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Mangrove ecosystems under threat in Indonesia: the Segara Anakan Lagoon, Java, and other examples

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Abstract

Indonesian mangrove forests are of major local and global importance for ecological and economic reasons. Indonesia has both the largest area of mangrove forests and the highest mangrove deforestation rate by country. Using the mangrove-fringed Segara Anakan Lagoon on Java as a prime example, this chapter explains the ecosystem services provided by mangrove-dominated coastal ecosystems, as well as the threats to it. Related governance approaches and interventions are discussed, while special emphasis is given to water quality, "Blue Carbon" storage, biodiversity, natural resource use, land use change, and the underlying political and societal dynamics. While ecosystem service supply is strongly impaired in the Segara Anakan Lagoon, mainly because of deforestation and high sediment deposition related to land use change, mangrove ecosystems in other areas appear to be in a better state. Finally, directions of future research and recommendations for policy and society are given.

Abstrak

Hutan bakau Indonesia sangat penting secara lokal dan global karena memiliki nilai ekologis dan ekonomis. Indonesia merupakan negara dengan wilayah hutan bakau terluas, namun laju deforestasi hutan bakaunya tertinggi. Menggunakan Laguna Segara Anakan yang bertipe hutan bakau tepian pulau di Jawa sebagai contoh utama, bab ini membahas tentang jasa ekosistem yang diberikan oleh ekosistem pesisir yang didominasi hutan bakau maupun ancaman terhadap jasa ekosistem tersebut. Pembahasan meliputi pendekatan dan intervensi tata kelola yang terkait, sedangkan penekanan khususnya adalah pada kualitas air, cadangan karbon pada ekosistem pesisir dan laut ('Blue Carbon' storage), keanekaragaman hayati, pemanfaatan sumber daya alam, perubahan penggunaan lahan, dan dinamika sosial politik yang mendasarinya. Meskipun pasokan

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jasa ekosistem di Laguna Segaran Anakan sangat buruk, terutama karena deforestasi dan tingginya sedimentasi terkait dengan perubahan penggunaan lahan, ekosistem bakau di daerah lain kondisinya lebih baik. Di bagian akhir bab ini disajikan arah penelitian kedepan dan rekomendasi untuk kebijakan dan masyarakat.

Chapter outline

7.1 Introduction

Mangrove forests are lining major parts of tropical and subtropical coasts and provide a wealth of functions and services that are important for healthy coastal ecosystems and human well-being. They are highly productive and support biodiversity, serve as nurseries for juvenile stages of coastal fish and other organisms, provide coastal protection against waves and storms, and help to maintain water quality. In addition, they are highly efficient natural sinks for carbon dioxide, provide nontimber forest products for the local population like, e.g., firewood and honey, and serve as sites for tourism (Huxham et al., 2017; Wells et al., 2006). While the intimately connected ecological and economic relevance of mangrove ecosystem functions and services increasingly comes into the focus of science and society, mangrove forests are under threat from a diverse array of human interventions and climate change effects (Chowdhury et al., 2017; Jennerjahn et al., 2017). This is of particular importance in Indonesia, which holds the largest mangrove area by country (3,112,989 ha; Giri et al., 2011), but also exhibits the highest area loss (−48,205 ha between 2000 and 2012; Richards and Friess, 2016). There, the major climate change effects, i.e., sea level rise, warming of air and surface waters, aridity, and increased storminess, are of minor importance compared with human interventions, mainly logging, conversion to other land uses, pollution, and overharvesting of wood and fishery resources (Alongi, 2015; Jennerjahn et al., 2017; Richards and Friess, 2016).

