# Fish biodiversity and Profitability:An Ecological-Economic Model in search of a Tradeoff

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# Background

The environmentally sustainable use of fish resources is central to fisheries management, given the long-term importance of this sector in terms of nutrition and employment.

But today's major concern relates to the unsustainable levels of exploiting fishes with such practices that lead to the depletion of fish stocks, disruption of ecological equilibrium and reduction in diversity.

# Case studies

- **Fishing down the food web (Pauly et al, 1998)-**A recent re-analysis of FAO catches statistics documents progressive 'fishing down' of food chains as fishing effort responds to depletion of original target stocks.Where one species is exploited more than another their relative abundance changes, as in the North Atlantic (Sherman, 1990).
- **Fishing down the value chain (Kasulo and Perrings, 2001)-**As the most valuable species are overfished, they are quickly replaced by catches of less valued ones. It is seen that a large share of today's global catch consists of less valuable species.
- 'Fishing down the food web' implies that the value of fished stock decreases, but this may not be captured until they make it to the market.
- Whatever be the fishing sequence, demand or supply driven, it will have an impact on fish biodiversity with a change in composition and relative abundance of harvested species.
- So a change in biodiversity affects productivity and hence the value of the fishery.

# Issues in biodiversity

- The study of biodiversity involves both 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).
- Ecologically, the Simpson index, expressed as: $D_t = \sum (Y_{it}/Y_t)^2$,

  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.
- In fisheries, as most of the species caught are marketed, an economic value of a species can be approximated by using market prices (Hanemann, 1988).
- The rationale for social-economic valuation of biodiversity lies in the fact that the signals generated by the market system i.e., prices lead to excessive rates of biodiversity loss (Heywood, 1995).
- Market prices influence the exploitation of a fishery and hence the level and direction of effort
- Targeting of effort towards particular species leads to elimination of highly valued species, and to a reduction in biodiversity and productivity (Barbier et al., 1994).
- So a desire to increase profits may hamper economic biodiversity conservation and thereby affect the value of the fishery.
- 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.
- Simpson's economic biodiversity index is: $B = \sum( P_i Y_i/TR )^{2,}$

  where $P_i$ is the per unit price of species i, and TR is the total revenue.
- 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.

# Case Study

- This study focuses on the Digha fishery in West Bengal on the eastern marine coast of India on the Bay of Bengal as a micro case study in an attempt to analyze the relationship between biodiversity and profitability present there, if any.
- It has been 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 etc.Thus total 37 varieties of fish are found here.
- These varieties have been divided into five groups considering their importance from the viewpoint of their demand and price.
- They are *Hilsa, Chinese and Silver Pomfret, Black Pomfret and Prawn*. More than 50% of the total value of catch was contributed by these four species.
- Individual contributions of other 33 species in terms of value are not very significant. Also these other 33 varieties of fish such as (in local vocabulary) sardine, mackreal, chela, para and American bhetki have a very low price range in the market. These have been grouped under the heading '*others*'.

# Literature review

The issue of investigating any relationship between biodiversity and profitability has largely been neglected in the literature for this particular location.

Existing empirical works for Digha fishery relating to estimating sustainability are essentially biological and static in nature (Central Marine Fisheries Research Institute, 1984; Guha, Neogi, Das and Chakraborty, 1994, Das, Neogi and Chakraborty, 1996; Das, Neogi and Chakraborty, 2000; Dhar, 2004, Jana, 2004).

Guha and Neogy (1996) have considered a study for Digha coastal belt of East Medinipur district of West Bengal to determine the socio-economic status of marine fishermen in this coastal region.

Das, Neogy and Chakraborty (2000) have studied sustainability of marine fishery for the Digha- Shankarpur coastal belt in the context of the overfishing problem raised by George et. Al (1980) and James (1988).

All these studies have focused either exclusively on sustainability aspect of fisheries or on profitability and marketing aspects of fisheries.

