Evolution of trends in Sri Lankan mangrove research and future prospects

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Received: 17.09.2023 Revised: 18.02.2024 Accepted: 26.02.2024 Online: 15.03.2024

Abstract The trend of sporadic surveys and qualitative descriptions of Sri Lankan mangrove flora in the first half of the 20th century has gradually changed to include quantitative studies on floristics, nevertheless, studies on quantification of fauna associated closely with mangrove ecosystems are scarce. Microbial diversity, especially in soil, and its ‘contribution to the detritus cycle are the least studied. The tendency to engage in short-term research at convenient sites affects the quality and relevance of research output with some redundancy, resulting in a marginal contribution to the knowledge base on mangrove ecology. Studying mangrove ecosystem functions/ services demands long-term collection of data that would have made them less attractive research ventures. Research on trophic relationships, detritus and nutrient cycling, habitat and pollination functions too have had the same fate. The Indian Ocean tsunami in 2004 triggered a considerable interest in the coastal protection function of mangroves, as it was evident that mangroves and other coastal vegetation provided superior resistance to tsunami waves than hard engineering coastal protective structures. This has led to an unprecedented trend of mangrove afforestation for coastal defense, more than to research on planting techniques and maintenance to enhance the survival and growth of seedlings. This is still an under-researched aspect. Escalating recognition of blue carbon as a climate-smart solution and the development of market mechanisms for blue carbon trading have induced a considerable research interest in quantifying the mangrove blue carbon stocks, especially in the soil. Research on atmospheric carbon removal capacity/rates of mangrove plants/forests through photosynthesis however, lags behind for the reason that it requires data collection for a longer period that demands greater financial and labour investment. The urgency created by the current climate change crisis for effective solutions to reduce atmospheric greenhouse gases may provide a conducive environment for mangrove research.

Keywords: Mangrove research, Sri Lanka, ecological services, biodiversity and blue carbon

INTRODUCTION

Mangrove ecosystems gained attention of the Western scientists as ecological service providers only since the late 1960s with the research conducted in Florida mangroves, on their potential contribution to nutrient cycling and therefore coastal fishery production (Heald 1971; Odum 1971). Mangroves in Florida have been inventorised since 1936. However, they have been treated as non-commercial species and considered unproductive forest land in Florida (Brown 2015). Although written records are unavailable, the situation of mangroves elsewhere, including Sri Lanka, may not have been different. Low tidal amplitude in seas around Sri Lanka and coastal topography that restrict inter-tidal areas to narrow strips, and thus naturally limit the extent available for mangrove occupation along most of the Sri Lankan sheltered coasts may also have naturally contributed to the low interest vested on them. Evidently, the native fishermen around lagoons and estuaries in Sri Lanka (and maybe in other south and southeast Asian coastal areas too) however, were well aware of the influence of mangroves (the plants and the areas they occupy) on the sustenance of aquatic life that supports their livelihood and hence their own sustenance. The traditional brush parks, an artisanal fishing method operated in some lagoons/estuaries in Sri Lanka, especially in Negombo estuary, provides robust evidence to the indigenous perception and knowledge of goods and services provided by mangroves (Amarasinghe 1988; Amarasinghe *et al*. 2001) and the brush park fishermen cultivate and manage multi-species mangrove woodlots, primarily for extracting twigs and branches to construct brush parks and also for other services such as provision of nursery habitats and shoreline protection.

Scientific interest in the ecological services of mangroves throughout the tropics and sub-tropics gained momentum with the findings from research based on mangrove ecosystems of Florida that revealed their potential in sustaining nutrient cycles and trophic interactions in the coastal waters through production of detritus, which represent the major energy flow that takes place between autotrophs and heterotrophs in coastal food webs (Heald 1971; Odum 1971; Odum and Heald 1975). Revelation of the potential contribution of mangroves to coastal fisheries (Heald & Odum 1970) was an incentive to divert attention to research on the production and regulatory functions of mangroves. Consequently, the previous connotation that mangroves are mosquito-infested wastelands, yet to be reclaimed for other land-uses, changed gradually and more research was conducted to have an insight into their ecological functions/services given freely to sustain life in the coastal areas (Heald & Odum 1970; Christensen, 1978; Day *et al.*, 1987; Alongi & Dixon 2000). These findings on ecosystem functions rendered mangroves a life-supporting value and demanded in-depth research to elucidate their true capacities to sustain life in coastal areas, as it may vary with the bio-physical conditions prevailing in respective localities. This is a synopsis of trends in mangrove research in Sri Lanka and an analysis of knowledge gaps yet to be filled with future research for an enhanced understanding of the ecological functions of mangrove ecosystems that may assist their conservation and management.

