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Towards a Green Deal for Coastal Ecosystem with Special Reference to *Sundarbans* under Changing Climate[1]

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The fact that the *Sundarbans*, a typical representation of the coastal ecosystem, and a treasure trove of natural resources, is degrading fast under the combined assault of man, nature and climate change, is no longer confined to scientific discussions, but has become a concern in public discourses. The issue at stake being the well being (habitat, health, livelihood and income) of the people, urgent remedial measures is warranted. Amongst the numerous issues seeking solutions, this paper addresses three concerns: i) increasing freshwater scarcity, which is limiting agricultural growth; ii) drainage congestion, causing flooding of farms and farmsteads; iii) and overexploitation coupled with pollution of resources in the coastal waters due to crowding of ventures, leading to fall in provisioning and other ecosystem services. Three innovative approaches are advanced to resolve these critical issues. The first suggestion speaks of closing few identified estuaries by suitable engineering structures, to create fresh water reservoir, and to do away with the need of protection bunds along the closed length on either side of the estuary. The second intervention advocates tidal river management (TRM) to enlarge the estuary sections along the estuary, where beels (large and deep-water bodies) are available. The third intervention is about extending farming in off-coast sea. Unlike land, sea offers the opportunity of practicing three-dimensional (3-D) farming in the water column. Several technology models, which enable growing various useful seaweeds, corals, fishes at varying depths, not only offer new areas for farming, but also sequester more carbon, absorbs phosphorous and nitrogen, which are the major pollutants of coastal waters. The planning, design and operationalization of estuary management practices are based on complex hydraulic phenomena. In addition, the built environments always carry the burden of trade-off, and the suggested interventions are no exception to this rule. Further research is necessary to arrive at balanced decisions as per TEEB AgriFood Framework, for internalization of externalities embedded in the value loss of natural capital. Some of the identified research and data gaps include: estuary regime modelling for design of protection structures, hydro-salinity modelling to settle the competing issues crop vs brackish water aquaculture, mapping of coastal ecosystem resources for natural capital accounting (NAC). The suggested interventions, if properly implemented, will turn out to be a green deal – 'minimizing trade-offs and increasing synergies between enhanced human outcomes (crops, fish, water supply, etc.) and the health of the natural environment'

*(**Key Words:** Estuary, Beel, TRM , 3D farming, Seaweeds)*

Coastal ecosystems, which occur at the junction of land and water, encompass both terrestrial as well as marine habitats and include salt marshes, mangroves, wetlands, estuaries, and bays (UNEP, 2006). There prevails a distinctly different environment in respect of energy flow and biodiversity. Being intricately linked to upstream terrestrial ecosystems on landward side and marine ecosystems on seaward side, they are impacted by activities happening in the other two dominant systems. These interactions between a highly variable natural environment and the growing pressures from anthropogenic interventions and climate change (Box 1) produce multiple stresses (Jennerjahn and Mitchell, 2013). In South Asia, *Sundarbans*, lying in the in the delta of three mighty rivers Ganga-Brahmaputra and Meghna, is one the major coastal ecosystems under threat both from anthropogenic and natural pressures. Upstream water diversions, frequent threat of cyclonic storms, sea level rise, and flooding leading to soil erosion, sedimentation, impeded drainage, sinking of

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delta, seawater intrusion and consequent salinization of productive soil and water, have sapped the resilience of land and people in this region (Bhattacharya *et al*., 2013; Ernesto *et al*., 2018; Kay *et al*., 2015; Raha *et al*., 2012; Sen, 2016). In other words, the built environment has led to deterioration of the region's natural resource base, rendering it incapable of sustaining the economic development and maintaining it's regulating and aesthetic services. This ecosystem, being the source of food and livelihood security of a large population (Sen, 2016), is in urgent need of rehabilitation through well designed eco-friendly interventions.

Eco-innovations for sustaining the economic developments

Eco-innovation refers to any form of innovation that reduces the impacts on the environment, enhances resilience to environmental pressures, or achieves more efficient and responsible use of natural resources (Andersen, 2008; Carrillo-Hermosilla, 2009). Realizing the economic, environmental and social benefits of maintaining and improving the natural ecosystems, the need for introducing the innovations are being increasingly discussed in global forums (TEEB, 2009). A series of such connected changes that reduce use of natural resources and decrease the release of harmful substances would lead to a green economy. In future, GDP growth should come not from increased resource use, which introduces environmental pressure, but from increased efficiency through a low-carbon circular economy. The nexus approach, which is emerging as an instrument for developing research agendas and development planning should be looked upon as an opportunity for a New Green Deal (Tyagi, 2017).