# Motivation

The Digha Fishermen and Trader's Association regulates fishing activities in that area and acts as a profit-maximising unit within a larger competitive fish market. But a void exists in terms of bioeconomic modeling of the fishery in a dynamic profit-maximisation set-up in the literature.

Also the question of biodiversity needs to be addressed in the light of various reports(Rao, 2000) of the marine fisheries of West Bengal. The sustainability and profitability of the Digha fishery needs to be studied through the incorporation of biodiversity indices in an otherwise standard fisheries model.

So this paper focuses on the incorporation of biodiversity factor in bioeconomic models and studies the dynamics of the profit-maximising regime thereby estimating the dynamic maximum economic yield and net present-value of fishery profit that is maximized here. Sensitivity analysis with respect to small perturbation in discount rate examines its impact on profit under different biodiversity scenarios.

In this context we examine whether economic biodiversity conservation is in conflict with profitability of the fishery.

Such an integrated study considering biodiversity and profitability is practically non-existent for Digha fishery and relatively neglected for the Bay of Bengal coast of India specially for the state of West Bengal.

Our study attempts to fill up this lacuna as Digha fishery is important in context of livelihood of the fishermen.

# Standard Gordon-Schaefer model

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

$dX/dt = rX[1-(X/K)]-qXE,$ (1)

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

$dX/dt = 0 \Rightarrow rX (1 - X/K) = qXE$

or, $X = K (1 - q/rE)$

The Gordon-Schaefer production function is

$Y = qXE$ (2)

where Y is the catch rate or harvest rate of fish stock.

On substituting the value of X in the above equation, we have

the catch per unit effort

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

# Modified Gordon-Schaefer model

We have the expression for growth of fish biomass as

$(dX/dt)=rX[1 – (X/K)] – qAXE,$ (4)

where A is the biodiversity index it *may be the ecological or the economic biodiversity index.*

In steady-state equilibrium,

$X = K [1 – (qKA/r)]$

The Gordon-Schaefer production function is

$Y = qAXE$ (5)

On substituting the value of X in the above equation, we have

$Y = qKAE [1 – (qAE/r)]$ (6)

The catch per unit adjusted effort can be expressed as

***$(Y/AE) = qK [1 –(qAE/r)]$*** (7)

# Schnute's model

- It defines a population growth function in terms of U, i.e., catch per unit of adjusted effort (Y/AE) as

$$1/U(dU/dt) = rU(1 - U/qK) - qAEU, \qquad (8)$$

- Equation (8) has been obtained by considering Y/AE = U and by using the Gordon-Schaefer production function so that Y = qAEX implies X=U/q. It is to be noted that A is ecological or economic biodiversity index, as the case may be.

- Dividing both sides of Equation (8) by U, we have

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

- The equation can be framed after time averaging and thereby smoothing out the data as

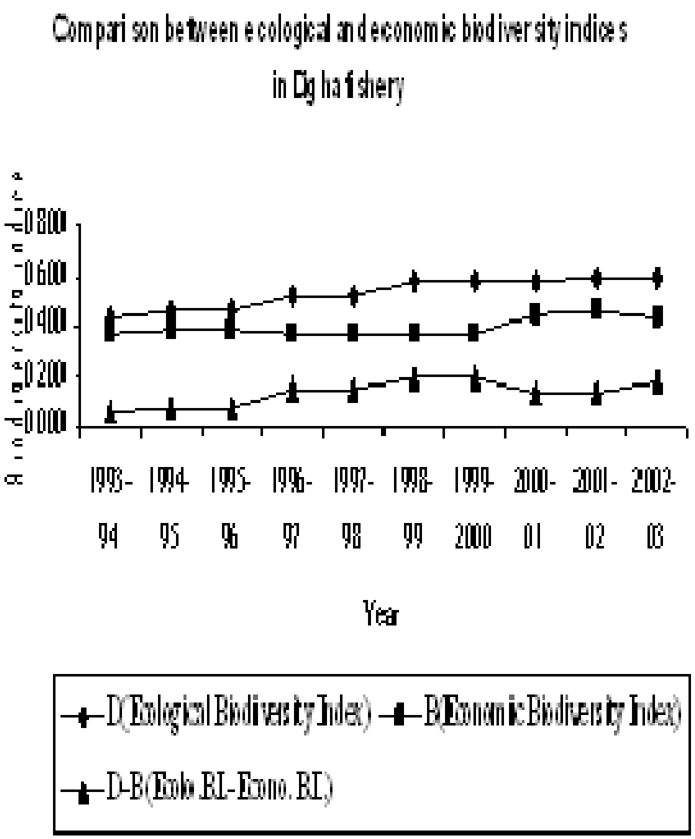
$$\ln X_t^* = r - qE_t^* - (r/qK)U_t^* , \qquad (9)$$