Maintaining the structures and functions of mangrove forests is not only of importance for the continued supply of all their ecosystem services but also for seagrass meadows and coral reefs, adjacent coastal ecosystems whose well-being is intimately linked to the existence of healthy mangrove forests. For example, coral reefs provide physical protection from waves and storms to seagrass meadows and mangrove forests, while the latter reduce the risk of eutrophication and siltation of seagrass meadows and coral reefs through accumulation of land-derived nutrients and sediments (e.g., Alongi, 2009; Guannel et al., 2016). Understanding the structure and functions of mangrove ecosystems under these multiple stressors is a major step toward developing measures for their conservation and sustainable use. The Indonesian–German research and education program "Science for the Protection of Indonesian Coastal Marine Ecosystems" (SPICE) provided the frame for this in its cluster "Mangrove Ecology and Sustainability." The structure, functions, and ecosystem services of mangroves as well as human impacts, their causes, and governance and management issues were investigated with multi- and interdisciplinary approaches in several regions of Indonesia, but with a geographic focus on the mangrove-fringed Segara Anakan Lagoon (SAL) in south central Java. Other regions that were less intensively studied are the Berau Regency in Kalimantan and the Togian Islands in east Sulawesi, but the results of which are also reported here.

The SAL is an area rich in natural resources and mainly nourished by the inputs from the Citanduy, the fifth largest river of Java, and the tidal exchange with the Indian Ocean. The lagoon ecosystem has been threatened by overfishing, logging of mangrove wood, high sediment and organic matter input from the catchment area, and pesticide and oil pollution (White et al., 1989). Management programs have been conducted for decades to overcome these problems (Asian Development Bank, 2006; Olive, 1997), but have had little success.

Therefore, more than a decade (2004–2016) of research was conducted in the SPICE cluster "Mangrove Ecology and Sustainability" to provide new insights on cause–effect relationships, to quantify these relationships, to assess ecosystem service supply, and to analyze governance and management regimes of Indonesia's mangrove ecosystems.

The long-term research program SPICE allowed us to advance the understanding of (1) the dynamics and drivers of social–ecological change, (2) the connectivity and adaptability of mangrove ecosystems and related social systems, and (3) governance and management challenges in times of global change. As the name says—Science for the Protection of Indonesian Coastal Marine Ecosystems—our research results provide the means to increase awareness among stakeholders on the ecological and economic relevance of mangrove forests, and they provide knowledge that can support the development of measures toward conservation and more sustainable use of these exceptional ecosystems. The research also directs attention to the critical roles of political structures, misfits between state-led management approaches and realities on the ground, and widespread conflicts over natural resources, which to date have limited the potential for more sustainable management of these resources.

7.2 The study areas

Mangrove forests occur in six environmental settings, which can be very different in their hydrodynamics, geomorphology, biogeochemistry, and flora and fauna composition. These are (1) river-dominated, (2) tide-dominated, (3) wave-dominated, (4) composite river- and wave-dominated, (5) drowned bed rock valley, and (6) carbonate settings (Woodroffe, 1992). The SAL is a combination of a river- and tide-dominated system, the areas under study in the Berau Regency are mainly tide-dominated with a partial river dominance, while the Togian Islands belong to the carbonate settings (Fig. 7.1).

The SAL is a 25-km-long, shallow estuarine lagoon located on the south coast of the densely populated island of Java (Figs. 7.2 and 7.3). It is separated from the Indian Ocean by the rocky mountainous Nusakambangan Island and connected to it by two inlets at its