Analysis of Thematic Content of Published Research Findings on Sri Lankan Mangroves

Publications on mangroves, approximately during the past 100 years, from the early 1900s to 2023 were analysed for their content to trace the evolution of trends in Sri Lankan mangrove research and it is graphically presented in Fig.1.

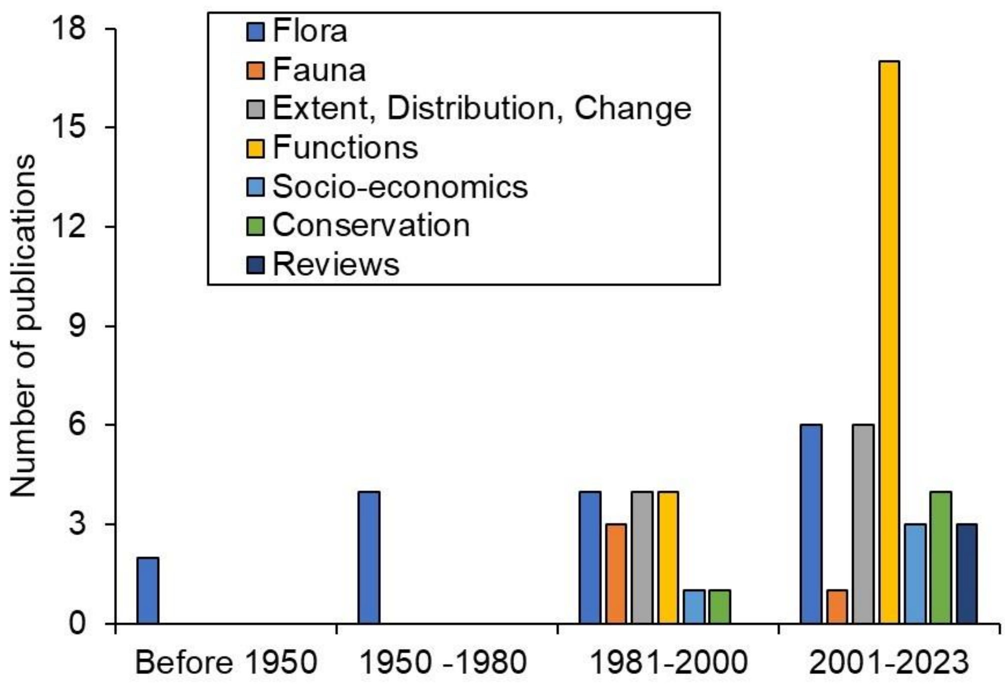

Fig 1 Research undertaken in major thematic areas relevant to mangrove ecosystems in Sri Lanka from the early 1900s to 2023.

Mangrove studies restricted to plant species richness in the early 1900s have expanded in terms of numbers and thematic areas at the dawn of the new millennium. Intensification of this trend in the first quarter of the 21st century however has not been able to venture into most mangrove services, except for the carbon sequestration function of mangroves that has come into limelight under the current climate change circumstances. Mangrove research that has already been performed on various themes and the knowledge gaps yet to be filled through research are discussed in the following sections.