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

# Data

- Data has been collected from the Digha Fishermen and Fish Traders' Association in Digha covering the period 1993-94 to 2002-03.
- Catch is measured as kg. of fish landed and effort is represented by fishing months.
- Collected data show that mainly four species of marine fish dominate the Digha fishing industry in terms of both prices and quantity: Hilsa, Chinese and Silver Pomfret, Black Pomfret and Prawn. Other varieties have a very low price range in the market such as kanta, sardine, mackreal, chela, para and American betki - clubbed under the heading 'others'.
- Catch figures show that a popular food fish species hilsa is on a decline. The total landing of hilsa has declined to 1% in 2002-2003 whereas its contribution was 34% in 1993-1994. In contrast, the total landing of the species such as *sardine*, *chhela* and *kaante* has increased from 43% in 1993-94 to 75% in 2002-2003. The pomfrets group contribute around 14% of total landings with prawns 13%.
- Digha *Mohona* (Estuary), in recent years, has seen a shift in composition of fish species harvested towards catches of fish species of very low value (ranging between Rs. 4– Rs.35 per kg.) consisting of sardine, chhela and kaante clubbed under the heading 'others'. *This transition in composition of 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's indices is carried out by using the data on catch for the fishery of Digha estuary.

# Graph




- Curve D reflects the ecological biodiversity index over the period 1993-2003.
- Curve B reflects the economic biodiversity index over the period 1993-2003
- The third curve D-B plots the difference between the ecological and economic biodiversity indices over the period 1993-2003.
- ***The figure alongside suggests a decline in economic biodiversity in Digha fishery associated with a shift in fish catch from high-valued to low-valued species.***

## Regression results of the Schnute models (equation 9) in its modified forms (1) with introduction of ecological biodiversity index (2) with introduction of economic biodiversity index

| Equation of Schnute model | Constant | Coefficient of $E_t^*$ | Coefficient of $U_t^*$ | $R^2$ statistic | $\bar{R}^2$ statistic |
|---|---|---|---|---|---|
| **with inclusion of *ecological* biodiversity index** | 1.10174 (4.52187) | -0.0003181 (-3.56027) | -0.00260084 (-2.6065) | *0.643079* | *0.5538487* |
| **with inclusion of *economic* biodiversity index** | 1.29711 (5.88448) | -0.0002845 (-4.67727) | -0.0026378 (-3.39413) | ***0.732351*** | ***0.665439*** |

(t-values are given in the parentheses)

Note: (1) $E_t^* = (_{t-1} + _t)/2$, $_t = E_t D_t$ and $U_t^* = (U_{t-1} + U_t)/2$, $U_t = (Y_t/E_t D_t)$