Scope of this paper

The issues connected with sustainable realization of the economic benefits of coastal system are many, however, this article is limited to three important aspects: i) creation of fresh water storage through closure of some estuaries to meet the increasing demand from different sectors, ii) tidal river management to take care of sedimentation and erosion to reduce drainage congestion), and iii) introduction of 3-D farming inestuaries and off-coast areas for reducing estuary pollution and increasing income and livelihood opportunities.

Creation of fresh water storage through estuary closure

The estuary closure, which involves construction of structure (which could be permanent - dam, or partially permanent structure such as,weir, and temporary structure like coffer dam) (Fig.1), has been practiced for thousands of years, with one or more of the following purposes (Schultz *et al*., 2013; Sitharam, 2017).

i) Reclamation of low lying tidal land: Most of the estuary closures were primarily undertaken to reclaim land for agriculture and other such purposes. The Zuiderzee and Delta works are two success stories under this category (Schultz *et al*., 2013)

ii) Creating a fresh water reservoir: Providing for shortages during dry season, tidal inlets have been used in several places, including

Box 1: Major pressures affecting estuaries (Jennerjahn and Mitchell, 2013)

Human impacts:

Agriculture, urban and industrial activity: Dredging (Direct impact on the seafloor, turbidity, contaminant release and spoil ground effects); Foreshore infrastructure (Direct clearing of habitat) Fishing (Removing species that make up part of the ecosystem)

Climate change:

Less inflow from rivers (Reduced flushing), Higher sea level (Pressure on freshwater species); Higher temperatures (Heating of shallow water affecting biological activities such as spawning)

Extreme events:

Heatwaves (severe heating); Major rainfall (Washes large slugs of pollutants into an estuary)

"In a worst scenario sea level may rise between 1.07 to 2.00 m by 2100 A. D. due to delta sinking and climate change with melting of ice sheet".

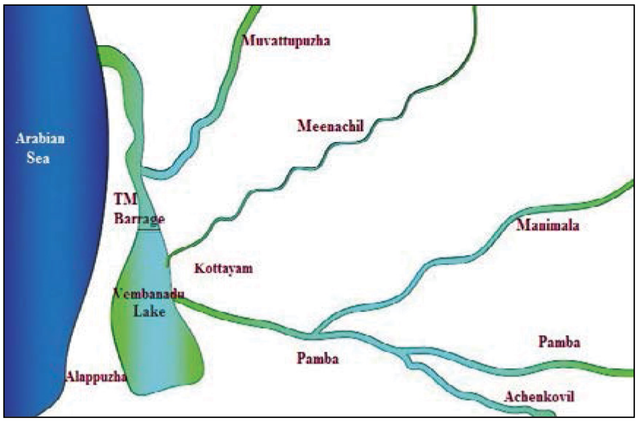


Fig. 1. Thanneermukkom Barrage across Vembanad Lake (Source: Sitharam, 2017)

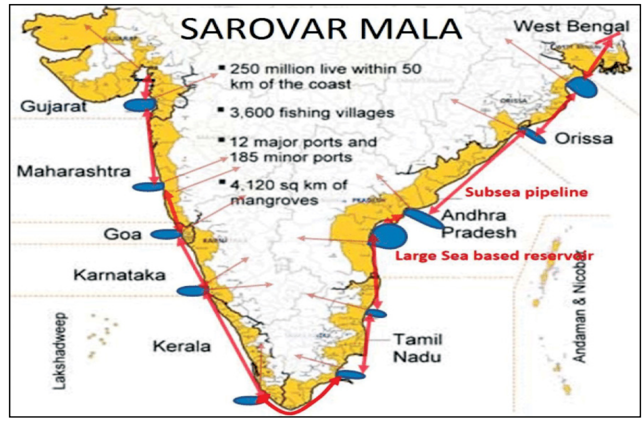


Fig. 2. Map showing some locations for creation of fresh water reservoir on east and west coasts (Source: Sitharam, 2017)

the Duriangkang reservoir on Batam island in Indonesia, and closure works in Korea (Young *et al*., 2009; Verhagen, 1995)

iii) Creation of a tidal energy basin: In the initial phases, the Kalpsar project also had provision for generating electricity by harnessing tidal energy (Anonymous,1999). But the proposal was later on dropped for cost reasons. But the closure dam of the Siwha estuary in Seoul in Korea is a dam for the creation of tidal power, which has been successfully operated.

iv) Shortening of the length of a sea defense: Closing the estuaries causes reduction in embankment lengths and decreased maintenance costs. This has been one of the major gains in Brouwersdam project in the Netherlands and Feni River closure in Bangladesh (Stroeve, 1993)

A global inventory of the closed tidal basins, which have been subject to closure through dams, was undertaken in 2007 on the eve of the 75th anniversary Zuiderzee Scheme (Schultz *et al*., 2013). The post-reclamation issues in respect of water quality in the reservoir, land subsidence, sea level rise and host of other issues dealing with sustainable development have been flagged in this report.

