has long dominated the analysis of renewable resources (Schaefer, 1954; Beverton and Holt, 1957). For many years the objective of fishery management was to maintain this maximum

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biologically sustainable yield from a fishery, with limited concern for social, economic and environmental factors. However, in recent times optimum yield has been defined to be the amount of fish prescribed on the basis of the maximum sustainable yield from such fishery as modified by any relevant economic, social or ecological factors.

Globally, the number of people living within 100 km of the coast increased from roughly 2 billion in 1990 to 2.2 billion in 1995 -39% of the world's population. However, the number of people whose activities affect coastal ecosystems is much larger than the actual coastal population because rivers deliver pollutants from inland watersheds and human settlements to estuaries and surrounding coastal waters. As coastal and inland populations continue to grow, their impacts-in terms of pollutants loads and the development and conversion of coastal habitats-can be expected to grow as well. These have a marked influence on fish catch and as such offer arguments for changing fishery management paradigms towards a more coherent ecosystem approach. An ecosystem –restoration plan is needed which should work on water discharges and water pollution prevention and other causes of estuarine habitat degradation, which affect fish catch.

The role of fisheries management as a whole is that of managing the harvesting of this renewable resource and maintaining stocks at levels which permit their rational and sustainable exploitation. But often poor estuarine management has led to concerns related to the misuse and overuse of resources through excessive harvesting of fish stocks. A pattern of 'sequential exploitation' of fish resources has occurred, whereby fish stocks have been gradually drawn down from accessible to less accessible areas and from valuable to less valuable species.

A long-held view of the development of fisheries is that they initially exploit more abundant, more easily caught species, and switch over time to increasingly less abundant, less easily caught species. More recently, a study in FAO global fishery statistics has shown this to be true. It is seen that harvesting does lead to a shift from long-lived, high-trophic level fish towards short-lived, low-trophic level fish species. This has been termed "fishing down the food web" (Pauly et al., 1998). The economic explanation is that fisheries are market-driven and this influences fish harvesters to focus on high economically valued species gradually moving to low economically valued species as the first category gets fished out. Kasulo and Perrings (2001) have called this phenomenon "fishing down the value chain". Such extraction has been made possible through the increased use and development of new technologies like improved gears and vessels. However, such practices have meant losses of biological diversity.

Several measures like imposition of closed seasons, minimum sizes of fishes caught, regulation of mesh size and limitation on gear types have been advocated to address this problem. Here methods applied involve mostly imposing restrictions on the types and specifications of equipment used during fishing. At the core of such measures lies the specification of minimum mesh sizes, as a means of increasing the ability of fishing gear to select larger, more mature fish, leaving behind more juvenile stock. But conventional fishery management is reluctantly coming to accept that such technical measures alone (e.g., mesh size of fishing gear) will be sufficient to maintain or rebuild fish stock. Rather mesh regulations must be coupled up with biodiversity concerns in a multispecies fishery. This is because mesh regulations depends on the mechanical selection of different sizes of fish by the gear being used. In reality, each species requires a different mesh size. Excessive fishing effort at any mesh size not only reduces potential catches and profitability, it may in the long run reduce stock sizes to the point where the stock can no longer reproduce satisfactorily, causing it to collapse. So one must incorporate fishing effort that is adjusted to needs of multispecies fishery through the conservation of biodiversity. This is an important consideration in fishery management decisions relating to protection of biodiversity and which ultimately leads to measures that also sustain fisheries.

The study of biodiversity includes ecological and economic considerations. The ecological aspect relates to human actions that affect the number and persistence of species. The economic aspect looks at the economic driving forces that affect biodiversity as a result of human intervention and are a cause of their loss (Holling et al., 1995). One widely used ecological index, the Simpson index is expressed as:

$$D_t = \sum_{i=1}^{s} (Y_{it} / Y_t)^2$$

where Y_{it} is the catch of the ith species harvested in period t, Y_t is the total catch in period t and s_t is the number of species harvested in period t is a popular measure of species dominance. To capture the economic value of species, the Simpson's biodiversity index is modified such that it uses market values of species caught rather than the total amount of species caught. Now, the actual amount of the species will be weighted by price. Therefore, the Simpson's index becomes:

$$B_t = \sum_{i=1}^{s} (P_{it} Y_{it} /TR)^2$$

where B_t is the economic biodiversity index, P_i is the per unit price of species i, and TR is the market value of the total fish catch. When all the species have the same market value, the solution for economic biodiversity index is the same as the ecological biodiversity index. When the community is dominated by species of high market value, economic biodiversity index will be greater than an ecological biodiversity index of the same community and vice versa.

Another related concern deals with long enduring perturbations into coastal environments through the continuous influx of various wastes, which is a severe threat to the ability of these systems to generate ecological services. For many nearshore species, land-based and coastal threats are harmful, as these fish species depend on coastal areas for spawning, growth and stock replenishment. Changes that alter the larvae and juveniles here can greatly affect populations and distribution of adult fish. Estuaries have long been the focal point for much human activity. As the meeting place of sea and river, they have provided quiet and sheltered water for fishing. But the effluents get poured in the estuaries and have badly polluted the lower reaches of many estuaries. Fish and fisheries must be considered in relation to all these uses and abuses[3].

2. The Present Study

Our paper looks into the problem of fishing when water is polluted and this pollution leads to a loss of biodiversity. This twin problem has been addressed simultaneously and modelled in an aggregated Gordon-Schaefer model. It has then being applied for the Digha fishery. Digha is located in the West Midnapore district of the State of West Bengal of Eastern India and lies in the southern most part of the state on the bank of Bay of Bengal. It is situated nearly mid-way along the relatively straight shoreline between the huge Ganga-Brahmaputra delta in the east and the joint Mahanadi-Brahmani-Boitaroni delta in the west. From the geo-morphological point of view, Digha is located on the eastern fringe of the Subarnarekha delta along the south west shore line of West Bengal and on the eastern border of Orissa. Our case study area is Digha estuary of West Bengal, India, where the Khadalgobra and the Ramnagar canal meet the Bay of Bengal. It is a key breeding area mostly for hilsa, a popular and traditional fish species of Bengal. They live in the sea for most of their lives, but migrate at least 1,200 km up any river system according to their spawning behaviour.

