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The current status of *Halophila beccarii*: An ecologically significant, yet Vulnerable seagrass of India

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Abstract:

We reviewed the current status of a Vulnerable seagrass, *Halophila beccarii* from the coast of India using the published data from 1977-2020. We found that the seagrass, *H. beccarii* has a pan India distribution on both east and west coast. It is abundant in the intertidal silty-muddy region on the west coast, while on the east coast it is found on sandy habitats, with few exceptions of muddy habitat. *H. beccarii* was found to be associated with mangroves or smaller seagrass species within a depth limit of 1.7m. Low salinity and high nitrate levels were observed for the *H. beccarii* meadows of the west coast due to its association with mangroves. The nutrient levels in *H. beccarii* meadows of India were comparatively lower than other seagrass meadows. Most of the research on *H. beccarii* has focoused on its morphometrics (41%), reproductive (33%) and distribution (29%) along the coast of India. Reproductive traits such as flowering and fruiting varying according to the seasons of each coast due to the influence of monsoon and its associated temperature, salinity and nutrient influx. *H. beccarii* has a great potential of various bioactive compounds, which needs further investigation. Habitat disturbance, anthropogenic pollution and coastal development are the major cause of declining *H. beccarii* ecosystems in India. Significant loss of the seagrass was observed from the west coast of India due to increased coastal development activities. There is a significant need in quantifying *H. beccarii* population trends, impact of climate and anthropogenic stressors, economic values of ecosystem services and the role of ecological connectivity for better conservation and management of *H. beccarii* seascapes across India. There is a need for integration of research outcomes in policy framing for preventing the decline and further loss of this vulnerable seagrass ecosystem.

Keywords: Seagrass, Ocean Turf grass, climax communities, Indian Ocean region, IUCN, Population traits, conservation, management

Highlights:

- *H. beccarii* has a distribution on both east and west coast of India
- Habitat disturbance is the major cause for *H. beccarii* loss
- There is a critical lack of data on the population trends of *H. beccarii*
- Research on *H. beccarii* has declined after declared as Vulnerable
- Immediate actions on population trend is necessary to prevent further loss of *H. beccarii*

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1.Introduction:

Seagrasses are marine angiosperms (in the class Monocotyledoneae) that have evolved from terrestrial plants and have evolved physiological adaptation to survive underwater. These underwater marine plants form vast meadows found in all bioregions of the world except Antarctica and support a range of keystone and ecologically important marine species from all trophic levels (Orth et al., 2006). These ecosystems provide 24 different types of ecosystem services (Short et al., 2011; Nordlund et al., 2016) and contribute significantly to the health of coral reefs, mangroves, salt marshes and oyster reefs (Duke et al., 2007; Heck et al., 2008 Unsworth et al., 2010). The ecological interaction between seagrasses and the surrounding coral reef and mangrove ecosystems plays a significant role in stabilizing of the coastal environment, thus enriching the bio-physical support for other associated coastal communities (Kathiresan & Alikunhi, 2011; Guannel et al., 2016; Mishra and Apte, 2020a). Seagrasses due to their high primary production acts as source of energy for various food webs of marine ecosystems, either through direct herbivory or through detritus cycle (Hemminga and Duarte, 2000). They also transfer nutrients (N and P) and organic carbon to the deepest parts of oceans that help in sustaining various trophic levels (Duarte et al., 2005). Their carbon sequestration capacity is 35 times faster than terrestrial plants and they store more carbon (Duarte et al., 2013) and contribute significantly to coastal “Blue Carbon” (McLeod et al., 2011) that helps in mitigation of climate change (Howard et al., 2014). Seagrass ecosystems form important habitat and nurseries for various fish population, endangered sea cows and seahorses (Green and Short, 2003; Cullen-Unsworth et al., 2018) that directly support artisanal fisheries and the livelihoods of millions of coastal communities in tropical regions (Björk et al., 2008; Nordlund et al.,2017). Along with supporting fisheries and acting as carbon sink, seagrass meadows protect the shoreline diminishing wave energy and trapping sediments (Ondiviela et al., 2014), regulating nutrient cycling (Costanza et al., 2014) and acting as bioindicators of coastal pollution (Lewis and Devereaux, 2009).

Additional ecosystem services of seagrasses include many features such as filtration of water from suspended sediments, recycling of nutrients through leaves, rhizomes and roots (Short et al., 2011). Recent reports have proved seagrass can also filter coastal water from pathogens that can reduce contamination in seafood and can reduce coral bacterial diseases (Cullen-Unsworth and Unsworth, 2018).Though seagrass ecosystems are valuable in terms of ecosystem functioning, they have not received international and social attention unlike other charismatic ecosystems, such as coral reefs and mangroves in terms of research, management and conservation practices (Nordlund et al., 2018). Globally 30% of seagrass meadows have been lost in the last two-four decades (Murray et al., 2012; Howard et al., 2014) due to a combination of anthropogenic disturbances and global change scenarios and a further 30-40% loss is predicted to be lost in the next 100 years (Waycott et al., 2009; Pendleton et al., 2012). Short et al., (2011) provided valuable status of 67 seagrass species worldwide with extinction risk assessment and *Halophila beccarii* was one of the seagrasses that was on vulnerable list of International Union for Conservation of Nature (IUCN) in South-East Asia, including the coast of India. The loss of *H. beccarii* seagrass meadows are directly linked through habitat modification or indirectly linked to human induced disturbances (IUCN, 2010).

India and its vast extensive coastal ecosystems are part of South Asia (including other countries such as Pakistan, Sri-Lanka, Bangladesh and Maldives) and South-East Asia [due to Andaman and Nicobar Islands (ANI)] in the Indian Ocean region (Patro et al., 2017; Fortes et al., 2018). These diverse coastal ecosystems surrounding India consist of mangroves, coral reefs, salt marsh and seagrasses. While much of the attention has been towards mangroves and coral reefs, similar significant ecosystems such as seagrass are poorly understood (Jagtap, 1996; Patro et al., 2017). In India seagrass beds are declining due to human induced disturbances (Thangaradjou et al., 2009; Nobi et al., 2011; Kaladharan and Anasukoya, 2019; Mishra and Apte, 2020a) and lack of interest from scientific community on seagrasses has added to the foes (Jagtap et al., 2003; Mathews et al., 2010a; Patro et al., 2017; Bhatt and Patro, 2018).

The seagrass ecosystems of India consist of 16 out of 19 species found in South-east Asia, covering an area of 516.59 sq Km (Geevarghese et al, 2018) up to a depth limit of 21 m (Bayyana et al., 2020). *Halophila beccarii* Aschers. commonly known as 'Ocean Turf Grass' is distributed on both east and west coast of India (Parthasarathy et al., 1988; Jagtap, 1991; Jagtap et al., 2003) including the islands of Andaman and Nicobar (Savurirajan et al., 2015). Except the Indian coast, they also have a wide distribution in South-East Asia (Short et al., 2011) including their presence from the coast of Sri Lanka (Udagedra et al., 2017), Bangladesh (Abu Hena and Short, 2009; Masum Billah et al., 2016), Malaysia (Zakaria et al., 2002; Fakhrulddin et al., 2013), Philippines (Liao and Geraldino., 2020), Thailand (Aye et al., 2014; Hiranphan et al., 2020) and Viet Nam (Hang Phan et al., 2017). *H. beccarii* acts as one of the pioneer species in the ecological succession process leading to mangrove formation of the Indian coast (Jagtap, 1985; Untawale and Jagtap, 1991; Parthasarathy et al., 1988, 1991). The plant is tolerant to wide fluctuations in salinity, temperature and tidal fluctuations and requires high nutrient content (Untawale and Jagtap, 1981; Jagtap, 1991; Greve and Binzer, 2004; Fakhrulddin et al., 2013) for growth and production. However, *H. beccarii* is listed as Vulnerable category under the IUCN Red List (Short et al., 2011) and it has been found as endangered in Sri Lanka (Udagedra et al., 2017) and locally extinct in Philippines (Liao and Geraldino., 2020). This suggests the vulnerability of this small seagrass species is increasing around the Indian Ocean region. Saying that, there is a significant knowledge gap on *H. beccarii* research in India compared to other seagrass species like *Thalassia hemprichii*, *Cymodocea serrulata*, *C. rotundata*, *Enhalus acoroides*, *Halophila ovalis*, *H. ovata* and *H. decipens*.