Case for creation of freshwater reservoir in *Sundarbans* estuaries

The opportunities for augmentation through closure of the estuaries are limited to only few selected coastal regions on east and west coast in India (Fig. 2). As early as 1980, tidal channel in Guelph of Khambat, was visualized as a possible site envisaging building a dam for establishing a huge fresh water reservoir for irrigation, drinking and industrial purposes. Considerable experience has been gained in planning the development of large estuary project in the course of feasibility studies over last two decades (Anonymous, 1999). Recently, locations of few sites suitable for Increasing the freshwater water supplies is considered essential for imparting the resilienceto the socioeconomic and biophysical systems in *Sundarbans*, and exploring the feasibility of estuaryclosure to create freshwater storage, has been identified as part of the action plan (Earnesto *et al*., 2018).

It was as early as 1960's, that the River Research Institute in collaboration with Netherlands prepared a proposal, which remained unimplemented, to build a barrage across the Saptamukhi River to store fresh water and to protect area from natural disasters (Delft Hydraulics, 1968). During last 50 years since the inception of the idea of creating a freshwater storage by damming Saptamukhi River, the technology of creating such infrastructures has vastly improved and the demand for freshwater has gone up. Based on the assessment of various options by World Bank to reduce the vulnerability of *Sundarbans* to natural hazards (Earnesto *et al*., 2018) and the intensive scientific deliberations in the Conclave of Indian National Academy of Engineering (Anonymous, 2013), the idea to build fresh water reservoir across the Supathamukhi River gets reinforced. The target areas expected to be covered under each phase are shown in Fig. 2. Recently, Sitharam (2017) has also identified number locations on east and west coasts for developing freshwater reservoir through estuary closure (Fig. 2).

If undertaken, these developments will lead to rationalized lengths of embankments, creation of freshwater storage and protection of precious land from tidal surges.

In Bangladesh, they have implemented Feni River closure dam as early as 1985. Coast and polder development are important components of their integrated land and water resources management programmed under which Nijhum Dwip, and surrounding area have been selected as a pilot project for first track study (GoB, 2015). Activities under the project would involve construction of two cross dams at both ends of Nijhum Dwip channel and development of 5 km^2 fresh water reservoir; construction of cross dam between Nijhum Dwip and Damar Char for Land Reclamation; Establishment of mangrove afforestation for disaster reduction and land accretion; and reclamation of about 40 km^2 of sub-aqueous delta shallow delta.

Important characteristics of estuaries in *Sundarbans*

Wave climate

Wave climate is defined as the distribution of wave height, period, and direction averaged over a period of time for a particular location (Wiegel, 1964). The waves are characterized by five parameters - period, frequency, amplitude, wavelength, and height. In locations close to the shore, the prevailing winds, storms and bathometry modify the waves. The wave climate in *Sundarbans* has changed in recent years and has become tide dominated with tidal range varying between 3.7 to 5 m (Hazra *et al*., 2002). There is a progressive sedimentation of estuaries like Saptamukhi resulting in increase in the height of tidal bore to more than 6.4 m. The statistics on heights and periods of wave constitute an important factor in estuary structure design works.

Tidal characteristics and their annual variation

The data on tidal surge constitute an important design parameter. The tides in the estuarine areas of *Sundarbans* are semi-diurnal in nature with two successive tidal cycles per lunar day *i.e*., 24 hours 48 minutes, and influence the hydraulic behavior of the estuaries. Based on the data obtained from Institute of Water Modelling (IWM), Komol (2011) has simulated the tidal behavior of a number of estuaries in Bangladesh. Similar attempt has been made by Bhattacharyya *et al*. (2013).

Cyclone phenomenon

The *Sundarbans* are located in the cyclone prone region. In tropical regions cyclones are intense low-pressure area with organized convection and wind at low levels. A cyclone is characterized by its maximum pressure drop, maximum wind speed, and its radius to maximum windspeed. For example, Cyclone *Aila*, that hit the coast of West Bengal, Bangladesh and Myanmar on May 25 of 2009 had a wind speed between 74-120 km h^{-1} (severe cyclonic storm), while the lowest pressure was 968 mbar. A storm surge of 2-3 m above tide levels was experienced along the coasts of West Bengal and the adjoining areas of Bangladesh (Sen *et al*., 2010). The design of the closure dams has to keep up with the surges created by such cyclones.