Digha has a sprawling fishing economy. The catch generally includes fishes like Hilsha, Pomfret, Mackreal. Prawns, Sharks, Sea urchins etc. In fact this whole belt is endowed with rich biotic diversity (Meenbarta, 1998). Some villages are completely dominated by the fishermen. With the introduction of diesel using powerboats, deep fishing and mechanization in fishing is taking an upturn[4]. Tourism is a phenomenon that has come into prominence much later in the occupational profile of the resident population of Digha (Chattopadhyay, 1995). But this area of

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[3] GESAMP (1990) states that eutrophication caused by excess nutrients from sewage discharged into coastal waters is an expanding problem. The initial effects are of altered species compositions leading to local changes in biodiversity gradually moving towards more severe effects like mass mortalities of fish. This is because the pressures from a wide array of human activities show no signs of diminishing and the maintenance of economically healthy estuaries and their fishes depends very much on well-defined management policies.

[4] The trawlers are in operation for about 10 to 11 months in a year and generally they are rested in the months of April-May. Usually a fishing trip lasts for about five days in sea and after the catching, thje catch is landed in the harbour where from they are sold in the wholesale market at Digha. According to the Digha Fishermen and Fish Traders' Association, the wholesale fish market at Digha Estuary accounts for Rs. 70 crore a year (Ganguly, 2004). Aso a large portion of the catch is ice packed and sent to the wholesale market in Sealdah of Kolkata and Howrah for auctioning by the local agent auctioneers. Besides sending the catch to Kolkata sometimes fishes like pomfret and sea urchins are sent directly to Chennai or Viasakhapatnam for marketing.

the sea has lost its pristinity. Waste disposal from its burgeoning tourism industry generating pollution is affecting fisheries adversely (Ghosh et al., 2004). In 1996, the public health engineering department of the Government of West Bengal had undertaken a project to collect all the wastewater discharged by the hotels in Digha and treat it before discharging into the sea. This sewage treatment system set up by the public health engineering department to prevent marine pollution and stop the sewage from flowing into the sea from this bustling tourist resort has proved to be completely ineffective (Jana, 2003).

Digha, being quite near to many urban centres and also being very easily accessible, is thus a major tourist spot and is experiencing high coastal pollution level associated with the rapid growth of the town itself. Combination of such influences act against a backdrop of long –term environmental changes that have an effect on fisheries resources and their exploitation and so must be considered in an integrated assessment.

The estuaries in West Bengal have seen both freshwater fishes and migratory marine species spawn during the monsoon. In the last three decades (1960-1990), there have been catastrophic changes. Hilsa, an anadromous fish, which used to constitute about 70% to 80% of total fish landings, is disappearing (Rao, 2000). Changes in salinity and hydrology cause large shoals of hilsa to congregate near the head of the Bay, but they do not enter the estuary. Instead, marine catfish have become dominant here. The last few decades have witnessed anthropogenic changes in coastal waters of the Bay of Bengal. Biodiversity has been adversely affected and multispecies communities are changing to single-species dominance. The pollution of coastal areas, which serve as nursery grounds for commercially valuable species of hilsa and prawns, might ultimately affect their stocks in the Bay. Along the coast, the catch of hilsa is on the decline because of pollution, and conservation measures are now necessary. The major rivers of the Bay of Bengal drain 200 km^3 of water and 12.0×10^9 tons of silt during the monsoon season, which influence and govern the ecosystem's dynamics (BOBP, 1994). These enormous quantities of silt discharged by the river systems in the Bay of Bengal have the potential to act as carriers of pollutants discharged by industries at the mouth of the estuaries. The effects are reflected in decreased growth rates and reduced potential of fish. Digha, with its vibrant tourism industry, has attained significant urbanization. Thus the general picture indicates a decline in the estuarine fishery caused by pollution and reduced water flow.

A study of the problem of water pollution-led loss of biodiversity and its impact on the level of catch per unit of effort is thus necessary. We address these two major problems simultaneously and model them in the Section 3. Section 4 presents data, results of model estimation and optimum values of the variables. Section 5 reports results of sensitivity analysis. Section 6 incorporates some concluding remarks.

3. The Model

In a standard fishery model, we have the expression for net rate of growth of fish biomass as

$$\dot{X} = rX(1 - X/K) - qXE \qquad (1)$$

where r is the intrinsic growth rate of fish stock , X is the fish stock, K is the carrying capacity of fish stock, q is the catchability coefficient and E is the effort used.

At steady state, $\dot{X} = 0 \Rightarrow rX(1 - X/K) = qXE$

This implies that

$$X = K(1 - q/rE) \qquad (1a)$$

The Gordon-Schaefer fish production function is

$$Y = qXE, \qquad (2)$$

where Y is the catch rate or harvest rate of fish stock. Substituting X from (1a) in equation (2), we have

$$(Y/E) = qK - q^2(K/r)E \qquad (3)$$

In the Gordon-Schaefer model, environmental factors can affect fish biomass through its growth function. Hence, in this study, the environmental variable is incorporated into the model through its growth function. Introduction of an environmental factor implies a parametric shift of the logistic curve and we can rewrite equation

(1) as

$\dot{X}$ = rX(1-X/K-eW)-qEX, (4)

where W is the environmental quality variable, and e is a parameter that relates how much one unit increase of the environment variable reduces the relative growth of the fish biomass X. The need for such an inclusion stems from the fact that one needs to study whether besides their level of effort the total catch of fishermen is significantly affected by the weather variable factor, which here represents the level of pollutants washed into the estuary. The amount of rainfall in Midnapore district is used as a rough indicator of the level of water pollution. Intensive rainfall can lead to larger deposits of sediments and nutrients in the estuarine area. The Bay of Bengal receives an annual precipitation of 11,000 km^3 and it washes off sediment brought by the rivers amounting to 4 x 10^9 m^3 (Rao, 2000). So, the use of rainfall figures captures the impact on water quality.

The most marked effect of biodiversity loss occurs on the productivity of the resource. Changes in fish diversity affect fisheries via their impact on the wider aquatic ecosystems that support fish production (Barbier et al., 1995). Therefore fish production depends not only on the level of effort and fish stock but also on the level of fish biodiversity. The biodiversity variable can be introduced in the Gordon-Schaefer model through the production function that specifies a relationship between fish biodiversity as an input and fish catch as an output. The effect of species diversity on fish productivity can be captured through an additional term in the fishieries production function (Kasulo and Perrings, 2001).