Distribution and Extent of Mangroves in Sri Lanka

Distribution of mangroves along the Sri Lankan coastline was mapped in 1982 with other land uses through the interpretation of aerial photographs that cover the entire island. Nevertheless, unreliable ground truthing has markedly reduced the accuracy of these maps with respect to coastal wetlands, where mangrove areas are identified as “swamp”, “mangrove swamp” or “marsh” and mangrove areas have not been distinguished from salt marshes where they mostly occur in juxtaposition. Distribution of mangroves and their extent in Puttalam lagoon and Dutch Bay, situated on the northwestern coast of Sri Lanka, has been mapped using the same aerial photographs used to prepare the land-use maps in 1982 (Kanakaratne *et al.* 1983). Thorough ground truthing to distinguish mangrove areas from salt marshes and salt flats has produced a more accurate map of mangrove distribution in the area. Although selected mangrove areas have been investigated for their extent using satellite images (Dahdouh-Guebas *et al.* 2000; Jayatissa *et al.* 2002, Weragodatenna & Gunaratne 2015; Perera *et al.* 2008; Veettil 2022) there is no concrete measurement over the total extent of mangroves in Sri Lanka. The total mangrove extent of 15,670 ha, published in 2012 (Edirisinghe *et al.* 2012) is about 4000 ha less than the extent of 19,758 ha published in 2021 (Premakantha *et al.* 2021), indicating methodological improvement by using high-resolution satellite imagery and meticulous ground truthing by field researchers conversant with mangroves, especially because mangroves often occur in discrete patches in the narrow inter-tidal areas prevalent under the micro-tidal conditions and also their occurrence adjacent to salt marshes.

Research on Mangrove Biodiversity and Biogeography

The earliest publications on Sri Lankan mangrove flora date back to over a century (Tansley and Fritsch 1905) and it is a qualitative description of mangroves in estuaries of southern Sri Lanka. During the following seven decades, very few publications have been produced on mangrove biodiversity and they are mostly general accounts of plant descriptions, species composition, zonation, and distribution (Chapman 1947; Abeywickrema 1956, 1960, 1966; Aruchelvam 1968).

A review on publications available from the last four decades (1980 – 2020) reveals that the research trend observed since 1905 has not changed significantly in the 21st century as most of them are on the diversity of mangrove flora and fauna, their taxonomy, and ethnobiological aspects. Besides, research on mangrove flora outnumbers that on fauna (Fig. 1), and they are mostly based on mangroves of Negombo estuary (Arulnayagam *et al.* 2021), the closest mangrove area (350 ha in extent) to the capital city Colombo, the accessibility of which is relatively easy. Dedicated mangrove research reported from Sri Lanka is few and far between. Since floristic studies do not demand longer periods of time, most research is planned for very short periods in locations selected for convenience. There have been only a handful of long-term mangrove projects in Sri Lanka that have produced publications based on data collected continuously for 1 – 2 years. (Amarasinghe & Balasubramaniam 1992; Pahalawattaarachchi & Amarasinghe 1997; Perera & Amarasinghe 2014).

Faunal studies have mostly been qualitative (De Silva & Balasubramaniam 1984; Pinto 1986; De Silva & De Silva 1989), nevertheless, aquatic organisms associated with brush park fishery in the mangrove areas of Negombo estuary have been researched in depth (Amarasinghe *et al.* 2001).

Biogeography of mangrove plant species has been studied more extensively than that of faunal species (Jayatissa 2012; Amarasinghe & Perera 2017: Perera *et al.*2019, Madhushanka & Ranawana 2022), nevertheless, the knowledge available is incomplete and research/ surveys on mangrove fauna are confined to selected localities (Jayasundera *et al*., 1999; Sarathchandra *et al.* 2018). Poor accessibility to mangrove areas on northern and southern coasts during the 30-year civil unrest that prevailed in those areas until 2009, has brought research on natural ecosystems to a standstill. Naturally, this state of affairs has negatively affected mangrove biogeographical studies within Sri Lanka.

Microbial diversity, processes, and functions in Sri Lankan mangrove ecosystems, especially associated with soil and detritus cycle are marginally studied (Pahalawattaarachchi & Amarasinghe 1996) while research on lichen diversity (Maduranga *et al.*, 201;, Ranawaka *et al.* 2022) and endophytic microorganisms in mangrove plants have gained momentum, for the pharmaceutical value of their metabolites with antibiotics, anti-cancer and anti-inflammatory properties (Rathnaweera *et al.* 2016; Ukwatta *et al.* 2019; Ravimannan & Sepali 2020).