Stratification of fresh and saline water layers in the reservoir

When the water masses of different properties form different layers, which act as barrier to mixing - the process is known as stratification. The success of creating freshwater reservoir in estuaries depends on stratification. The water layers are arranged according to density and therefore least dense water floats over the higher density water. Since both temperature and salinity affect density, the combination of salinity and temperature difference defines the resultant density of water mass (Geyer and Ralston, 2011). The water of lower salinity and higher temperature, which is less dense, floats over water of high salinity or lower temperature. The variation in density with temperature and salinity is often expressed by empirical equation of the form (Crowley, 1968).

$$D_{ts} = 1+\{10^{-3}[(28.14-0.073t-0.00469t^2)+(0.802t)(s-35)]\}$$

D = density in kg m^{-3}, t = temperature in °C, and s = salinity in ppt

As may be seen from the equation above, salinity has much higher influence on density as compared to temperature, and therefore the differences in density will have dominant influence on the vertical stratification in the reservoir (Schumann *et al*., 1999). Maintenance of stratified conditions enables flushing of saline water from the reservoir through sluice outlet, and makes water useable in shorter time. But high velocity winds act as mixing agent and can destroy stratification through air entrapment. The entrainment process is governed by Richardson number, represented by the relative density differences between the upper and lower layers ($R_i = \varepsilon g h_0/u^2$, where, ε is the relative density difference between two layers $(\rho_s - \rho_r)/\rho^2$, h_0 = thickness of the upper layer; u = wind introduced shear velocity)

Common problems encountered in estuary closure projects

The creation of freshwater storage by a closure dam may result in several externalities including prevention of fish migration, changes in groundwater levels, water quality issues resulting from discharge of sewage water, and other chemicals laden runoff from the catchments, upwelling from reservoir bottom, pollution and siltation of in the reservoir of itself reducing its storage capacity, and reduction brackish water fishery (Schultz *et al.*, 2013). It is beyond the scope this paper to discuss all these issues in detail; however some relevant experiences gained from closures are briefly enumerated.

One of the main effects of estuary closer is the disappearance of brackish water zones, change of microbial diversity in habiting patterns, and a decline in fish diversity as happened in Yeongsan Reservoir (YSR), Korea, which had beenconstructed by a 4.35 km long dam in 1981(Young *et al.*, 2009). They also observed reduction in storage capacity due to siltation. Also, water quality in YSR was affected by complex physico-chemical and hydrological phenomena, including saline and thermal stratifications and pollutant loadings leading to eutrophication. Similar effects were noticed in Lake Hachirogata project, where sedimentation rate increased after reclamation in proximity to the agricultural zone. Higher levels of dissolved total nitrogen and dissolved total phosphorus (DTP) were found in both surface and bottom waters. Large amount of mobile phosphorus (42-72% of TP) trapped in sediment increased the risk of phosphorus release and intensification of algal blooms (Jin *et al.*, 2016). It has been inferred by the authors that high sediment phosphorus and phosphorus mobility is a source of pollution in the coastal environment. The post-closure studies (Jin *et al.*, 2016; Schultz *et al.*, 2013) suggest that, water within and outside the closure should be carefully controlled and regulated for environmental sustainability of the freshwater reservoir.

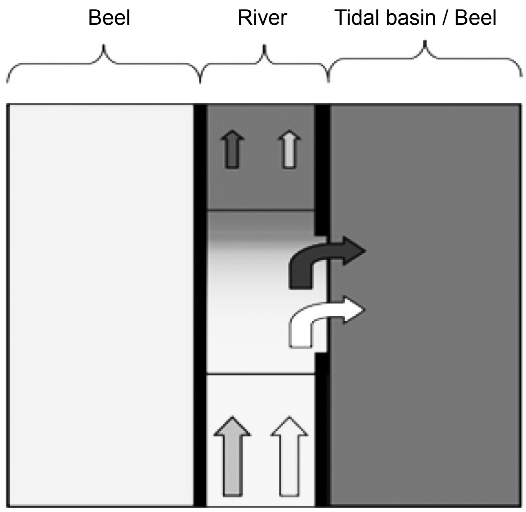
Tidal river management (TRM) for ameliorating of waterlogging and sedimentation

The TRM is an eco-technological concept, designed to solve the waterlogging problem, while at the same time, improving the environment (Amir *et al.*, 2013). It is essentially an old practice, perfected by the local communities over a long period of time (de Die Leendert, 2013; Kibria and Mahmud, 2010), with a new name, as the first mention of the term TRM is found in the Environment Assessment Report by Center for Environmental and Geographical Information Services in 1998 (CEGIS, 1998). Incidentally, the wise use of this community practice was first recorded by Willcocks (1930), who observed that sediment management was the main water management issue in coastal Bengal. This practice, in some ways has been in use in Netherlands, United States and Belgium (de Die Leendert, 2013).