Equation (2) now becomes: Y = qAEX, (5)

where A is the biodiversity index. Here AE is the biodiversity-adjusted effort applied in the fishery. Here, A may represent either ecological or economic biodiversity index, i.e., A = D or B as defined earlier. The growth function becomes $\dot{X}$ = rX (1–[X/K]) – qAEX.

When both biodiversity-adjusted effort and an environmental quality variable is introduced in the standard model, we have the expression for growth of fish biomass as

$\dot{X}$ = rX[1 – (X/K) – eW] – qAXE, (6)

where eW focuses on the impact of water pollution, A is the biodiversity index and AE is the biodiversity-adjusted effort applied in the fishery.

In the steady-state equilibrium, $\dot{X}$ = 0 => rX [1 – (X/K) - eW] = qAXE, and

X = K [1 – (qKA/r) – eW] (7)

The Gordon-Schaefer production function then is

Y= qAXE (8)

Substituting X from (7) in the above equation, we have

Y = qKAE [1 – (qAE/r) – eW] (9)

The catch per unit of adjusted effort can be expressed as

(Y/AE) = qK – q^2KAE/r –qeKW. Alternatively,

(Y/AE) = qK [1 –(qAE/r) – eW] (10)

For estimation purposes, we have followed the approach of Schnute (1977). The Schnute equation can be modified through the simultaneous introduction of biodiversity index and an environmental quality variable. It defines a population growth function in terms of U, defined as the catch per unit of adjusted effort (Y/AE). Then,

$\dot{U}$ = rU(1 – U/qK - eW) – qAEU, (11)

where A can be the ecological or economic biodiversity index, as the case may be.

The Gordon-Schaefer production function Y = qAEX implies that X=U/q. Dividing both sides of Equation (11) by U, we have ($\dot{U}$ /U) = r – qAE – (r/qK)U – reW. This implies that

$1/U(dU/dt) = r - qAE - (r/qK)U - reW$

After time averaging and thereby smoothing out the data the equation can be framed as

$$\ln X_t^* = r - qE_t^* - (r/qK)U_t^* - reW_t^*, \qquad (12)$$

where $X_t^* = U_t^*/U_{t-1}^*$; $E_t^* = (E_{t-1} + E_t)/2$; $U_t^* = (U_{t-1} + U_t)/2$; $W_t^* = (W_{t-1} + W_t)/2$; $E_t^* = E_tA_t$ and $U_t^* = Y_t/E_tA_t$ where $A_t = D_t$ or B_t.

The parameter estimates obtained from the regression analysis of equation (12) show the effect of the inclusion of both biodiversity and environmental quality variables over time. Here, the main intention remains to capture the effect of loss of biodiversity and that of water pollution on relative catch per unit of adjusted effort that may affect the productivity of a fishery adversely.

4. Data, Regression Results and Optimum Values of the Variables

Data for this study have has been collected from the Digha Fishermen and Fish Traders' Association[5] in Digha covering the period 1991-92 to 2001-02. Catch is measured as kg.of fish landed and effort is represented by fishing months[6]. It has observed in Digha coastal areas that total marine fish landing mainly consists of sardine, hilsa, coila, pomphret, croakers, Bombay duck, catfish, ribbon fish, shark, shankar, prawn[7] etc. Thus total 37 varieties are found here. These varieties have been divided into five groups considering their importance from the viewpoint of their demand and price. Collected data show that mainly these five groups of marine fish dominate the Digha fishing industry in terms of both prices and quantity. They are Hilsha, Chinese and Silver Pomfret, Black Pomfret, Prawn and others. Pomfrets group contribute around 14% of total landings with non- penaeid prawns 13% and hilsa shad having a share of 6%. Other varieties have a very low price range in the market such as (in local vocabulary) kanta, sardine, mackreal, chela, para and American bhetki. Digha Estuary, in recent years, has seen a shift in fish species harvested towards catches of fish species of very low local value (ranging between Indian Rs. 4– Rs.35 per kg.) consisting of sardine, chela and kaante clubbed under the heading 'others'. This transition in fish catch from high valued to low valued species points to the role of the market and the effects of economic forces in loss of biodiversity. The decline in the dominance of hilsa in total catch reflects not only a decline in the trophic level of fishes but can also be associated with its economic value.

A comparative analysis of the unweighted and weighted Simpson indices is carried out by using the data on catch per species for the fisheries of Digha estuary. The Simpson economic biodiversity is constructed by weighting the simple ecological Simpson's index by average prices so as to capture fluctuations in value. It will capture any shift that may occur in fish value resulting from the over-exploitation of high-valued species. Figure 1 shows a comparison between the Simpson unweighted and weighted indices, and it is seen that the value of the weighted index is lower than that of the unweighted index.

It is because of the differences in the value of the species caught that the differences in the two indices occur. The lower values of the weighted indices in comparison with the unweighted index reflects that on average catches are dominated by less valuable species. If catches had been dominated by valuable species, price weighting would increase their dominance even further and the weighted indices would have higher values than unweighted indices (Kasulo and Perrings, 2001). This is seen in our figure and so it suggests a decline in biodiversity associated with a shift in fish catch from high-valued to low-valued species. To analyse these factors equation (12) has been estimated and the results are given in Table 1.

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[5] Annual Reports of the Digha Fish Traders' Association, Various issues.

[6] Fishing effort has been calculated on the basis of a composite index constructed by us. It has been taken to be the weighted average of number of fishing hours involved in catching fish through fishing boats and trawling boats where the weights are the number of trips by fishing boats and trawling boats in an year.

[7] The biological names of some of the fishes are given in the parantheses: sardine (*Sardinella gibbosa*), hilsa (*Hilsa Tenualosa ilisha)*, coila, silver pomphret (*Pampus argenteus*), black pomfret (*Parastromateus niger*), croakers (*Johnius belangerii*), Bombay duck (*Harpadon nehereus*), catfish (*Arius jella* Day), ribbon fish (*Eupleurogrammus muticus*), shark (C*archarhinus limbatus)*, mackerels (*Rastrelliger kanagurta*), prawn.