Therefore, the objective of the proposed review is to collect various information of *H. beccarii* ecosystems from literature survey and derive the current knowledge gaps on *H. beccarii* research. We will use the DAPSIR model developed by Smith et al., (2016) to understand the effects of various drivers that have increased the Vulnerability of this seagrass around the coast of India and propose feasible management practices for better conservation and management of these seascapes.

2. Materials and Methods

We searched various search engines including Scopus, Google Scholar, ISI Web of Knowledge, Science Direct, JSTOR and Research Gate with key words like *Halophila beccarii*, India, distribution, diversity, carbon sequestration, bioactive compounds, morphometrics and ecosystem services. Single words and a combination of two or more words were used on the various search engine platforms. Searches included all articles published until or cut-off date 27th July 2020. Data was collected from peer reviewed, grey literature and various reports and were compiled and disseminated according to the category they fit in. We found a total of 187 research publications on seagrass ecosystems of India between the year 1977 to 2020 and identified further 38 relevant publications from the references of these articles. Then, we read through the full texts to sort out the relevant publications regarding to the ecology of *Halophila beccarii*. Other than ecology we also sorted out the articles related to various biochemical, physico-chemical, morphometrical, trace elements and ecosystem services articles. The units/values obtained from the articles related to various parameters collected from literature review were converted to similar units for better comparison. The data generated from literature survey was used with the DAPSIR conceptual framework (Smith et al., 2016; Elliott et al., 2017) to provide management and assessment issues for *H. beccarii* ecosystems of India. The DAPSIR framework uses a combination of Drivers-Activities-Pressure-State-Impact and Response parameters to assess the impact of multiple threats and their cumulative impacts for better management of ecosystems by the local authorities (Griffiths et al., 2020).

3.Results and Discussion

We found a total of 54 number of publications that was related to various studies of *H. beccarii* (Fig.1). *H. beccarii* studies comprised 9.5% of the total seagrass research in India, while *Cymodocea serrulata (11.6%), Syringodium isoetifolium (11.3%)* and *T. hemprichii* (10.5%) had higher number of studies respectively. The higher percentage of studies belonging to the above three seagrass species is directly related to their pan India distribution and presence of large meadows (Jagtap et al., 2003; Purvaja et al., 2008). A total of 54 (9.5%) number of publications were found for *H. beccarii,* out of which 26 number of publications were based on individual *H. beccarii* studies, whereas 32 were part of mixed seagrass species. There were 10 out of 26 and five out 36 review articles, from both individual and mixed studies respectively. In the decade wise publications, the first record of seagrass research in India was based on *H. beccarii* before 1980s, thus consisting 100% (Fig.2). In the last four decades seagrass research in India has grown significantly, with *H. beccarii* consisting around a ca. of 25% of research publications. However, research publications on *H. beccarii* has decreased by 7% after it was declared as Vulnerable by IUCN in 2011 (Fig.2). The various categories of studies on *H. beccarii* is presented in Fig.3 and discussed below.

3.1. *Physico-chemical parameters*

The physico-chemical parameters of both east and west coast are different (Table 1). The depth limit for *H. beccarii* on the west coast was up to 1 m, while that on the west coast was up to 1.7 m. However, there were certain variables which were not reported from the west coast, such as water depth, photosynthetic active radiation and certain nutrients (Table1), but are reported from the east coast. This bias in data made it difficult to compare these variables with other seagrass ecosystems of India, reported by Thangaradjou et al., 2018. The salinity range (5-35) on the west coast (Untawale and Jagtap, 1977; Jagtap et al., 2003) is more fluctuating compared to that of east coast (Bharathi et al., 2014; Pati et al., 2014 and references there in). *H. beccarii* meadows of the west coast have 1.5-fold higher nitrate levels compared to the east coast (Table 1). This difference can be due to the presence of *H. beccarii* meadows alongside mangroves on the west coast, while that of east coast is mostly with seagrasses (Jagtap and Untawale, 1977; Jagtap et al., 2003). However, most of the environmental variables such as salinity and nitrate levels data from the west coast are more than three decades old and there is a significant need of new data collection from the *H. beccarii* meadows is necessary from the west coast. Interestingly, when compared with other seagrass meadows of India, the nutrient levels in *H. beccarii* meadows on each coast is comparatively lower (Table 1).

3.2. *Distribution of H. beccarii in India*

H. beccarii commonly called as Ocean Turf Grass, is a small submerged creeper that belongs to family Hydrocharitaceae and has a pan India distribution on the east coast and west coast including the islands of Andaman and Nicobar (Fig.3and 5). *H. beccarii* distribution comprises 29% of studies on both coast (Fig.4). The seagrass was first was recorded from Chilika lagoon, Odisha in the east coast (den Hartog 1971) and on the west coast by Untawale and Jagtap, (1977) at Mandovi Estuary, Goa. Untawale and Jagtap, (1981) proposed that the plant migrated to the west coast from other locations of west coast of Indian Ocean through a peculiar phenomenon of 'one jump migration', where the plant transports and establishes itself through plant fragmentation (Lipkin, 1972). Savurirajan et al., (2015) recorded this phenomenon at their study site of Hado bay in Andaman and Nicobar Islands of India, where a cyclone damaged site of *H. beccarii* was naturally restored from plant fragments from another site and Hang Phan et al., (2017) observed this phenomenon in the lagoon of Viet Nam. This short distance dispersal of *H. beccarii* plays a significant role in its migration and meadow maintenance and colonisation (Hang Phan et al., 2017).

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Through its distribution on both coast of India, *H. beccarii* has been found in shallow sandy and silty or muddy or clayey habitat within a depth limit from zero to 1m on the west coast (Parthasarathy et al., 1988; Jagtap, 1991) and one to 1.7 m on the east coast (Jagtap, 1996; Mathews et al., 2010), that is reflected through its presence near to mangrove zonation or mangrove mudflats. This association of *H. beccarii* was observed at Pichavaram mangrove area, Tamil Nadu on the east coast of India (Parthasarathy et al.,1988,1991; Bharathi et al., 2014) and the mangrove zones of Mandovi estuary, Goa (Untawale and Jagtap, 1977; Jagtap and Untawale, 1981; Jagtap, 1991), Shirgaon creek mangroves, Achra creek and Kolamb mangrove creek, Maharashtra (Jagtap, 1991, Apte et al., 2016), Kumbala and Kadalundi estuary, Karnataka (Kaladharan and Asokan, 2012) on the West coast of India (Fig.3 and 5). Though *H. beccarii* is mostly associated with mangrove areas, this seagrass was also found associated with other seagrasses such as *Halophila ovata, Halophila ovalis, Halodule uninervis* and *Halodule pinifolia* in Chilika lagoon, Odisha (Sahu et al., 2014; Pati et al., 2014), Pullicat lake, Andhra Pradesh (Vani et al., 2018), Palk bay and Gulf of Mannar, Tamil Nadu, (Ramamurthy, 1981; Raghavan and Deshpande, 1982; Parthasarathy et al., 1988, 1991), Puducherry coast (Kalimuthu et al., 1995) and Hado bay, Andaman and Nicobar Islands (Savurirajan et al., 2015) on the east coast of India (Fig.3). Other than mangroves and seagrass, *H. beccarii* was also found being associated with seaweeds, such as *Hypnea valentia* on the east coast (Parthasarathy et al., 1988; Kalimuthu et al., 1995) and *Enteromorpha linza* in Kadalundi estuary, west coast (Kaladharan and Asokan, 2012). This association with mangroves or seaweed (e.g. *Ulva intestinalis*) has also been observed from the coast of Bangladesh (Abu Hena and Short, 2009; Abu Hena et al., 2013) and Malaysia (Zakaria et al., 2002). Being present in the shallow intertidal region, the plant has developed adaptation mechanisms to avoid desiccation during low tides by utilizing the sediment pore water content and forming thin layer of water films on leaf surface, for which the presence of leaf hairs plays a significant role (Untawale and Jagtap, 1981; Jagtap, 1991).