The construction of embankment to keep away the coastal estuarine river flow from the flood plain is the usual practice in coastal areas, which decreases the tidal prism (the volume of water entering the river during high and low tide), resulting in decreased flow velocity leading to settling down of sediment in tidal rivers (de Die Leendert, 2013; Rahman, 1995). This causes drainage congestion and waterlogging in cultivated land.As the drainage capacity of the rivers decreases it leads to waterlogging, as is the case with some areas in the southwest delta (IWM, 2012; Kibria and Mahmud, 2010). The drainage congestion has been a matter of grave concern in delta region as it led to serious flooding of agricultural land and the rural habitats with considerable impacts on economy of the region (ADB, 2007; IWM, 2010).

Process of TRM

In the estuarine rivers, daily there are two cycles of tides, the high tide which brings in muddy water flow with high concentration of sediments, which when let into the flood plain by cutting the embankment, settles there when the water flows back into the river during low tide. Generally, a low-lying depression in the floodplain (tidal basin), locally called '*beel*', which is filled with water throughout the year and lying adjacent to the sediment-laden tidal rivers, is part of this system (Amir *et al.*, 2013). While returning to the sea during low tide, the water stored in these tidal



A: No TRM

Tidal prism: low

Volume water in: low, Sediment in: medium

B: TRM

Tidal prism: increased, Volume water in: high, Sediment in: high

River flow u/s of basin: low, River flow d/s of basin: high, Sediment: settles in beel

Fig. 3. *Schematic diagram of TRM process (Source: de DieLeendert, 2013)*

basins pushes its way through the narrow rivers with increased flow velocity (Fig. 3). This causes erosion of the riverbed, thereby increasing the size of the rivers. In this process the land level in the flood plain is raised, while the river bed deepens. As there is no deposition of sediment in the river bed, the drainage capacity of river is increased. Based on analysis of field data from inlets through sandy barriers on West Coast of United States, O'Brien (1931,1976) proposed the following relationship between the size of a tidal inlet and the tidal prism (mean tidal volume)

$A = c\,P^n$

where, A = minimum inlet cross-sectional area in the equilibrium condition, c = an empirically determined coefficient, P = mean tidal prism and n = an exponent usually ≤ 1

Attempts to develop scientific basis for understanding the process were made, which led to establishment of relationship between the cross-sectional area of the river and the tidal volume (Le Conte, 1905; William, 1919; Willcocks, 1930). William (1919) noted that the section at any particular point bears a direct relationship to the tidal reservoir capacity above that point.

Shampa and Pramanik (2012) applied this relationship in Hari River tidal basin and observed that the cross-sectional area of a tidal channel reduced in size if the tidal prism is reduced. It is for this reason that delinking of a tidal channel from the tidal system causes reduction in the tidal prism in the downstream of the closure point. The usefulness as a tool to prevent waterlogging caused by river bed sedimentation was upheld by scientific and financial institutions like Asian Development Bank and Institute of Water Modelling (ADB, 2007; IWM, 2010).

The process of TRM essentially involves sediment transport. For this purpose, MIKE 21, developed by Danish Hydraulics Institute (DHI, 2007; Warren and Bach,1992) is a professional software package, consisting of six modules, and is the most versatile tool to simulate physical, chemical or biological processes in flows of rivers and estuaries. The different modules of this software are used to simulate hydrodynamics, advection-dispersion, short waves, sediment transport,water quality, eutrophication and heavy metals. Amir *et al*. (2012) have used this model to study the technical feasibility of various sediment management options.

The key message is: Tidal basin management (TRM), by increasing the river's tidal prism and cross section, controls sediment deposits in tidal rivers in an economic and environmentally friendly way.

Experiences with TRM practice

The concept of TRM has been implemented in several tidal basins of Jessore in the south west coastal zone of Bangladesh, where waterlogging was rampant due to river silting (Amir *et al*., 2013; Khadim *et al*., 2013; Kibria and Mahmud, 2010). In the evaluation of TRM in *Beel Bhaina* tidal basin, it was found about 26% of the sediment and silt entering the *beel* was retained, raising the land elevation by1.82 m in an area of 770 ha over period of 14 years (1997 and 2011) (Khadim *et al*., 2013). Further, just in four years (1997-2000), the depth of the Hari River just upstream of *Beel Bhaina* increased by 4 m, and as much as by 14 m in some downstream locations indicating the success of TRM. For continued success, TRM has to be practiced on rotational basis. The rapid assessment made by the Institute of Water Modelling (IWM, 2010) on the basis of data generated by CEGIS confirmed that the rotational TRM approach was not only technically suitable, and economically viable, but was socially acceptable option, as it took care of the interest of different stakeholders such as crop growers and fishers, etc. (Shampa and Pramanik, 2012).