Figure 1: Comparison between ecological and economic biodiversity indices of Digha fishery

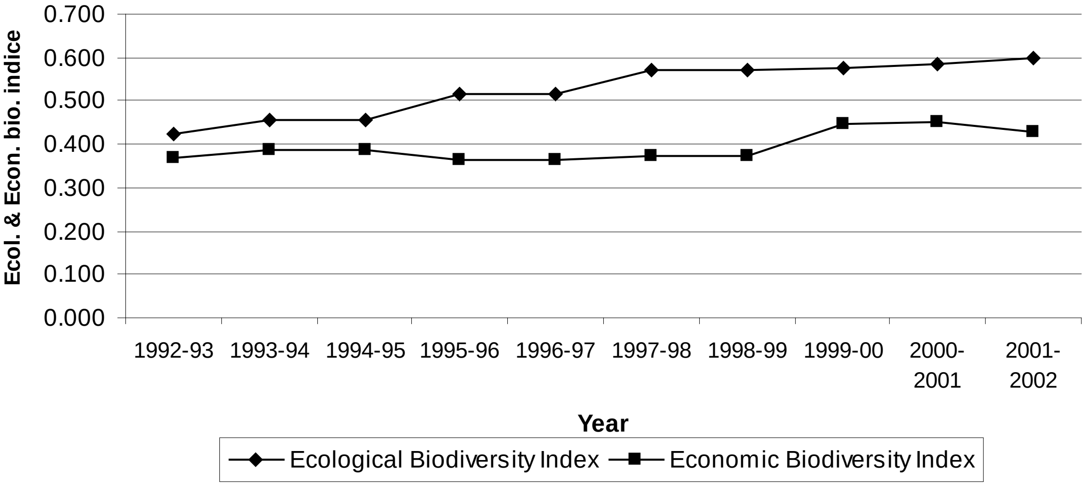

Table 1: Regression results of the Schnute models in its modified forms (1) with environmental quality variable and ecological biodiversity index (2) with environmental quality variable and economic biodiversity index

Equation of Schnute model	Constant	Coefficient of AE	Coefficient of U	Coefficient of W	R^2 statistic	Adjusted R^2 statistic
ecological biodiversity index and weather	4.16421 (3.67554)	-0.0004353 (-5.78885)	-0.0029904 (-4.8797)	-0.0015041 (-2.55941)	0.861737	0.802481
economic biodiversity index and weather	2.92939 (2.00819)	-0.0004551 (-3.29691)	-0.0029269 (-2.94028)	-0.0009481 (-1.26947)	0.896241	0.851772

(t-values are given in the parentheses)

When the ecological biodiversity index is introduced along with the environmental quality variable in the model and regressed, R^2 is 86%, with all parameter estimates having expected signs and are statistically significant at 5% level of significance. The model including the environmental factor and the economic biodiversity index registered a better performance. It can be seen that an improvement occured after the introduction of a weighted economic biodiversity index and now the model explains about 89% of the variation in fish biomass, which is a good fit for the regression line. Since it helps to explain a large proportion of the variation in fish biomass, this equation is used for parameter estimation of the model.

One can now estimate the optimum values of the variables under different biodiversity scenarios and in the context of alternative regimes. The economic biodiversity index that has been considered in our regression procedure is actually the average of the economic biodiversity indices constructed over the time horizon of our study. Generally, the value of B ranges from 1 for the lowest diversity (where the fishery is dominated by species of the same value) to 1/s, where s is the number of species, giving a high level of fish diversity (where fishes have a wide range of differentiated market values). In this context, we have compared three different biodiversity scenarios, reflecting fishing down the value chain that is occurring in the fishery in Digha: one, a scenario where the fishery has a wide range of different valued fish species i.e., high level of economic diversity, another being the average level of economic biodiversity in the fishery and the third, a scenario where the fishery has fish species mostly of similar values i.e., low level of economic diversity.

The optimal values of the variables have been calculated under different regimes: maximum sustainable, the open access and the profit-maximising regime. Both the static and dynamic values of the variables have been calculated for the profit-maximising regime. The need for deducing the dynamic values become important since to judge the sustenance of the fishing industry static rent maximization is not optimal if the objective is to maximize present value of profit. The results have been obtained by using the parametric values given in Table 2. These values are tabulated under three alternative biodiversity scenarios of the fishery. Since in Digha fishery, the Digha Fishermen and Traders' Association regulates the local fishing activities and acts as a competitive profit-maximising unit in the larger regional fish market, we have ultimately focused on the dynamics of the profit-maximising regime.[8]

Table 2: Values of the parameters of the Digha fishery model

Parameter	Notation	Value	Unit
Intrinsic growth rate[a]	r	1.5	dmnl./year
Catchability coefficient[b]	q	0.000019	1/fishing hours
Environmental carrying capacity of fish stock[c]	K	2725631.8	Kg.
Coefficient of environmental quality variable[d]	e	0.0003236	dmnl./mm.
Average weighted economic biodiversity index[e]	B	0.3946	dmnl
Environmental quality variable[f]	W	1382.5	mm.
Average price[g]	p	43.637616	Rs./kg./year
Average cost[h]	c	46.65569	Rs./fishing hour
Discount rate[i]	δ	0.11	dmnl./year

[a] the intercept value of the regression of the modified equation

[b] the value of the coefficient of the effort function of the regression of the modified equation

[c] calculated by using the value of the coefficient of the catch per unit effort function and then plugging in the values of r and q

[d] calculated by using the value of the coefficient of the environmental quality variable and then plugging in the value of r

[e] the average of the economic biodiversity indices constructed for the period under study

[f] here rainfall has been taken as a proxy to the environmental quality variable and so for W we use the average level of rainfall of the period under study

[g] it is the aggregative average of the prices of all fish species under our consideration during the time period of our study

[h] it is the total cost incurred by fishermen calculated on the basis of their wages both for labour in boats and trawlers

[i] it is approximated by the current market rate of interest

4.1. Biological maximum sustainable regime solution-

The maximum sustainable yield (MSY) level of effort is derived by modifying the sustainable-yield function. The logistic growth function is

$$X_{t+1} - X_t = rX_t(1 - (X_t/K) - eW), \qquad (13.1)$$

and the Gordon-Schaefer production function is

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[8] This is utilized further in sections 5 and 6 in our exercise in sensitivity analysis and resulting policy implications.