Research on Mangrove Vegetation Structure

Floristics alone is inadequate to understand the ecological status or the capacity of an ecosystem to deliver goods and services to support life, which is determined by its processes and functions. Floristic richness along with the relative density of constituent species/populations consisting of individuals of varying size, age, and performance will determine the structure of vegetation that facilitates the various processes which in turn will result in the functions or services.

In the past few decades, the scope of studies on mangroves has extended from qualitative description of floristics to analyses of vegetation structure based on quantitative data collected using standard sampling methods (Amarasinghe & Balasubramaniam 1992a; Jayasundera *et al.* 1999; Perera *et al.* 2013; Prasanna *et al.* 2019), enabling comparison of floristic diversity and vegetation structural complexity by calculating α- diversity values and complexity indices. Environmental factors that influence mangrove vegetation structure have been researched and revealed that soil salinity and nutrient availability contribute most to structural variability (Perera *et al.* 2013; Cooray *et al*. 2021).

Very few research is focused on the influence of vegetation structure on gross and net primary productivity (Jayakody et al. 1999), carbon sequestration (Perera & Amarasinghe 2014), and other ecological services provided by mangroves such as coastal protection (De Silva & Amarasinghe 2021).

Research on Mangrove Dynamics

Mangroves undergo changes in extent and structure, hence, provision of services/functions, due to natural and anthropogenic causes. A few mangrove areas in Sri Lanka have been studied for their vegetation dynamics due to economic development activities such as inland irrigation (Jayatissa *et a.*, 2002; Dahdouh-Guebas, *et al.* 2000) and shrimp culture (Amarasinghe & Perera, 1995; Bournazel *et al.* 2015) using aerial photographs and satellite images. Research on functional dynamics of mangrove ecosystems such as primary production, carbon sequestration, nutrient cycling, and habitat provision have not been reported hitherto, which may be due to the unavailability of historical data on these aspects.

Being located in the land-sea ecotone, mangroves are vulnerable to sea level rise due to climate change, and a single study has been reported on the potential impact on mangrove extent in the Negombo estuary using GIS (Perera *et al.* 2018).

Research on the Primary Production Function of Mangroves

Net Primary production of mangrove ecosystems is the kingpin in mangrove ecosystem functioning as it is the most vital process that provides energy to sustain all forms of life associated with them. Estimating net primary production (NPP) requires data on litter production and plant biomass increment at least for 12 months, encompassing the seasons with varying rainfall and atmospheric temperature conditions that affect plant growth. NPP of a few mangrove areas have been studied (Amarasinghe & Balasubramanim 1992b; Pahalawattaarachchi, & Amarasinghe 1995; Perera & Amarasinghe 2016). Primary productivity or the rate of production of a mangrove ecosystem is a critical datum that provides insight into its ecological and conservation status and management implications.

The impact of changing environment due to natural and anthropogenic causes, on the primary productivity of Sri Lankan mangroves is yet to be researched. Net Primary productivity of mangrove stands is vital in understanding their functional importance in supporting life and therefore the need for their conservation for the vital ecological services they perform. Remote sensing techniques, combined with algorithm models, have been proven to be promising methods for NPP estimation. High-precision and real-time NPP monitoring in heterogeneous areas require high spatio-temporal resolution remote sensing data, which are not easy to acquire by single remote sensors, especially in cloudy weather (Zhang *et al.* 2019).

Research on Trophic Relationships and Nutrient Cycling

Knowledge of trophic interactions in an ecosystem is vital to understanding its capacity to support biodiversity as it involves the transfer of energy from autotrophs/plants to other organisms in the ecosystem while nutrients/elements are dissociated and released for reuse (nutrient cycling). Quantifying the production and dynamics of detritus, the partially decomposed organic matter, that transfers photosynthetically fixed solar energy by the plants to heterotrophs in the ecosystem, is vital to value the potential contribution of mangroves to support coastal life. Mangrove litter decomposition is a major function that generates food for detritivores (as particulate organic matter) and microorganisms (as dissolved organic matter). Very few studies (Amarasinghe 1997; Pahalawattaarachchi & Amarasinghe 1996) are reported on mangrove litter decomposition and fungal succession associated with the process, that contributes to maintaining mangrove and coastal food webs, on which the near-shore fisheries are dependent on. The role of detritivores in litter decomposition and nutrient cycling is yet to be revealed as no research on food webs in Sri Lankan mangrove ecosystems has been undertaken.