In TRM, one has to consider a number of complex issues arising due to inter connectivity, and interdependence of river system as well as the diverse interests of the croppers and fish pond farmers stakeholders (ADB, 2007). For success of this practice, it is important that beels are available along the river course. To ensure the required environmental flow in the tidal basin, siltation should be limited to raise the level, no more than 1-1.5 m (Shampa and Pramanik, 2012). This is important from consideration of serving the interest of crop farmers and fish pond farmers.

Extending farming into the sea

There is very high competition for terrestrial area from urbanization, industry, ports and harbor installations on landward side of the coastal ecosystem. There is another pressing reason to go for off-coast farming, and it is decreasing prospects of traditional crop agriculture supporting livelihood in this region. In their analysis, the FAO suggest diversification and increased income from off-farm activity (Dixon *et al*., 2001). Growing economic distress due to increased population pressure and stagnation of agriculture in coastal areas can, to some extent, be taken care of by shrimp culturing. But very often, there are conflicts between crop agriculture and shrimp culture, arising due to different water and salinity regime requirements. On the other hand, in coastal ecosystem, estuary which is home to both abiotic and biotic components (Box 2), is highly productive in terms of nutrient from different sources promoting other living resources with an average natural primary productivity (NPP) of 80000 $Kcal^{-1}$ m^{-2} yr^{-1}, as compared to only 27000 $Kcal^{-1}$ m^{-2} yr^{-1} in case of agricultural land (Internet accessed on July10, 2018), and can be harnessed to increase food security by adopting innovative technologies. But in spite of the tremendous potential for exploiting the synergy of agri-aqua farming system, it has not received much attention (Swaminathan, 2015). Extending farming to near and off-coast areas offers a good solution, as sea farms can be designed to restore ocean ecosystems, mitigate climate change, and create blue-green jobs-while ensuring healthy, local food for communities (Delaney *et al*., 2016; Duarte *et al*., 2017; Farnand *et al*., 2017). So, there is a strong case for intensifying estuarine farming through innovative farming practices and extending mari-culture in off-coast areas in multiple innovative ways. Some of the important options are discussed.

Box 2: Abiotic and biotic components and the food chain in estuaries

Abiotic components:

Nutrients such as phosphorous, nitrogen, salts -composition varies on daily and seasonal basis

Biotic components:

Producers: Phytoplanktons - micro-organisms that manufacture food by photosynthesis and absorb nutrients; mangroves, sea grass, weeds, salt marshes

Consumers:

Primary consumers: Zooplanktons that feed on phytoplanktons

Secondary consumers: Worms, shellfish, small fish feeding zooplanktons

Tertiary consumers: Fish, turtles, crabs, starfishes that feed secondary consumers

Decomposers: Fungi and bacteria active in decay of dead organism

Farming fish is more climate smart than raising land-based animals

"Scientists have found that farming fish is better for the climate than raising land-based animals. Fishes are much better than cows, pigs, and chickens at converting feed into food because they are cold-blooded and don't need to use energy to warm themselves, don't need to fight gravity, and have smaller skeletons. Unlike land animals, estuarine fish don't need to be fed fresh water" (Gunther. M., 2018)

Seaweed and seagrass farming

Seaweeds comprising numerous algal groups have been used initially for domestic purposes as food and feed, and later in industrial uses (gels, fertilizers) (Delaney *et al*., 2016). But over the years the industrial use of seaweed biomass has shifted as fertilizers and a source of potash, via iodine production, to hydrocolloid extraction (Synytsya *et al*., 2015). Quite opposite to land-based crops, seaweed farming is a zero-input activity as it requires no additional fresh water, fertilizer, pesticides, feed or soil to grow. It receives everything it needs from the sun and the sea (Gertz, 2017). So, it could provide an alternative source of biomass for the sustainable production of food, chemicals and fuels (Lehahn *et al*., 2016; Neori, 2016). The most basic module of aquatic farming is a floating platform having aquatic weed base on a bamboo platform, as is being practiced in Bangladesh (Practical Action Internet). But possibilities of increasing the productivity of seaweed by artificially enhancing the nutrients through the fully engineered processes (chemical fertilization of surface water around seaweed raft farms) to only pumping of nutrient-rich water to the surface, and to support naturally floating beds, have been experimented (Alejandro *et al*., 2017; Notoya, 2010).

The capacity of the seaweeds to improve the marine environment by taking up dissolved nitrogen, phosphorus, and carbon dioxide has been very actively researched. Recent review by Alejandro *et al*. (2017) that bioremediation, environmental impacts (mostly impacts of introduction) on the development of farming technologies, and to some extent chemical products (bioactives), were the main subjects of interest. Seagrass meadows can increase aragonite saturation by up to 2.9 units, and the pH by 0.38 thereby reducing seawater acidity, which gives boost to corals (Jones, 2016). Though the sea plants from seagrasses to plankton, constitute only 0.05 percent of the plant biomass on land, they are very efficient at absorbing carbon. They cycle through, roughly the same amount of carbon every day as all the land-based plants, and it has been named 'blue carbon' (Nellemann, 2009).