$Y = qBE_tX_t$. (13.2)

In equilibrium,

$X_{t+1} - X_t = rX_t(1 – (X_t/K) – eW) – qBE_tX_t = 0$ (13.3)

and so

$X_t = K(1 – qKB/r – eW)$. (13.4)

We get the sustainable yield function as

$Y_t = qKBE_t(1 – qBE_t/r – eW)$. (13.5)

By differentiating equation (13.5) with respect to effort, setting the derivative to zero, and solving for effort, we have

$\partial Y_t/ \partial E_t=qKB(1-2qBE_t/r - eW)=0$. (13.6)

Thus, $E_{msy}=r(1 – eW)/2qB$. (13.7)

The associated levels of stock and catch are calculated by setting the derivative of the logistic growth function with respect to X to zero

$X_{msy}=[K(1 – eW)]/2$ (13.8)

Substituting the value of X_{msy} in equation (13.8) in the sustainable yield equation gives:

$Y_{msy}=[rK(1 – eW)^2]/4$. (13.9)

The above equation gives the maximum sustainable catch that occurs at

$X_{msy}=K(1 – eW)/2$ corresponding to effort level $E_{msy}=[r(1 – eW)]/2qB$.

The maximum sustainable values of the variables in the modified framework have been calculated using the values of the parameters given in Table 1.The results are shown in Table 2.

4.2. The open access regime solution-

Under open access, as $\Pi_t = pY_t-cE_t = 0$, (14.1)

so $pY_t = cE_t$, where Π_t is the net revenue, p is the price of fish and c is the unit cost of effort. In terms of the logistic growth function, the equilibrium-effort level is determined by the equations $X_t = K(1 – qKB/r – eW)$ and $Y_t = qBE_tX_t$. Thus,

$\Pi_t = pY_t – cE_t = pqBE_tK(1 – qKB/r – eW) – cE_t = 0$ (14.2)

Solving this equation for the equilibrium-effort level gives

$E_{oa} =[r(1 – c/pqBK - eW)]/Bq$. (14.3)

The corresponding catch and stock levels are

$Y_{oa} = cBE_{oa}/p$ (14.4)

$X_{oa} = c/pqB$ (14.5)

The open access values of the variables in the modified framework have been calculated using the values of the parameters given in Table 1. The results are shown in Table 2.

4.3. The optimal or profit-maximising regime solution-

Static framework:

Here we intend to estimate the values of the fish biomass, level of harvest and associated effort under a static framework for the Digha estuarine fishery. Under steady-state,

$X_t = K[1 – (q/r)BE_t – eW]$ (15.1)

and $Y_t = qBE_tX_t$ (15.2)

Profit-maximisation occurs at $d\Pi_t /dE_t = 0$

or, $pdY/dE_t = cdE_t/dE_{t\ ,}$ (15.3)

or, $E^*_{static} = r(1 – eW)/2qB –rc/2pq^2KB^2$. (15.4)

Similarly, by substituting equation (15.4) in (15.1), we get

$X^*_{static} = K/2(1 – eW) – c/2pqB$ (15.5)

We get the value of Y^*_{static} by substituting equations (15.4) and (15.5) in equation (15.2)

$Y^*_{static} = qBE^*_{static}X^*_{static}$. (15.6)

Finally, optimal profit can be estimated as

$\pi^*_{static} = pY^*_{static} - cE^*_{static}$. (15.7)

The optimal values of the variables in the static framework have been calculated using, again the values of the parameters given in Table 2. The results are shown in Table 3.

Table 3 compares between the different values of the variables computed under the three regimes at different levels of diversity present in the fishery which are represented in figures 1-3.

Table 3: Optimum values of the variables under different regimes and alternative economic biodiversity scenarios

	Maximum Sustainable Solution			Open Access Solution			Profit Maximising Solution (static framework)		
	Stock (kg.)	Harvest (kg./year)	Effort (fishing hours/year)	Stock (kg.)	Harvest (kg./year)	Effort (fishing hours/year)	Stock (kg.)	Harvest (kg./year)	Effort (fishing hours/year)
Situation 1: High economic biodiversity	7,53,123.41	3,12,144.99	1,09,070.33	2,81,397.41	37,932.42	1,77,393.24	5,24,223.27	1,51,242.13	75,922.91
Situation 2: Average economic biodiversity	7,53,123.41	3,14,130.99	55,633.18	1,42,634.33	42,785.20	1,01,412.83	5,93,615.70	1,95,160.63	43,850.66
Situation 3: Low economic biodiversity	7,53,123.41	3,12,144.99	21,814.06	56,272.69	44,902.93	41,998.23	6,36,785.62	2,23,157.24	18,444.38

In Situation 1, with high economic diversity in the fishery, the maximum sustainable yield (3,12,144.99 kg./year) is the highest when compared with the other two regimes. Following this is the catch level under profit-maximising solution (1,51,242.13kg/year) followed by that under open-access regime (37,932.42 kg/year). The stock level is the highest under the maximum sustainable solution (7,53,123.41kg) followed by that of the profit maximizing level (5,24,223.27 kg) and is the lowest under the open access situation (2,81,397.41 kg). Effort level under open access (1,77,393.24 fishing hours/year) is the highest while that under profit-maximisation level of effort is the smallest. So, we find that the open access solution registers the smallest catch level associated with the highest level of effort.

Figure1: Comparison of optimum stock in Digha fishery under different property right regimes and under alternative biodiversity scenarios

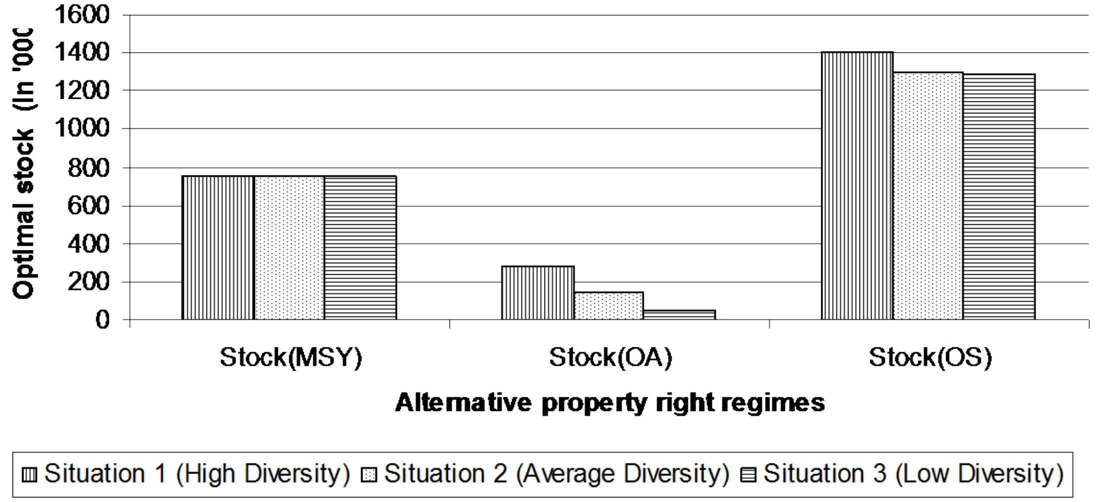


Figure 2: Comparison of optimal harvest for Digha fishery for different property right regimes and under alternative biodiversity scenarios