Research on Carbon Sequestration Function

With the escalating demand for means to abate climate change through the reduction of greenhouse gasses, mangroves are currently being reckoned as an essential component of climate change strategies such as REDD+ and blue carbon trading for their superior capacity to sequester carbon, especially in soil (Alongi 2012). Market mechanisms are being developed rapidly to trade carbon sequestration service (blue carbon) that promotes mangrove conservation and expansion and also demands quantification of this function. Estimating blue carbon stocks has thus gained the attention not only of scientists but also of the carbon trading and brokering companies to fix prices for carbon credits.

Estimation of mangrove biomass is essential to quantify the organic carbon content in it and researching allometric relationships between easily measurable plant variables such as girth/ diameter at breast height (gbh/dbh) and biomass is a pre-requisite. Since the growth of plants is heavily influenced by local climatic and edaphic conditions, biomass partitioning in mangrove species in the local context produces more accurate and reliable data on biomass and carbon contents. Allometry of only four common true mangrove species in Sri Lanka, i.e. *Rhizophora mucronate, Avicennia marina* (Amarasinghe & Balasubramaniam 1992a), *Bruguiera gymnorrhiza, Lumnitzera racemose* (Perera *et al.* 2012) have been studied hitherto.

The unique capacity of mangrove soils to sequester organic carbon, as a consequence of soil anoxia, bestows them the superiority of carbon sinks. Total organic carbon (TOC) in mangrove soils in wet, dry, and intermediate climatic zones has been investigated (Perera & Amarasinghe 2015, 2019a, 2019b; Cooray *et al.* 2021a, 2021b).

The role of mangrove crabs in carbon burial has been studied in the mangrove areas of the Negombo estuary (Abeysekara & Amarasinghe 2017). *Terebralia palustris* has been observed to feed directly on fallen mangrove leaves in the mangroves of Erumathivu island (Amarasinghe 1997) nevertheless, no in-depth studies are reported. The impact of animal grazing on mangroves, especially *A. marina* in mangrove areas on the northwestern coast is yet to be researched.

Coastal Protection Function

The capacity of mangroves (and also other coastal vegetation) to reduce wave energy was well manifested in the event of the Indian Ocean tsunami in 2004, where damage from high energy waves was minimal in areas bordered by mangroves and other coastal vegetation (Miththapala 2008). In the aftermath, a considerable interest, both local and foreign, through mediation of NGOs and CBOs was focused on planting mangroves for coastal protection, rather than researching on using mangroves and other coastal plants effectively for coastal protection. Except for a couple of long-term research projects initiated to study the coastal protection function of mangroves, most attention has been focused on qualitative assessment of mangrove resistance to tsunami waves. Studies using GIS have revealed that coastal segments on the western and southern coasts with lower rates of shoreline erosion and coastal inundation hazards are located close to the mangrove and other coastal vegetation with varying structural complexity and diversity (De Silva & Amarasinghe 2021). Using the depth of tsunami deposits as a surrogate variable, resistance given by mangrove species and the porosity associated with vegetation have been able to provide an insight into the vegetation structure that can deliver the protection function. This provides knowledge to design mangrove green belts for the purpose (De Silva 2011).

Habitat Provision and Nursery Function

Since the mangrove faunal and microbial studies are not comprehensive, knowledge of the full potential of mangrove ecosystems in providing habitats, including the nursery habitats for aquatic fauna, especially the juveniles, is yet to be researched. Habitat availability is indicated by high species richness and abundance. Studies in the Chilaw Lagoon have shown a correlation between mangrove extent and vegetation structure with abundance of shrimps (Jayasundera *et al.* 1999) and fish catches (Sarathchandra *et al.* 2018). Aquatic organisms that use mangrove forest areas as nursery grounds are less well-researched.

Research on Anthropogenic Impacts on Mangroves

Besides assessing the potential impacts of shrimp farming on local livelihoods (Gunawardena & Rowan 2005) in the Rekawa Lagoon, no studies are reported on the effect of pollution (eutrophication, industrial effluent discharge, oil spills, etc.) on mangrove flora and fauna, indicating low incidence of pollution impacts on mangroves that may cause defoliation or plant death.