3.3. Morphometric traits

The morphometric features of *H. beccarii* is the most studied variable, comprising 41% compared to other variables from India (Fig.4) even though there is difference in number of publications from both east and west coast of India (Table 1). Various morphometric features of *H. beccarii* is better represented from east coast of India compared to that of the west coast. However, certain morphometric features like presence of epidermal spines (7-12 nos.) are only reported from the west coast (Untawale and Jagtap, 1977) and other features like canopy height and productivity are reported only from east coast (Bharathi et al., 2014). Various morphometric features like leaf thickness, petiole thickness, internode diameter, root length and root diameter are reported for the first time by Savurirajan et al., (2015), when they first recorded *H. beccarii* from the Andaman and Nicobar Islands (Table 1). The number of leaves of *H. beccarii* and leaf length are almost similar between the both coasts. However, the leaf width on the west coast is 5-fold higher than of the east coast (Untawale and Jagtap, 1977; Kaladharan, 2004). Among the various morphometric features, shoot density, above-ground (AG) and below-ground (BG) biomass are most studied on the east coast. The average shoot density of *H. beccarii* on the east coast is around 9 to 37-fold higher than that of the west coast. In general, we observed that AG biomass of *H. beccarii* was higher than BG biomass on the east coast, while there are no reports on BG biomass from the west coast. The AG-biomass of *H. beccarii* from the west coast was lower than that from the east coast. The general patten of higher AG than BG biomass has also been observed for *H. beccarii* around the coast of Bangladesh and Thailand respectively (Abu Hena et al., 2007; Aye et al., 2014).

3.4. Reproductive traits

H. beccarii reproductive traits constitute 33% of publications recorded from both east and west coast comprising a total of three number of publications (Fig.4). In general, the reproductive features of the seagrasses of India has been less explored. We found that, *H. beccarii* has both sexual and asexual mode of replication on the Indian coast (Jagtap and Untawale, 1981; Parthasarathy et al., 1988, 1991) and from the coast of Bangladesh and Viet Nam (Zakaria et al., 2002; Hang Phan et al., 2017). Sexual reproduction plays an important role in maintaining the genetic diversity, while asexual reproduction through clonal propagation helps in maintaining the meadows (Zakaria et al., 2002; Hang Phan et al., 2017). *H. beccarii* is monoecious and the flowers are strongly protogynous, with male and female flowers occurring in successive lateral shoots (Parthasarathy et al., 1988). The flowering seasons of *H. beccarii* in India varies between the east and west coast. In the east coast both flowering and fruits were observed within *H. beccarii* population from Feb-April (Parthasarathy et al., 1988, 1991), whereas in the west coast flowering and fruits have been observed as late as October-November (Jagtap and Untawale, 1981; Kaladharan, 2004).

The flowering of *H. beccarii* is followed by formation of large fruits, in which the number of seeds vary from one to four (Parthasarathy et al., 1988; Kaladharan, 2004). The fruits of *H. beccarii* are ellipsoidal, trilocular, 3.5mm length and 1.5mm width (Parthasarathy et al., 1988; Kaladharan, 2004). However, these differences in flowering and fruiting on east and west coast of India, can be attributed to the onset of monsoon and associated salinity and temperature changes (Jagtap and Untawale, 1981; Parthasarathy et al., 1988; Jagtap et al., 2003). The effects of monsoon are correlated with large inputs of freshwater in the estuarine zone and reduction in salinity levels, which affects *H. beccarii* reproductive features (Jagtap, 1981). Reproductive traits of *H. beccarii* plays a significant role in short dispersal of the seeds (Hang Phan et al., 2017) and a better understanding of the effects of various habitat disturbances on reproductive traits of *H. beccarii* is essential from the coast of India for better management practices, which has been recently reported for other mangrove associated seagrass such as *T. hemprichii* from the coast of Andaman and Nicobar Islands (Mishra and Apte, 2020b).

These differences in the morphometric features and reproductive traits of *H. beccarii* on the east and west coast can be due to three factors, i) the number of studies that have reported the morphometric and reproductive traits from east coast are higher than that of the west coast resulting in higher or lower average values ii) the influence of habitat and environmental variables, as most of the distribution of *H. beccarii* on the west coast is being associated with mangroves where the habitat disturbance is higher resulting in lower morphometric values, where that on the east coast is mostly with other seagrasses and seaweeds with lower disturbances and iii) the influence of monsoon and its associated salinity, temperature changes and nutrients influx , which is higher on the west coast compared to the east coast. This explains the wider leaves *H. beccarii* on the west coast.

3.5 Biochemical property and bioactive compounds

A pan India study on use of seagrass in local cultures revealed that *H. beccarii* is generally not used in local ethnobotanical purposes (Newmaster et al., 2011) resulting in only 7% of all bioactive compounds studies in India. *H. beccarii* being small in size compared to other seagrasses like *Enhalus acoroides* and *Syringodium isoetifolium* and their presence in muddy habitats restricts access for use in local cultures (Newmaster et al., 2011). Secondly, the nutritional value of *H. beccarii* leaves (29.16 K cal g^{-1}) are low with high tannin and phenol content that makes it non-edible without cooking (Pradheeba et al., 2011).However, this plant has immense potential in providing various bioactive compounds, which have been identified recently, with bioactive compounds as antidiabetic (Vani et al., 2018), anti-dengue fever treatment (Ali et al., 2012), antioxidants (Neelima et al., 2015; Kar et al., 2019) and against various human pathogens (Kavitha et al., 2020). Seagrasses like *T. hemprichii* that are also found associated with mangroves (Mishra and Apte, 2020a) have been found to be a good source of bioactive compounds (Mishra and Mohanraju, 2018).

3.6 Ecological significance of H. beccarii

H. beccarii being present in the upper intertidal zone supports a rich biodiversity of invertebrates, such as nematodes, polychaetes and molluscs (Ranjitham et al., 2008; Nedumaran and Manokaran, 2009; Mathews et al., 2010a). H. beccarii associated biodiversity studies represent 26% of the total seagrass studies in India. However, much of these studies are part of field surveys including other seagrasses. We found an interesting pattern of species association with *H. beccarii*, where the invertebrate species richness and abundance were higher during monsoon season (Nedumaran and Manokaran, 2009). This suggests that when other seagrass species (such as *Halodule pinifolia* and *Halophila ovalis*) have a decrease in biomass, density and associated species diversity, *H. beccarii* can invest in its productivity and increase its growth of morphometric features during monsoon due to high input of nutrients from land run-off (Jagtap, 1996; Jagtap et al., 2003; Mathews et al., 2010a; Manikandan et al., 2011a,c) that directly influences the shoreward migration of invertebrates to *H. beccarii* patches (Nedumaran and Manokaran, 2009; Mathews et al., 2010a). Other than serving as habitat for invertebrates, *H. beccarii* also serves as a nursery for various fish juveniles and acts as a food source for marine mega herbivores such as turtles and dugongs (Anand, 2012; Gamboj, 2012; Singh et al., 2004 and references therein).