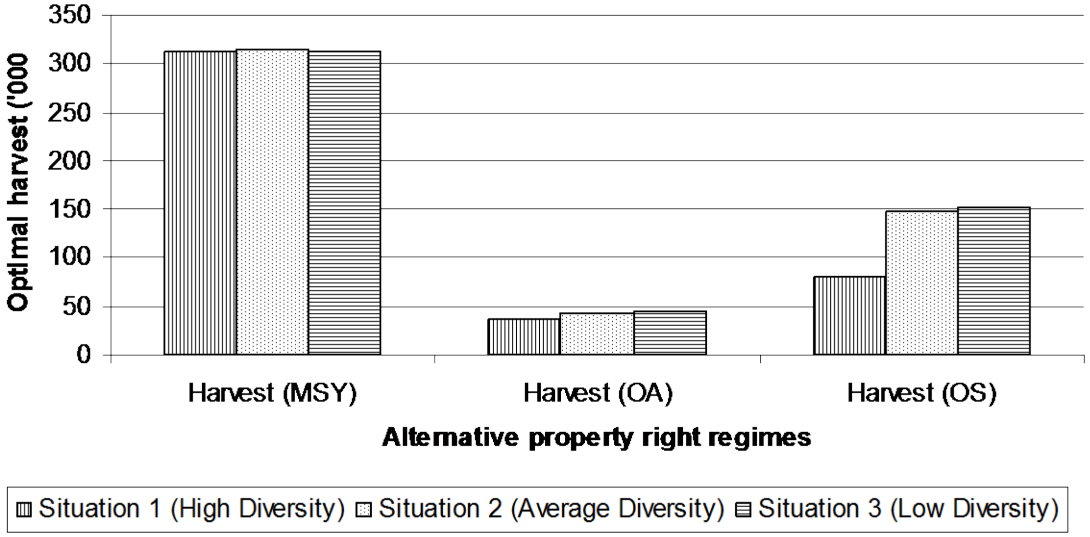
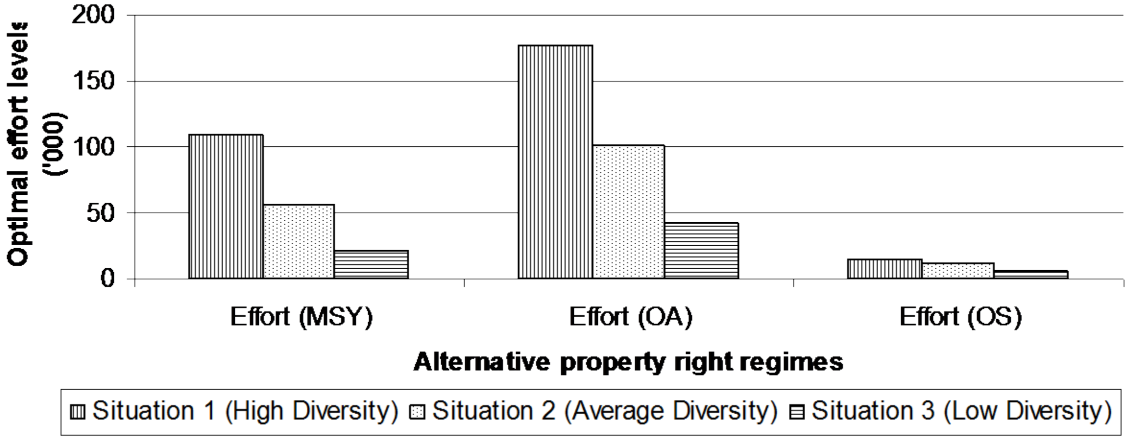


Figure 3: Comparison of optimal effort levels in Digha fishery for different property right regimes and under alternative biodiversity scenarios



In Situation 2, with average level of biodiversity prevalent in the fishery, we find that the harvest level is still the highest in case of maximum sustainable solution (3,14,130.99 kg/year); and its value is greater than Situation 1. The harvest levels of the other two regimes (open access solution: 42,785.20 kg/year; profit maximizing solution: 1,95,160.63 kg/year) also register an increase compared to the previous case. The open access level of effort is the highest combined with the smallest catch, even as effort levels under all the three regimes increase with increase in economic diversity level. The open access effort level (1,01,412.83 fishing hours/year) remains the largest effort level under all three types of regimes.

Under Situation 3, we have B = 1 representing a fishery where all the species are equally valued and can thus be treated as a 'single-species' fishery. Effort level for all the three types of regimes decreases as one fishes from a high diversity to a low diversity situation of the fishery. The optimal effort level is the smallest (18,444.38 fishing hours/year), its value decreasing over the three scenarios of diversity.

4.4. Dynamic framework:

In the dynamic framework, fishers seek to maximize the present value of profits over a time horizon 0 to T subject to the constraint of net growth of fish stock. The problem can be stated as

$$\text{Max. } \pi = \sum_{t=0}^{T} (pY_t - C_t)\,\rho^{t}\,dt, \text{ where } \rho = 1/1+\delta, \text{ and } \delta \text{ is the rate of discount,}$$

subject to

$$X_{t+1} - X_t = rX_t(1 - X_t/K - eW) - Y_t, \text{ where } Y_t = qX_t\, B\, E_t \text{ and } C_t = cE_t \qquad (16.1)$$

We can rewrite the problem as

$$\text{Max. } \sum_{t=0}^{T} (pqX_t\, BE_t - cE_t)\ dt,$$

subject to $X_{t+1} - X_t = rX_t\,(1 - X_t/K - eW) - qX_t\, BE_t$. (16.2)