(2) Dependent variable: $X_t^*$ , where $X_t^* = U_t^*/ U_{t-1}^*$

# Regression results

- The $R^2$ and $\bar{R}^2$ statistics indicate an improvement with inclusion of economic biodiversity as against ecological biodiversity index indicating the importance of the role of markets affecting fish harvested via price signals.
- The difference between the two models basically lies with the presence or absence of the economic forces that are at play.
- *The model with unweighted (ecological) biodiversity index expresses a sort of subsistence fishery, which is harvested for self- consumption and not marketed.*
- With the opening of a market, some species of fish are more in demand due to their high value and there is pressure on these species.
- *So, the model with weighted (economic) biodiversity index acts like a commercial fishery where high-valued fish is harvested for profit making.*
- The incentive to increase profit with the development of a larger market acts as a strong force to reduce biodiversity. In Digha, the fish harvested is not only sold locally but also has a large regional and export market and so fishing gears are adjusted accordingly targeting higher-valued fishes.
- Market plays a strong role in the harvest from the fishery.
- The weighted biodiversity index integrates the economic and biological influences on the fish species and therefore reflects more accurately the bioeconomics of the fishery.
- So the Schnute model incorporated with economic biodiversity index helps sufficiently to explain the interlinkages between economic biodiversity and fish harvest.

# Regression Results

- The model after the inclusion of a ecological biodiversity index registered an improvement in its performance as compared to the model where we used the ecological biodiversity index.
- Therefore, the use of the model with economic biodiversity index is more apt here as a management tool to sustain fisheries and in the process help conserve fish biodiversity.
- Since this helps explain a large proportion of the variation in fish biomass, so this equation is used for parameter estimation of the model.
- In this context, we have compared three different economic biodiversity scenarios, reflecting fishing down the value chain that is occurring in the fishery in Digha:

➢First, a scenario where the fishery has a wide range of different valued fish species i.e., *high level of economic diversity*.

➢Second, the current level of economic biodiversity in the fishery.

➢Third, a scenario where the fishery has fish species mostly of similar values i.e., *low level of economic diversity*.

# Values of the parameters

| Parameter | Notation | Value | Unit |
|---|---|---|---|
| **Intrinsic growth rate[a]** | r | 1.10 | dmnl./year |
| **Catchability coefficient [b]** | q | 0.0003181 | 1/fishing hours |
| **Environmental carrying capacity of fish stock [c]** | K | 1331685.933 | Kg. |
| **Average weighted economic biodiversity index [d]** | B | 0.3946 | dmnl |
| **Average price [e]** | p | 43.637616 | Rs./kg./year |
| **Average cost [f]** | c | 46.65569 | Rs./fishing hour |
| **Discount rate[g]** | δ | 0.11 | dmnl./year |

[a] the intercept value of the regression of the modified equation (9)
[b] the value of the coefficient of the effort function of the regression of the modified equation(9)
[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] the average of the economic biodiversity indices constructed for the period under study
[e] it is the aggregative average of the prices of all fish species under our consideration during the time period of our study
[f] it is the total cost incurred by fishermen calculated on the basis of their wages both for labour in boats and trawlers
[g] it is approximated by the current market rate of interest

# Profit-maximisation regime

- 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 focused on the dynamics of the profit-maximising regime.
- 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.
- Optimum values of the variables:
  - *Optimum level of fish stock:*

    $$X^*_{dyn.} = \frac{1}{4}\left[\{\Omega + K(1 - \delta/r)\} + \sqrt{[\{\Omega + K(1 - \delta/r)\}^2 + 8K\Omega(\delta/r)]}\right.$$
  - *Optimum level of effort:* $E^*_{dyn.} = (r/q)\{1 - (X^*_{dyn.}/K)\}/B$
  - *Optimal level of fish harvest:* $Y^*_{dyn.} = qX^*_{dyn.} BE^*_{dyn.}$
  - *Optimum level of NPV of profit:* $NPV^*_{dyn} = (pY^*_{dyn.} - cE^*_{dyn.})(1/1+\delta)^t$