H. beccarii being present at the land and sea interface possess higher bioindication potential to assess metal contamination of coastal ecosystem. However, in India there is only one research article from the west coast reporting about the trace metals (Ca, Cu, Fe, K, Mg, Mn, Na, Ni, Sr and Li) concentration in *H. beccarii* (Jagtap, 1983). The various other ecosystem services of *H. beccarii* are presented in Table 3. There is a significant gap in ecosystem studies of *H. beccarii* population regarding their carbon sequestration potential as research on seagrass carbon sequestration capacity has been very limited in India (Ganguly et al., 2017), even though the potential of *H. beccarii* is very high. Similarly, there is little information on their primary productivity of *H. beccarii* in India (Ghevade and Joshi, 1980).

H. beccarii play an important role in coastal protection and sediment stabilization (Jagtap et al., 2003; Kaladharan et al., 2018), but more studies are required on this aspect to understand the various process involved in the coastal protection services. *H. beccarii* and its association with mangroves or seagrasses acts as ecological engineers to enhance the water quality and increase associated biodiversity of coastal ecosystems (Jagtap et al., 1983; Mathews et al., 2010a; Purvaja et al., 2018). This ecological connectivity between mangrove-seagrass has been recently reported from India (Mishra and Apte, 2020a; Mishra and Kumar, 2020c) and should be further explored using *H. beccarii*, as this seagrass forms climax communities that helps in establishing mangrove population. This ecological connectivity between *H. beccarii*-mangroves can be utilised for better management and restoration of both mangroves and seagrass ecosystems of India.

3.6. H. beccarii Genetics

Karyomorphological studies of *H. beccarii* indicated the presence of diploid (2n=18) chromosomes (Vanitha et al., 2016), whereas genetic diversity and phylogeny of *H. beccarii* was carried out by Kar et al., (2018) indicating its polymorphic nature. However, both of these molecular studies have been carried out on *H. beccarii* from Tamil Nadu and Odisha on the east coast respectively. A more detailed study covering the sampling of this species from the

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entire coast of India is necessary to understand the genetic variation of *H. beccarii*, as local environmental variables determine both phenotypic plasticity and genetic response of seagrass (Nguyen et al., 2015; King et al., 2018). Supporting this evidence is a recent study on karyomorphological properties of *H. beccarii* from the coast of Thailand, that revealed in difference of *H. beccarii* karyomorphological properties from India and China (Hang Phan et al., 2017).

3.7. Threat analysis using DAPSIR model

Being present at the near interface of land and sea interaction with fragile muddy habitats, *H. beccarii* is prone to natural disasters and anthropogenic disturbances. Using the DAPSIR model, we found three main drivers, that have various Activities and Pressures associated with them which were interlinked and can have serious negative impacts on the *H. beccarii* population of India (Fig.6). The main threats (Drivers) to *H. beccarii* are through marine food provisioning and coastal urbanisation, which have various activities and pressures on the *H. beccarii* ecosystem. Both these drivers are based on various Activities, but we found that habitat disturbance consists a majority of the Activities, due to fishing, coastal development, sand dredging, boat anchoring, conversion of coastal habitats into salt pans and trampling due to tourism (Fig.6). These disturbances combined together mostly created multiple Pressure on the seagrass habitats and associated biodiversity, for example fishing (Activities) cause abrasion (Pressure) and that leads to habitat fragmentation and decrease in health and resilience of *H. beccarii* meadows (State Change). The various Activities and its associated Pressure and State Change are diagrammatically represented in Fig.6. However, the DAPSIR model suggests possible Response from management, which in case of *H. beccarii* is to reduce and minimize the effects of habitat disturbance.

In India a significant loss has been detected for this species due to various coastal developmental activities, for example, *H. beccarii* was found to be present in the Pichavaram mangrove area when Parthasarathy et al., surveyed in 1988, but the same species was absent in 2014, when surveyed by Bharathi et al., (2014) as a result of increase in fishing activities. A fundamental issue in India about environmental management of coastal resources is uncertainty and lack of interest of the scientific community in seagrass ecosystems, when compared to coral reefs or mangroves (Jagtap, 1996; Purvaja et al., 2008; Ganguly et al., 2017). Other than the various anthropogenic activities, climate change as a stressor is going to induce changes in thermal and salinity regimes (Fig.6), which will directly impact the productivity of *H. beccarii* ecosystems of India. Other than these pressures, the east coast of India is constantly battered by tropical cyclones and the seagrass ecosystems suffer a lot, for example in the Chilika lagoon, Odisha are the most suffered ecosystem (Banerjee et al., 2018).

4. Conservation and Management

The loss of biodiversity under the influence of multiple stressors is pushing ecosystem boundaries and associated biodiversity towards mass extinction worldwide (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, (IPBES), 2019) which emphasizes the importance of biodiversity conservation from anthropogenic disturbances and climate change scenarios. *H. beccarii* as a seagrass ecosystem has potential for climate change mitigation through carbon sequestration and storage capacity (Macreadie et al., 2019; Serrano et al., 2020). Secondly, it can provide refugee to various calcifying organisms from ocean acidification (Bergstorm et al., 2019). Most importantly its ecological connectivity with mangroves can influence resilience and adaptation to various climate change scenarios (Gillis et al., 2017). These features of seagrass ecosystem along with 24 different types of ecosystem services places seagrass as the third most important ecosystem in the world (Nordlund et al., 2016), which has called for better conservation and management of seagrass ecosystems worldwide (UNEP, 2020).

However, for *H. beccarii* the importance of conservation and management is more significant due to the Vulnerability of its population. Lack of population trends data in India on *H. beccarii* should be addressed. The seagrass research community of India has to come out of their shells to work collectively and collaborate with various regional research centres for better monitoring of *H. beccarii* ecosystems of India. This lack of interest is reflected over the last four decades of seagrass research in India, with more than 73.8% of seagrass publications in India is from Palk bay and Gulf of Mannar in the state of Tamil Nadu, even though seagrass ecosystems distribution is diverse (Fig.3). This lack of interest for seagrass research has been highlighted by various authors (Jagtap et al., 2003; Mathews et al., 2010a; Thangaradjou and Bhatt, 2018).