The current value Hamiltonian, $H_{c,}$ for this problem is

$$H_c = (pqX_t\, BE_t - cE_t) + \rho v_{t+1}\,(rX_t\,(1 - X_t/K - eW) - qX_t\, BE_t), \qquad (16.3)$$

where ρ (the co-state variable) is the current value shadow price associated with an incremental change in the fish stock, E_t is the control variable and X_t is the state variable. The first-order necessary conditions for a maximum are

$$\delta H_c / \delta E_t = 0 \tag{16.4}$$

$$\rho\nu_{t+1} - \nu_t = - \delta H_c / \delta E_t \tag{16.5}$$

and

$$X_{t+1} - X_t = \delta H_c / \delta\rho\nu_{t+1} \tag{16.6}$$

Equation (16.4) gives

$$(pqX_t B - c) - \rho\nu_{t+1} q X_t = 0$$

$$\rho\nu_{t+1} = p - (c/qX_t)$$

$$\nu_{t+1} = (1+\delta) [p - (c/qX_t)] \tag{16.7}$$

Equation (16.5) gives

$$\rho\nu_{t+1} - \nu_t = -pqE_t - \rho\nu_{t+1} r\{1 - (2X_t/K) - eW) + \rho\nu_{t+1}qE_t \tag{16.8}$$

Steady-state implies that $\nu_{t+1} = \nu_t = \nu^*$ and $X_{t+1} = X_t = X^*$. So, equation (16.8) becomes

$$\nu^*(\rho - 1) = qBE_t (\rho\nu^* - p) - \rho\nu^* r\{ 1 - (2X_t/K) - eW\} \tag{16.9}$$

Putting $\rho = 1/(1 + \delta)$ and using equation (16.7) (after putting $\nu_{t+1} = \nu^*$), we get

$$BE_t = (1/cq) (pqX_t - c) [\delta - r\{1 - (2X_t - K) - eW\}] . \tag{16.10}$$

Again, equation (16.8) at steady-state gives

$$BE_t = (r/q) \{1 - (X_t/K) - eW\}. \tag{16.11}$$

Comparing (16.10) and (16.11) and by letting $\Omega = c/pq$, we get

$$X^*_{dyn.} = \tfrac{1}{4} [\{\Omega + K(1 - \delta/r - eW)\} + \sqrt{[\{ \Omega + K(1 - \delta/r - eW)\}^2 + 8K\Omega(\delta/r)]}. \tag{16.12}$$

Once $X^*_{dyn.}$ is known, we can determine the optimum levels of effort and catch

$$E^*_{dyn.} = (r/q) \{ 1 - (X^*_{dyn.}/K) - eW \}/B \tag{16.13}$$

$$Y^*_{dyn.} = qX^*_{dyn.} BE^*_{dyn.} \tag{16.14}$$

Hence, the optimum level of NPV of profit is

$$NPV^*_{dyn} = \sum_{t=0}^{T} (pY^*_{dyn.} - cE^*_{dyn.}) (1/1+\delta)^t . \tag{16.15}$$

Here $X^*_{dyn.}$, $Y^*_{dyn.}$, $E^*_{dyn.}$ and $NPV^*_{dyn.}$ are respectively the optimal values of fish stock, harvest, effort and net present value of profit.

The optimal values of the variables in the dynamic framework have been calculated, as before, using the values of the parameters given in Table 2. The results are shown in Table 4.

From Table 4, we find that with progressively lower levels of biodiversity, stock size and effort decrease while fish harvest rises. This is evident when we look at Situation 1(catch: 79,312.17 kg./year; effort: 14,870.40 fishing hours/year) and compare it with Situation 2(catch: 1,26,329.54 kg./year; effort: 12,629.75 fishing hours/year) and Situation 3(catch: 1,52,923.61 kg./year; effort: 6,234.36 fishing hours/year). We also observe NPV of profit to increase with lower diversity (an increase from Rs. 9,74,557.84/year in Situation 1 to Rs. 17,33,954.10/year in Situation 2 and a further rise to Rs. 22,47,745.50/year). So diversity reduction is associated with a rising level of NPV of profit masking the existence of the potential threat from a loss of the value of the fishery.

For all the three types of regimes, we have derived results that are typical of single species Gordon-Schaefer models (Kasulo and Perrings, 2001; Conrad and Adu-Asamoah, 1986; Gallastegui, 1983). The maximum sustainable solution gives the highest level of catch while the open access solution gives the lowest level of catch among the three. The optimal profit-maximising solution gives the lowest level of effort.

Table 4: Dynamic profit-maximising values of the variables under three alternative biodiversity scenarios

	PROFIT-MAXIMISING SOLUTION (Dynamic Framework)			
Alternative scenarios of diversity of the fishery	Stock (kg.)	Harvest (kg./year)	Effort (fishing hours/year)	PV of profit (Rs.)
Situation 1: High economic biodiversity	14,03,567.7	79,312.17	14,870.40	9,74,557.84
Situation 2: Average economic biodiversity	13,34,194.2	1,26,329.54	12,629.75	17,33,954.10
Situation 3: Low economic biodiversity	12,91,007.7	1,52,923.61	6,234.36	22,47,745.50

5. Sensitivity analysis:

Change in discount rate on dynamic profit-maximising optimal solutions-

We consider first, *ceteris paribus*, the impact of perturbations in the discount rate, δ, (base δ= 0.11) on the optimal values of the variables. The optimal values of the variables given in Table 3 are considered as the base values in our sensitivity analysis. The discount rate here approximated by the market rate of interest represents the opportunity cost of investing in the fishery vis-à-vis other assets or allied industries like the tourism industry. We here have considered a range from 0.9 to 0.13 between which the market rate of interest has varied over the last 10 years as obtained from Reports on Currency and Finance of the Reserve Bank of India.

Table 5: Impact of perturbations of the discount rate, δ, (reference/base value: δ = 0.11) on optimal value of NPV of profit under three alternative scenarios- (1) high diversity (2) average diversity and (3) low diversity in the fishery model

Value of δ	**SITUATION 1: NPV of profit when a high level of economic biodiversity in the fishery is present**	**SITUATION 2: NPV of profit when current average level of economic biodiversity in the fishery is present**	**SITUATION 3: NPV of profit when there does not exist any economic biodiversity in the fishery**	**Gain in NPV of profit at the expense of fall of economic fish biodiversity from a high level to an average level**	**Gain in NPV of profit at the expense of fall of economic fish biodiversity from an average level to a low level**
	(1)	(2)	(3)	(4) = (1) - (2)	(5) = (2) – (3)
0.09	9,77,194.24	18,87,813.70	25,03,757.30	6,15,943.60	9,10,619.46
0.10	9,79,283.75	18,10,318.90	23,71,692.00	5,61,373.10	8,31,035.15
0.11	9,74,557.84	17,33,954.10	22,47,745.50	5,13,791.36	7,59,396.26
0.12	9,61,369.91	16,55,341.10	21,11,416.70	4,56,075.60	6,93,971.19
0.13	9,43,252.23	15,78,135.60	20,07,586.00	4,29,450.40	6,34,883.37

One can infer from the above table that, NPV of profit $_{\text{situation 3}}$ > NPV of profit $_{\text{situation 2}}$ > NPV of profit $_{\text{situation 1}}$. Another important observation is that the gain in NPV of profit associated with decreasing levels of biodiversity is highest when we contrast between Situations 1 and 3 than between Situations 1 and 2. So paradoxically it can be seen that greater endeavor to capture the most expensive species leads to greater losses associated with the fishery.