Surface and 3-D under water off-coast farming systems

It is a farming system, growing a mix of seaweed crops and shellfish - including mussels and oysters - at different depths in the water column under the sea surface (NOAA, 2018) is useful. This farming system is in operation in several countries including USA, Japan, Italy and China (Alejandro *et al*., 2016). Two basic modules are in vogue:

1) Open 3-D farming system consisting of horizontal ropes on the water surface, anchored to hurricane-proof floats, that connect to lines underwater supporting seaweed crops and interspersed with hanging net enclosures to grow scallops and mussels (Fig. 4b). Clam and oyster cages, also connected to the surface ropes, sit on the seafloor (Gertz, 2017).

2) Closed 3-D system in which production takes place inside biospheres - balloon-like pods pegged to the seabed at about 10-meter depth. These biospheres, filled with air work like the diving bells and many shelves running around inside of the dome, to sit plant pots (Fig. 4c). This is essentially a polyculture vertical farming system which requires zero input because the sea plants filter and sequester carbon, making it a sustainable food production system. The produce beinggrown includes red cabbage, lettuce, beans, basil, strawberries, a variety of herbs and medical/cosmetic plants. Some notable advantages, of this include: constant temperature inside the pod, natural evaporation that keeps the environment humid; high carbon dioxide levels inside the pods, so high photosynthesis; and no pests or diseases, so no need for pesticides.

a: Farming on surface floating on water surface

b: 3-D open farming under water

c: 3-D close farming in under water in biospheres

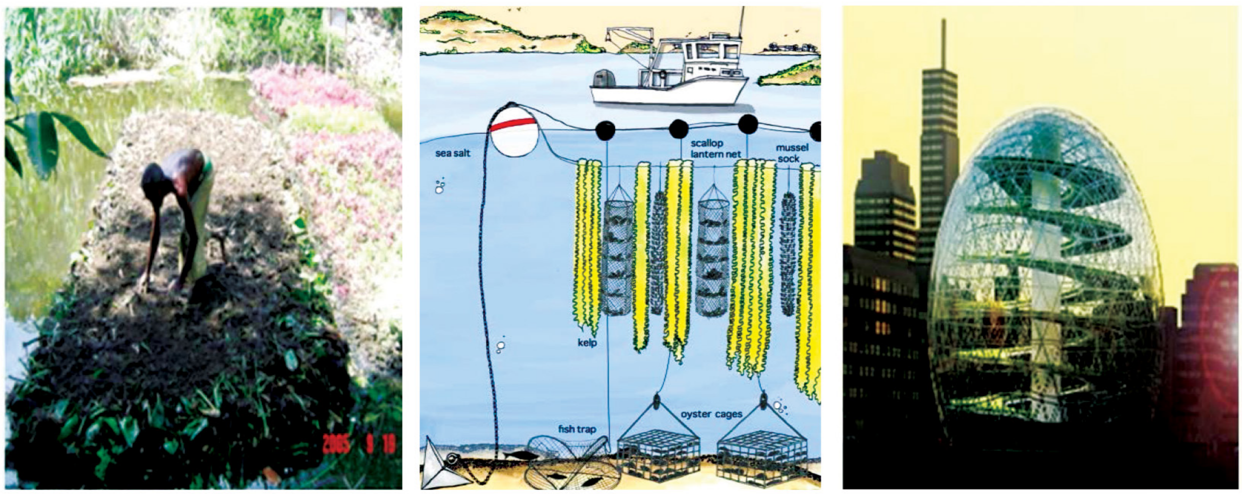


Fig. 4. *Different off-coast sea farming models (Sources: Practical Action; Gertz, 2017)*

Research deficit

Coastal ecosystem being sandwiched between the two giants -terrestrial and oceanic ecosystems, remains at the receiving ends. The approaches outlined in the previous sections, in so far as India is concerned, have not been explored much, and need continued research efforts to innovate the technologies and policies. Research into social and economic dimensions of coastal ecosystem is missing. Few important issues needing urgent attention are briefly discussed.

Regime modelling

The regime theory involves predicting behavior of estuary to changes caused by reclamation, engineering works, sea level rise and tidal range, etc. Information on this morphological evolution is required for making various management decisions and policies (Wright and Townend, 2006). Various empirical and analytical model are available for this purpose (DeVriend, 1995; O'Brien, 1931), but there are very scanty data to use them (Earnesto *et al*., 2018). Therefore, efforts are needed to study the available models and plan for data gathering mechanisms.