# Dynamic profit-maximising values of the variables under three alternative economic biodiversity scenarios

| | PROFIT-MAXIMISING SOLUTION (Dynamic Framework) | | | |
|---|---|---|---|---|
| **Alternative scenarios of economic biodiversity of the fishery** | **Stock (kg.)** | **Harvest (kg./year)** | **Effort (fishing hours/year)** | **PV of profit (Rs.)** |
| **Situation 1:** High economic biodiversity | 3,37,867.74 | 2,64,913.46 | 12,903.42 | 39,91,152.55 |
| **Situation 2:** Average economic biodiversity | 3,25,940.71 | 2,70,780.52 | 6,618.47 | 40,16,415.89 |
| **Situation 3:** Low economic biodiversity | 3,15,648.21 | 2,77,360.45 | 2,638.39 | 41,13,563.35 |

***So economic diversity reduction is associated with a rising level of NPV of profit masking the existence of the potential threat of a loss of the valuable fish species in the fishery.***

## Sensitivity Analysis:-

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

- The discount rate, approximated by the market rate of interest, represents the opportunity cost of investing in the fishery vis-à-vis other allied industries like the tourism industry.

- We have considered here a range from 0.9 to 0.13 between which the market rate of interest has varied over the last 10 years as envisaged from Reports of Currency and Finance of the RBI.

## 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 economic diversity (2) average economic diversity and (3) low economic diversity in the fishery model

| Value of δ | SITUATION 1: (NPV of profit)$_{\text{high level of economic biodiversity}}$ | SITUATION 2: (NPV of profit)$_{\text{average level of economic biodiversity}}$ | SITUATION 3: (NPV of profit)$_{\text{low level of economic biodiversity}}$ | 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** | 52,71,870.10 | 58,87,813.70 | 67,98,443.26 | 6,15,943.60 | 9,10,619.46 |
| **0.10** | 38,31,035.15 | 48,10,318.90 | 56,41,354.05 | 5,61,373.10 | 8,31,035.15 |
| **0.11** | 35,02,624.53 | 40,16,415.89 | 47,75,812.15 | 5,13,791.36 | 7,59,396.26 |
| **0.12** | 31,99,265.50 | 36,55,341.10 | 43,49,312.29 | 4,56,075.60 | 6,93,971.19 |
| **0.13** | 21,48,685.20 | 25,78,135.60 | 32,13,018.97 | 4,29,450.40 | 6,34,883.37 |

# Impact of perturbations of the discount rate, δ (contd)

- ***At any particular discount rate***,
- NPV of profit $_{\text{situation 3}}$ > NPV of profit $_{\text{situation 2}}$ > NPV of profit $_{\text{situation 1}}$
- The gain in NPV of profit associated with decreasing levels of economic biodiversity is highest when we contrast between Situations 1 and 3 than between Situations 1.
- The more rapid the depletion of economic fish biodiversity the proportionately larger gain in NPV of profit takes place.

- ***At falling discount rates***,
- NPV of profit increases steadily with larger investment in improved gears and vessels.
- The gain in the NPV of profit is higher when Situation 1 and 3 are compared against Situation 1 and 2.

# Impact of perturbations of the discount rate, δ (contd)

- One can infer from the above table that,

  NPV of profit $_{\text{situation 3}}$ > NPV of profit $_{\text{situation 2}}$ > NPV of profit $_{\text{situation 1}}$.
- The gain in NPV of profit associated with decreasing levels of economic 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 targeting of the capture of the most expensive species leads to larger losses associated with the fishery.
- One can hence conclude that maximisation 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.
- Changes in the discount rate have been found to affect fish catch and NPV of profit.
- Policies that lead to reduction in interest and discount rates will also lead to losses in biodiversity.
- So economic biodiversity conservation is at stake in a high profit-maximising regime.