This occurs as demand in the markets triggers off greater exploitation of the expensive species and in this process large amounts of cheaper by-catches are discarded. So the current trend towards the exploitation of only valuable fish species raises doubts about the profitability and hence sustainability of the fishery. One can hence conclude that maximization of profit and economic biodiversity considerations are ultimately in conflict with each other in the context of sustenance of a fishery. This underlines the importance of economic scarcity and the role of market demand for fishes in a fishery.

Change in intrinsic growth rate on dynamic profit-maximising optimal solutions-

The Digha estuarine fishery is already plagued with problems related to environmental pollution, which has a distinct impact on intrinsic growth rate of fishes. So an analysis with regard to changing intrinsic growth rates becomes more important in this connection.

From Table 6, we find that in comparison with the base value NPV of profit, the percentage change in level of NPV of profit is most dramatic for Situation 2 followed by Situation 3 and finally by Situation 1. So it can be seen that not only is the total amount of NPV of profit the least for the first situation the increase in total profit over increasing intrinsic growth rates is also slowest here. The Digha fishery attracts more and more the most expensive fish species, like hilsa and ultimately puts the value of the fishery at stake. So it seems that as r changes, the threat to economic biodiversity gets associated with increasing levels of profit. So just by regulating the level of pollution and increasing fish productivity the fishery cannot become profitable and sustainable. Policymakers and fishermen must also take into account the fact that any reduction of economic biodiversity can actually put the sustainability of the fishery at stake. So economic biodiversity conservation is essential for a high profit-maximising regime.

Table 6: Impact of perturbations in the intrinsic growth rate, r, (initially r = 1.5) on the optimal value of NPV of profit under three alternative scenarios- (1) high diversity (2) average diversity and (3) low diversity in the fishery model

Value of r	**SITUATION 1:** **NPV of profit when a high level of economic biodiversity of the fishery is present**	**SITUATION 2:** **NPV of profit when current average level of economic biodiversity of fishery is considered**	**SITUATION 3:** **NPV of profit when there does not exist any economic biodiversity in the fishery**	**Gain in NPV of profit at the expense of fall of economic fish biodiversity from a high level to an average level**	**Gain in NPV of profit at the expense of fall of economic fish biodiversity from an average level to a low level**
	(1)	(2)	(3)	(4) = (1) - (2)	(5) = (2) – (3)
0.5	7,86,758.63	10,40,402.00	12,11,162.00	1,70,760.00	2,53,643.37
1.0	9,22,927.95	16,03,978.30	17,71,744.50	1,67,766.20	6,81,050.35
1.5	9,74,557.84	17,33,954.10	22,47,745.50	5,13,791.36	7,59,396.26
2.0	10,05,012.10	20,17,655.80	27,02,611.40	6,84,955.60	10,12,643.70
2.5	10,27,096.70	22,92,898.90	31,49,107.10	8,56,208.20	12,65,802.20

6. Concluding remarks:

The bioeconomic model initially presented in this paper considers the important aspects of economic exploitation of a renewable resource as well as associated fundamental biological processes. The Gordon-Schaefer model modified by introducing economic biodiversity and environmental quality variables has been modeled and estimated by using Schnute method. It adds realism in exploring sustainability of fish catch in Digha estuary. This model is used to analyze the economic impacts on the fishery in Digha due to a reduction in the intrinsic growth rate and an increase in the discount rate: two parameters that are of fundamental importance to the population biodiversity and dynamics of the fish species. The change in population dynamics results in an adjustment of the sizes of the fish stocks, influencing the harvest of fish and subsequently the returns from fishing. Sensitivity analysis shows that a smaller intrinsic growth rate or a higher level of discount rate almost always leads to a lower standing stock of biomass of the fish species in the fishery. Also, the results of the sensitivity analysis show that the extent of the decline in stock size is more due to a fall in intrinsic growth rate than the change occurring due to an increased discount rate. The smaller stock sizes cause a long-term reduction of the amount of fish landed by the various fishing fleets. However, it has to be noted that the net present value of profits from fishing following the change in population dynamics does not reflect this negative trend. Some general qualitative assessments of the economic impacts of changes in fish biodiversity and population dynamics have been made possible on the basis of the sensitivity results. These could be useful in framing fishery management policy.

Sensitivity analysis of changes in intrinsic rate of growth is important in exploring fish harvest in the context of the level of pollution affecting the fishery. Our results indicate that any further reduction of intrinsic growth rate below the current level could be detrimental to this fishery, as it would have a direct adverse impact on NPV of profit. This is important for sustainable fishery management. Policymakers have to be careful while framing policies involving trade-offs between the development of fishing activities and the thriving tourism in Digha. Also, ensuring sustainability means maintaining the potential of fisheries resources to meet the reasonably foreseeable needs of future generations. Discount rates have the potential to significantly affect the intergenerational allocation of resources between harvesting and conservation and our sensitivity analysis reveals that higher discount rates produce lower net present value of profit. As fish biodiversity plays an important role in the value of a fishery, its conservation is necessary. So just by regulating the level of pollution, one cannot make the fishery sustainable. The policymakers and fishermen must also take into account the fact that degradation of economic biodiversity can actually put the sustainability of the fishery at stake. Our analysis finds that in the Digha fishery there exists a trade-off between economic biodiversity conservation and profit maximization. Policy measures have to be devised to minimize this level of conflict between them. One can increase the opportunity cost of fishing by providing alternative employment in nature-preserving tourism industry in Digha. Employment generation can be fostered by tourism at a low cost since it dos not require resources with a high opportunity cost. Such measures can restrain fishing effort thus reducing over-exploitation of the fishery and conserving biodiversity.

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