Hydro-salinity modelling for evaluating synergies and conflicts of crop and brackish water aquaculture

Inland coastal areas face the twin problems of tidal effects and salinity intrusion, which cause complex variations in water levels and flows in rivers, creating serious problems (Hoanh *et al*., 2009). On one hand, it adversely affects crop agriculture and fresh water aquaculture, but on the other hand opportunities for brackish water aquaculture are created. Hence, there is a need to evaluate the synergies and conflicts arising due to water and land use management in coastal zones. Needless to say, it would require estimation of nutrient loading from different watersheds, careful assessment of hydrology, lithology, soil type and land use practices (Jones, 1996). Tracking combined influence of pollution in streams, from point and nonpoint sources, caused by natural or anthropogenic processes would necessitate frequent measurement of flow and its quality (Winter and Duthier, 2000).

Estimations of ecological status of coastal and off-coast waters

Sustainable exploitation of the coastal water requires precise estimates of the ecological status represented by phytoplankton biomass (indexed by chlorophyll concentrations), total suspended matter, and dissolved organic substances, etc., which influence the light attenuation coefficient. Remote sensing has become a very valuable tool to address issues relating to assessment, quantification, and monitoring of ecosystem productivity and biodiversity, interrelationships between vegetation and water quality inestuaries, off-shore and open

Box 3: 3D Sea farming

3D farms are designed to address three major challenges: Increase off-shore production to ensure food security; transform from overfishing to restorative farming; and lay the foundation of a new blue-green economy.

The polyculture vertical farming system grows a mix of seaweeds and shellfish with zero external inputs, sequesters carbon and rebuilds reef ecosystems. These farms sit below the surface and leverage the entire water column, to produce high yields with a small footprint. These crops are used as food, fertilizer, animal feed, etc. (GreenWave, https://www.greenwave.org/greenwaveorg/)

ocean. The water column primary productivity, coastal eutrophication, and carbon budget can also be estimated from remotely sensed chlorophyll. Hyperspectral sensor prototypes, which can provide full spectral coverage over the visible wavelengths, can be made use of to discriminate optical disparities, to classify turbid waters (Hoepffner and Zibordi, 2009; Kaufmann *et al*., 2006).

Evaluation of coastal-ecosystem services

All development activities, by nature, will have physical, ecological and social impacts with trade offs attached to the activities. In general, valuation of marketable services is available, but very little work has been done for generating information on valuation of non-market services. It must be kept in mind that the global GDP is only half of the contribution that ecosystem makes to human well being (Costanza *et al*., 2014). In generating the GDP, there is invisible decline in assets, which are not measured. But sustainable development natural capital accounting (NCA), is very much needed. Decision support tools can provide useful insight on trade-offs, if they include both, the market and non-market goods and services (NRC, 2010; TEEB, 2009)

Policy framework

Common property resource is often mismanaged and the most common form of mis-management is overexploitation; and estuaries are no exception to this rule. In view of large number of stakeholders with different interests in the common property, there must exist a sound policy framework to guide the development, use and rejuvenate the coastal ecosystem (Modayil, 2012).

Epilogue

The need for more resilient coastal ecosystems, that supports the development goals without compromising with the environmental health of natural capital, can hardly be overemphasized. The three important elements in the development process are: human outcomes, natural environment, and the social environment, which remain in continuous interaction. Embedded as they are in nature, humans have fundamental influence on ecology and processes (Grumbine, 1994). If there is conflict in the human outcomes and social environment, it is a sure recipe for failure of the development process and environmental degradation; and coastal ecosystem development is no exception to this rule.

The vulnerability of the coastal societies to environmental shocks, and the consequent economic and livelihood issues caused by declining fresh water supply, increased sedimentation, erosion and flooding, and growing water pollution, can, to some extent, be minimized by creation of fresh water reservoir through estuary closure, TRM and adoption of 3-D farming into the off-coast sea waters.

No two estuaries are similar and have their own management problems. The health of the freshwater reservoir created and the truncated estuary demand appropriate coastal river catchment management. Built environment imposed on nature, must not exceed the carrying capacity of ecosystem.

The blue-green economy is an emerging concept, having tremendous potential to sequester carbon, andproduce food and other goods. Seaweed farming in coastal land, prone to floods, acidification and oxygen-depletion, would be good strategy for adaptation to climate change (Duarte *et al*., 2017). In pollution-constrained coastal land and waters, off-coast3-D farming appears to be a promising enterprise for ensuring food and livelihood security.

Finally, coastal ecosystems provide both market and non-market good and services. In order to move towards green economy, it is imperative that the condition and the value of all the ecosystem services are accounted for in formulating policies for sustainable development of the coastal system.

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