# Summary

- Our work started with the standard Gordon-Schaefer model which has been modified to include the biodiversity variable.
- A biodiversity variable has been 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.
- A fishing-up process has been observed whereby fish stocks are gradually depleted from large to small fishes, abundant to less abundant species and from easily caught to less easily caught species (Pauly et al., 1998).
- One biodiversity measure is introduced based on the observed pattern of sequential exploitation that fisheries go through as they develop.
- This is basically the Simpson's *ecological biodiversity index* that has been used here.
- One other index has been used here-the economic biodiversity index- based on the observation that in the development of a fishery the sequence of exploitation is from high-valued to low valued fish species (Boechlert, 1996).
- The Simpson's ecological biodiversity index has been modified here by weighting the former with market prices of the fish species.
- The Simpson's biodiversity index following Kasulo and Perrings (2001) has been used as the basis for developing a modified index because it is more sensitive to changes in dominant species.
- To incorporate the economic value of biodiversity, the *economic biodiversity index* used has been the weighted market price of fish species.
- The indices here been calculated on the basis of the catch data of the Digha fishery.
- It has been found that the economic (weighted) biodiversity index has lower values than the ecological (unweighted) biodiversity index. This suggests that fish catch in Digha fishery is dominated by less valuable species.

# Summary

- The parameters of the model has been estimated using Schnute's (1977) method, as it reduces the bias in the estimates resulting from errors in the measurement of variables.
- The model fit and the parameter significance improved with the introduction of the economic biodiversity index as against the ecological biodiversity index.
- This clearly shows that biodiversity plays an important role in the determination of the value of the fishery.
- This is specially true if the fishery is subjected to market forces where the market value of the species is taken into account.
- The bioeconomic analysis with ecological biodiversity index can be thought of as representing a subsistence fishery in which the species are not marketed but are solely exploited for food.
- But when a market for the fish opens up, some species are likely to be in more demand than others and this would create pressure on the valuable species.
- The bioeconomic analysis with economic biodiversity index therefore represents the commercial exploitation of the fishery.
- Loss of biodiversity is linked to the development of the market in that it leads to over-exploitation of valuable species, which results in a reduction in aggregate fish biomass.
- Since fish biodiversity plays a significant role it is imperative that its conservation be a priority.

# Concluding Remarks

- Our analysis has found that in Digha fishery there exists a trade-off between economic biodiversity conservation and profit maximization. It has been found that biodiversity conservation and profit maximization are in conflict with each other. The conflict between profit maximization and biodiversity conservation underlines the importance of economic scarcity. The fishery is exploited to meet market demand and any signals of scarcity as reflected by market prices induces further exploitation of the fishery. So a reduction in the over-exploitation of the fishery will increase not only biodiversity but also the value of the fish catch. Policy measures have to be so defined as to minimize the level of conflict between them.
- As a public good, fish biodiversity can best be conserved not only by the application of traditional management strategies, but also by using economic instruments. In particular, economic incentives that lead to loss of diversity should be replaced by those that encourage biodiversity conservation. In fact, the Convention on Biological Diversity has called for developing and adopting economically and socially sound measures that act as for the conservation and sustainable use of components of biological diversity incentives.

# Concluding Remarks

- Traditional fishery management strategies mostly involve gear restrictions, closed season and licensing. Gear restrictions involve prohibition of certain methods of fishing like mesh size restrictions. Enforcement of mesh size regulation is very difficult. Closed seasons aim at protecting fish stocks during critical stages like breeding. These policies have not been very effective in the case of Digha fishery. Licensing is aimed at limiting entry into the fisheries. It seeks to control the amount of effort by directly regulating the number of fishermen. This method has been partially effective in Digha fishery.

- The traditional fishery management strategies have largely focused on the biological aspect of the resource. Biological analysis relates sustainable catch with the amount of fishing effort but importantly this effort level is itself driven by economic forces. If this aspect is not considered, it has a negative impact on the biodiversity of the resource. Economic incentives and disincentives through price and tax policies can help stakeholders to conserve biodiversity. If fishing costs are sufficiently high relative to the price of fish, the fishery will not be exploited.

Thank You