However, for better management of *H. beccarii* ecosystem of India, there is a need of better integration of research and policy (Ramesh et al., 2018; Koshy et al., 2018). The DAPSIR model indicated better management practices of *H. beccarii* ecosystems are needed for reducing the impacts of various anthropogenic and climate change impacts. Though India has a National Environmental Policy (NEP, 2006) of the Government of India, it does not highlight the importance of seagrass ecosystems of India. However, the National Policy on Marine Fisheries (NPMF, 2017) clearly emphasizes the importance of seagrass ecosystems and its protection from anthropogenic impacts. Recently, the Ministry of Environment Forest and Climate Change of the Government of India has proposed an An Inventory of Seagrass and Seagrass Ecosystems of India (Koshy et al., 2018). This inventory proposed a series of guidelines to highlight the importance of seagrass ecosystems in India along with the valuation of their ecosystem services and long-term monitoring. These various initiatives need to be implemented properly and long-term research on *H. beccarii* from both east and west coast of

India is the need of the hour. Saying that, the critical knowledge gaps on *H. beccarii* research in India include

- Lack of *H. beccarii* population trends such as growth rate, productivity, recruitment and mortality rate
- Lack of scientific research on impact of multiple stressors (various anthropogenic pollutants and habitat disturbances) on *H. beccarii* eco-physiological functions
- Impact of ocean acidification on the population structure and carbon sequestration capacity of *H. beccarii* meadows
- Facilitative interactions between bivalves and *H. beccarii* ecosystems that reduce sulfide toxicity and maintains seagrass growth
- Effect of global warming and sea-surface temperature increase on *H. beccarii* photo-physiology
- Role of *H. beccarii* in carbon sequestration and storage and its economic gains
- Monitoring of *H. beccarii* meadows across the coastal seascape as coral reefs or mangroves
- Understanding the role of ecological connectivity between *H. beccarii* and mangroves in maintaining commercial fisheries
- Quantifying the economic values of various ecosystem services of *H. beccarii* ecosystems
- Understanding the genetic diversity and molecular adaptation to various stressors is important to decode the resilience of *H. beccarii* to multiple stressors

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Table.1 Range of various environmental variables recorded for *H. beccarii* from the west and east coast of India and compared with other seagrass ecosystems reported by Thangaradjou et al., (2018). Photosynthetic active radiation (PAR). No record (nr)

Environmental variables	**Range**		**References**		**Thangaradjou et al., 2018**
	West coast	**East coast**	**West coast**	**East coast**	
Depth	0-1	1-7	k	d	0-15
Water pH	nr	7.49-8.35		a, b, c, e, f	6-8.9
Water temperature (°C)	12.2-38.9	27.10-33.2	d	a, b, c, e, f	24-34.5
Salinity	5-35	26.32-30.06	i, j	a, b, c, e, f,	18.32-39.4
PAR (LUX)	nr	900-1100	nr	a	280-1440
Nitrate (µ M)	7.2	0.55-4.09	h	a, e, f	0.25-19.2
Nitrite (µ M)	nr	0.88-3.04	nr	a, e, f	0.03-7.32
Phosphate (µ M)	nr	0.98-4.32	nr	a, e, f	0.12-7.32
Silicate (µ M)	nr	3.29-8.99	nr	a, e, f	0.6-18.99

a) Bharathi et al., 2014; b) Pati et al., 2014; c) Nedumaran and Manokaran, 2009; d) Jagtap, 1996; e) Sridhar et al., 2008; f) Sridhar et al., 2009; g) Jagtap, 1991; h) Jagtap and Untawale, 1981; i) Untawale and Jagtap, 1977; j) Jagtap et al., 2003; k) Mathews et al., 2010a

Table 2. Morphometric variables, biochemical properties, of *H. beccarii* recorded from the coast of India. Dry weight (DW), Carbon (C), Not recorded (nr), Carbon (C): Nitrogen (N), Above ground (AB), Below ground (BG)

Variables	**Range**		**References**	
a. Morphometrics	**West coast**	**East coast**	**West coast**	**East coast**
No. of leaves	3-10	4.66-9.33	d	a, b, c
Leaf length (cm)	1-1.07	0.48-1.17	d, e	a, b
Leaf width (mm)	1.5-20	0.91-3.44	d, e	a, b
Leaf thickness (mm)	nr	0.05-0.13		a
Epidermal spines (no.)	7-12	nr	d	-
Canopy height (cm)	nr	4.5	-	f
Petiole length (mm)	7-14	8.57-13.85	d, e	a, b, c
Petiole thickness (mm)	nr	0.06-0.28	-	a
Internode length (mm)	nr	9.11-29.27	-	a,b
Internode diameter (mm)	nr	0.33-0.68	-	a
Rhizome diameter (mm)	nr	0.39-0.65	-	a, b
Root length (mm)	nr	9.25-33	-	a
Root diameter (mm)	nr	0.07-0.22	-	a
Shoot density (no. m^{-2})	420	3917-15707	l	a, c, g, h, i, j, k
AG Biomass (g DW m^{-2})	26.44	19.4-41.01	m	a, c, f, g, i, j, k
BG Biomass (g DW m^{-2})	-	17.07-33.71	-	a, c, f, g, i, j, k
Productivity (g C m^{-2} y^{-1})	nr	5	-	f
b. Biochemical				
Total chlorophyll (a+b)	nr	0.04-0.13		n
Protein (mg g^{-1})	393.12	0.70-132.0	p	n, o
Carbohydrate (mg g^{-1})	476.18	2.93-161	p	n, o
Lipid (mg g^{-1})	nr	0.9-1.05	-	n, o
Tannin (mg g^{-1})	nr	1.03-1.35	-	n, o
Phenol (mg g^{-1})	nr	2.1-3.75	-	n, o
Organic carbon (%)	30	nr	p	-
C: N	03:07	nr	p	-

a) Savurirajan et al., 2015; b) Ramamurthy et al., 1992; c) Parthasarathy et al., 1998 d) Untawale and Jagtap, 1977; e) Kaladharan, 2004; f) Bharathi et al., 2014; g) Mathews et al., 2010; h) Manikandan et al., 2011a; i) Manikandan et al., 2011b; j) Manikandan et al., 2011c; k) Kalimuthu et al., 1995; l) Kaladharan et al., 2018; m) Jagtap and Untawale, 1981; n) Pradheeba et al., 2011; o) Nobi et al., 1993; p) Jagtap and Untawale, 1981

Table.3 Various ecosystem services of *H. beccarii* from the coast of India. Ecosystem service variables are adopted from Nordlund et al., (2016) and modified for *H. beccarii* for Indian scenarios. Water Quality Index (WQI), Sea Life Index (SLI)

Sl. no	Ecosystem Service	Observations	References
1	Fish habitat	Nursery and habitat	Nair, 2002; Singh et al., 2004; Mathews et al., 2010; Kaladharan and Asokan, 2012; Kaladharan et al., 2018
2	Invertebrate habitat	Habitat for invertebrates like polychaetes, nematodes, gastropods, Molluscs, etc	Nair, 2002; Singh et al., 2004; Ranjitham et al., 2008; Nedumaran et al., 2009; Mathews et al., 2010a; Kaladharan et al., 2018; Meeran et al., 2018
3	Nursery (habitat for Juveniles)	Habitat for juveniles,	Nair, 2002; Singh et al., 2004; Mathews et al., 2010a; Kaladharan et al., 2018
4	Seagrass as food for coastal organisms (turtles, dugongs and herbivore fishes)	Food for dugongs and turtles	Gamboj, 2012; Anand, 2012; Kaladharan et al., 2018
5	Pharmaceuticals/Bioactive compounds	High phenolic and flavonoid compounds, antioxidants, Antidiabetic activity, anticancer compounds	Neelima et al., 2015; Vani et al., 2018; Kar et al., 2019; Vanitha et al., 2020
6	Coastal protection	For protection of sediment associated fauna	Kaladharan et al., 2018
7	Sediment stabilization	Soil amendments	Jagtap et al., 2003; Kaladharan et al., 2018
8	Productivity	Primary production, oxygen production	Ghevade and Joshi, 1980; Nobi 1993
9	Ecological connectivity with mangroves	Healthy seagrass biodiversity	Jagtap et al., 2003; Purvaja et al., 2018
11	Source of information (water quality, bioindicator of coastal contamination)	Use of seagrass ecosystems for WQI, SLI, Bioindicators of Metals	Mathews et al., 2010a; Purvaja et al., 2018, Jagtap, 1983