Research on Mangrove Reforestation/Afforestation

Blue carbon, being attracted as a natural climate solution, blue carbon ecosystems such as mangroves, have recently gained more attention in securing their protection and expansion. Afforestation (planting in areas that have not supported mangroves before), more than reforestation (planting in denuded or degraded mangrove areas) is the common practice in Sri Lanka, for the reason that most of the denuded mangrove areas are irreversibly converted to other land-uses and hence are unavailable for reforestation. Only three, out of 23 afforested sites in Sri Lanka have been able to achieve more than 50% survival, and inappropriate species and site selection along with poor post-planting care have been identified to be the potential causes of failure (Kodikara *et al.* 2017), nevertheless, no publications on research addressing the issues are available.

Eco-physiological research on mangrove seeds, seedlings, saplings and sub-adults of mangrove species is essential to generate the important missing knowledge that is essential to select the suitable sites and species, especially for afforestation, planting regimes and post-planting maintenance procedures. The influence of salinity on the germination of mangrove seeds (Wijayasinghe *et al*. 2019) and seedling survival and growth (Jayatissa *et al*. 2008, Kodikara *et al*. 2018; De Silva & Amarasinghe 2021) has been researched to find out the best salinity levels for the purpose. In practice, however, for the sake of convenience, *Rhizophora mucronate* seedlings are widely used for afforestation, irrespective of the soil salinity of respective planting sites. Research on the influence of hydrology on planted seedlings, together with nutrient availability are aspects that need to be researched.

Human Dependence on Mangrove Resources and Services

The extent to which coastal communities are dependent on goods and services provided by mangroves directly or indirectly has been researched in a few coastal areas in Sri Lanka (Pinto 1986; Amarasinghe 1988). Community knowledge on ethnobiological importance of mangrove resources and services has been assessed as an indication of their capacity to manage, conserve, and improve the governance of mangrove ecosystems (Nijamadeen *et al.* 2023).

Future Prospects of Mangrove Research

Relatively low investment of research on functional aspects of mangroves than on floristics is common with respect to mangrove areas elsewhere too (Li & Lee 1997). Low mangrove floral diversity is another convenience factor that most researchers are attracted to floral studies, unlike mangrove faunal research which requires laborious sampling and analysis due to their high diversity. Besides, the availability of state research funding for ecological studies is relatively scarce and the situation is aggravated due to economic crisis in the aftermath of the COVID-19 pandemic. This current state of affairs is not conducive for researchers to venture into long-term studies.

Global priority given to climate solutions through blue carbon trading however may create funding opportunities for mangrove research in the future that may be utilized to initiate dedicated research on the following aspects of mangrove ecosystems in Sri Lanka.

1. Net primary productivity (NPP) of mangrove ecosystems, including that by mangrove plants, algae and phytoplankton
2. Ecophysiology of mangrove plant species- growth under varying environmental conditions (soil salinity, temperature, predator pressure, and nutrient availability)
3. Carbon sequestration in mangrove plant biomass and soil under varying climatic and edaphic conditions
4. Trophic relationships – food webs and connectance
5. Detritus and nutrient cycling
6. Characterizing mangrove areas as spawning and nursery grounds (Habitat function)
7. Impact of eutrophication on mangrove services
8. Hydrology of mangrove areas and methods to improve hydrological conditions to suit afforestation in potential sites for planting
9. Factors affecting mangrove seedling growth under natural conditions
10. Mangrove soil microbial diversity, abundance and processes
11. Pollinators
12. Penological patterns of true mangrove species in different climatic zones
13. Methods to propagate mangrove species other than *Rhizophora mucronata*.
14. Eco-physiology of mangrove seedlings (salt exclusion, ion regulation, photosynthesis, and nutrient uptake under varying climatic and edaphic conditions) to support successful mangrove cultivation
15. Microbial diversity and their contribution to nutrient cycling
16. Pests and diseases of mangrove plants
17. Predators of mangrove seeds, seedlings, and mature plants (Herbivory)
18. Impact of reforestation/afforestation on the capacity of carbon sequestration and other ecological services of Sri Lankan mangrove ecosystems.

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