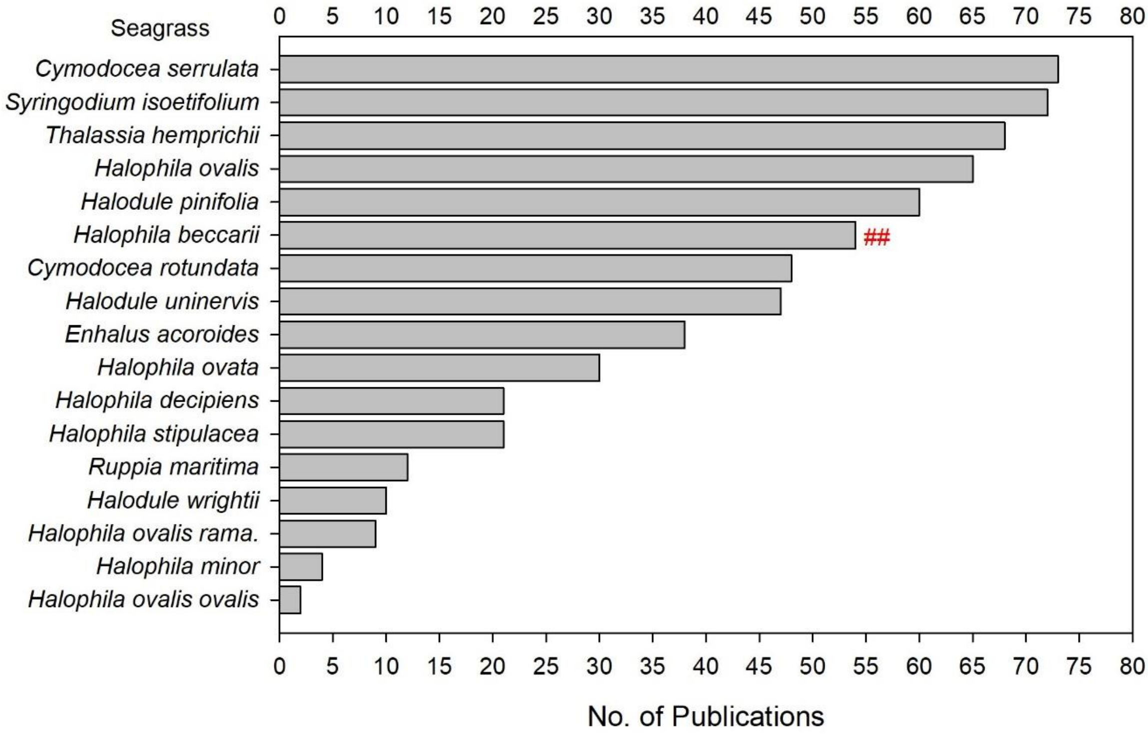

Fig.1. Number of publications from 1970 to 2020 on various seagrass species of India including *H. beccarii* (red #).

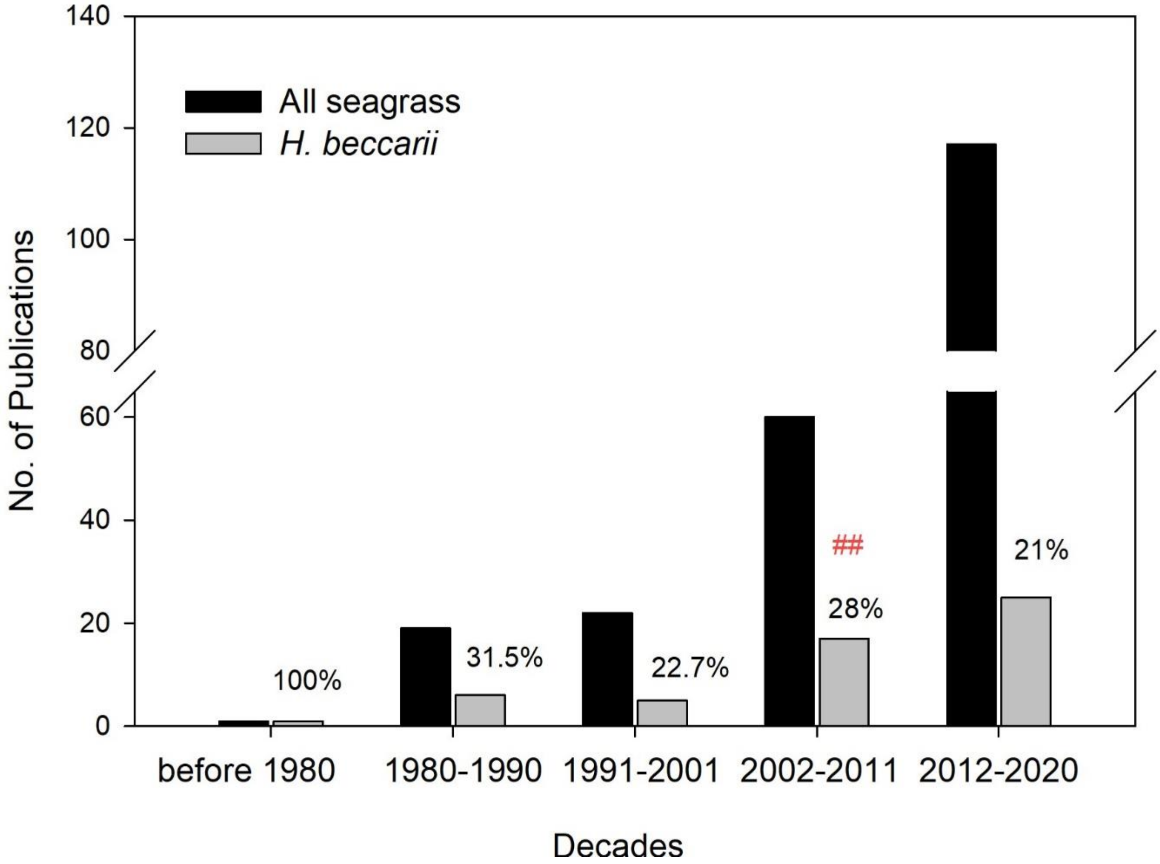

Fig.2. Decade wise number of publications on *H. beccarii* from the coast of India. The number of *H. beccarii* publication out of the total number of publications for each decade is provided as percentage. Red # indicate the year *H. beccarii* was declared as Vulnerable by IUCN.

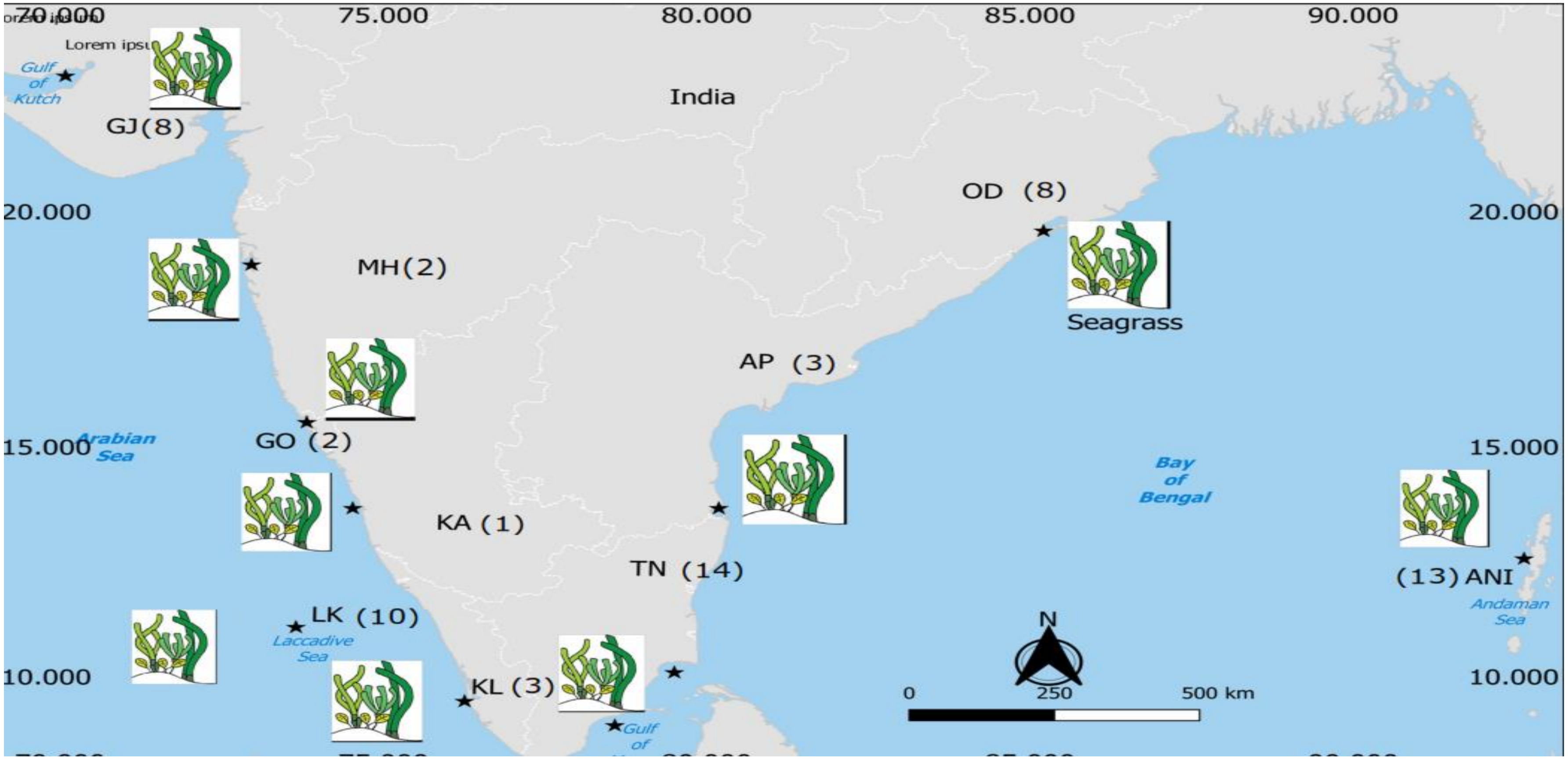

Fig.3. Map showing the States and islands that have seagrass ecosystems around the east and west coast of India. Numbers in bracket for each state indicate the number of seagrass species found in each state including *H. beccarii*. Odisha (OD), Andhra Pradesh (AP), Andaman and Nicobar Islands (ANI), Tamil Nadu (TN), Kerala (KL), Lakshadweep island (LK)*, Karnataka (KA), Goa (GO), Maharashtra (MH), Gujarat (GJ). *There is no report for presence of *H. beccarii* at LK.

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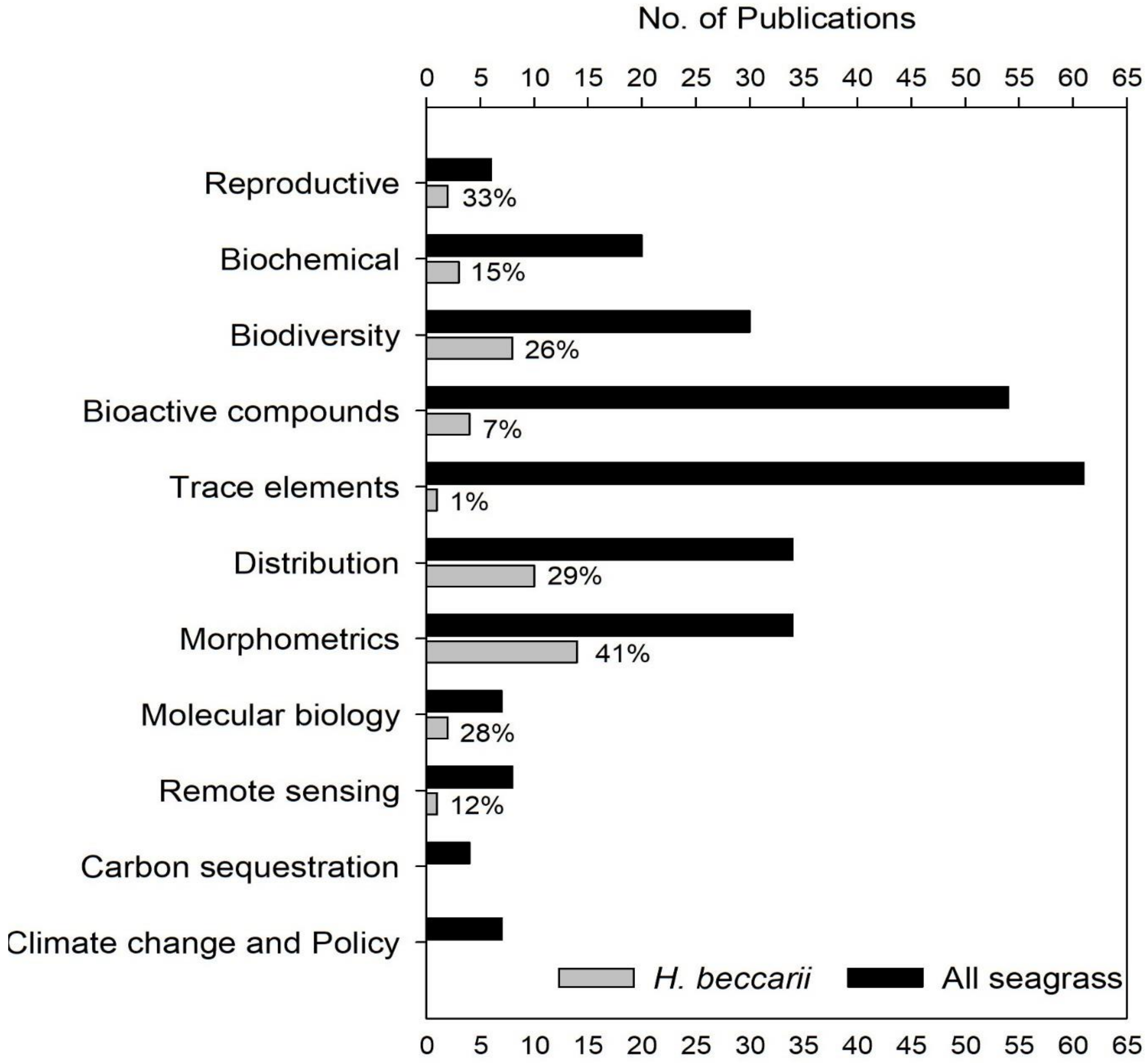

Fig.4. Number of publications on various parameters of all seagrass species and that of *H. beccarii* in India. The number in percentage indicate the contribution of *H. beccarii* in each variable.

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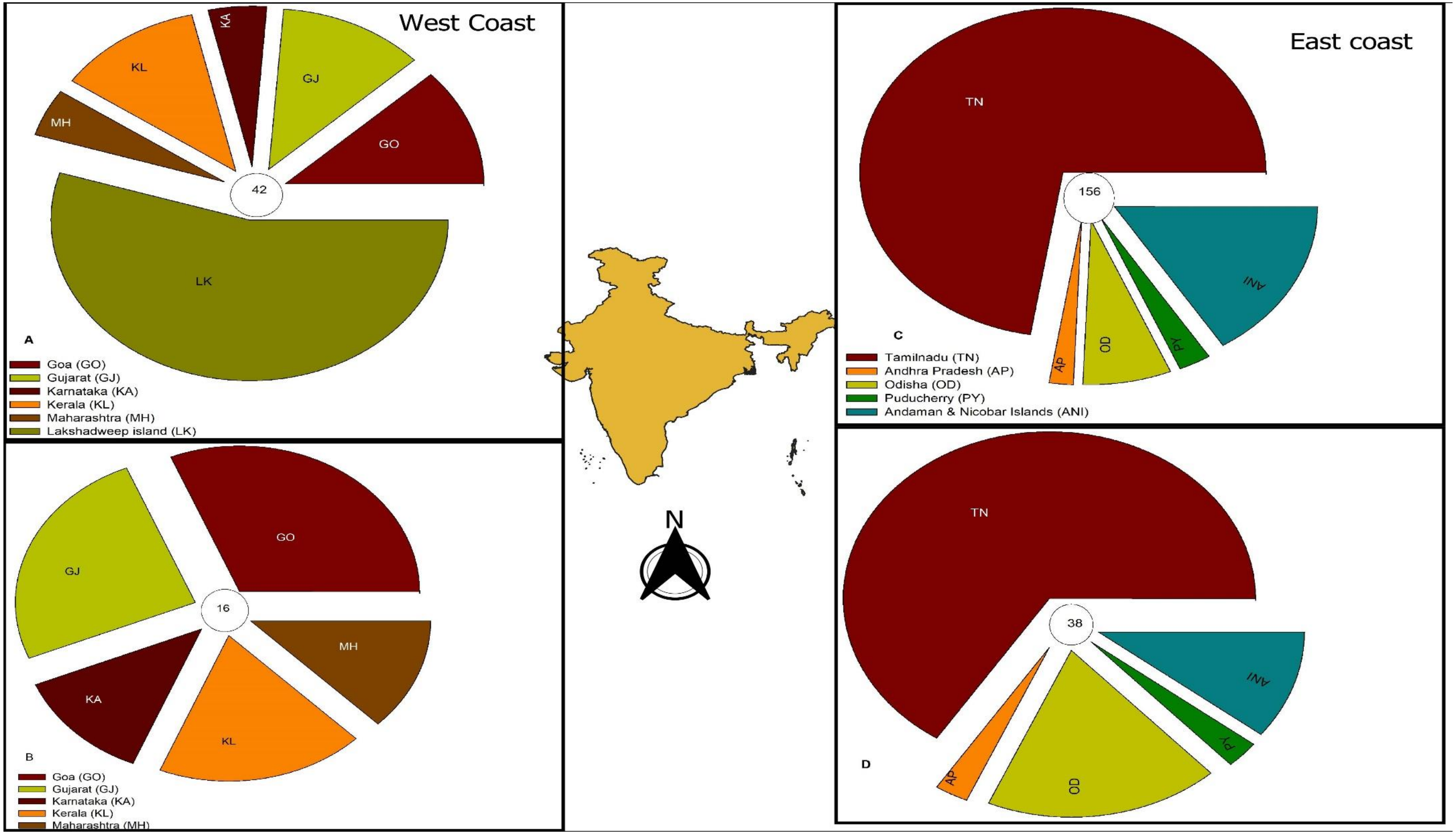

Fig.5. Total number of seagrass publications state wise of all seagrass species in the West coast (A) and for only *H. beccarii* (B) and East coast (C) and *H. beccarii* (D). The number in the middle of the circle for each pie chart represents the total number of publications.

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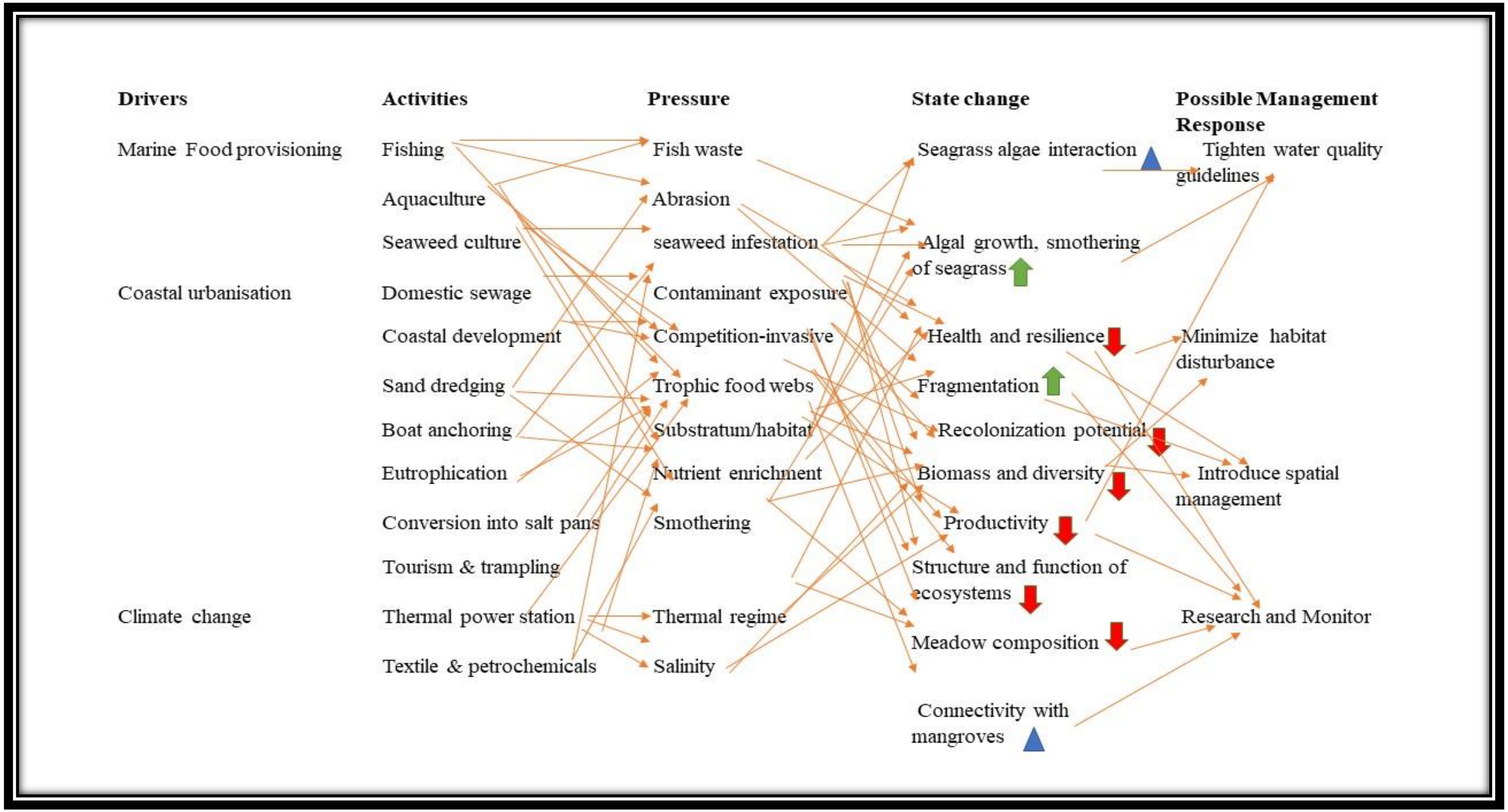

Fig.6 The DAPSIR model for *H. beccarii* from the coast of India. Green arrows indicate (increase), red arrows indicate (decrease) and blue triangles indicate (not studied). The Drivers, Activities, Pressures were collected from the literature survey and the State of change and Possible management response were adopted.

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