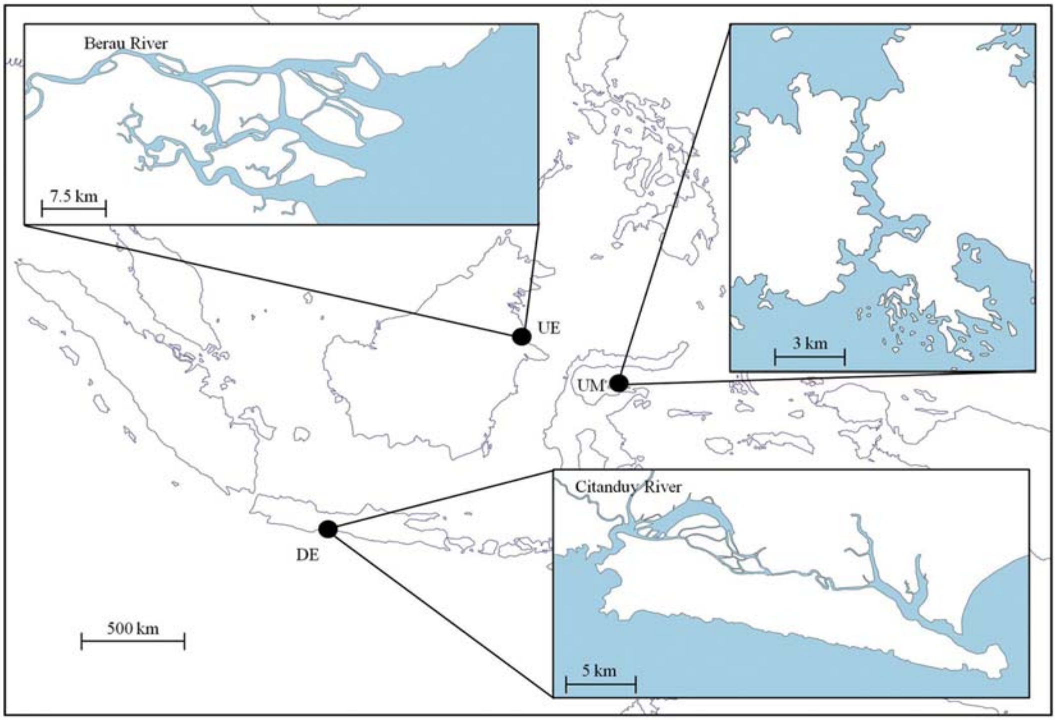

FIGURE 7.1 Map of the study areas in Indonesia including the Segara Anakan Lagoon, Java, the Berau Regency, Kalimantan, and the Togian Islands, Sulawesi. *Adapted from Weiss et al. (2016).*

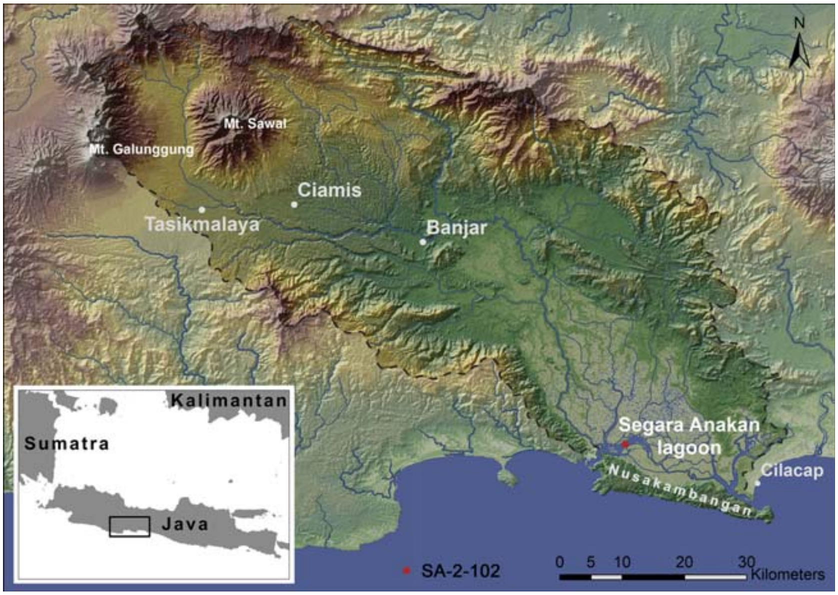

FIGURE 7.2 The Segara Anakan Lagoon and its catchment area. *Adapted from Lukas (2014b).*

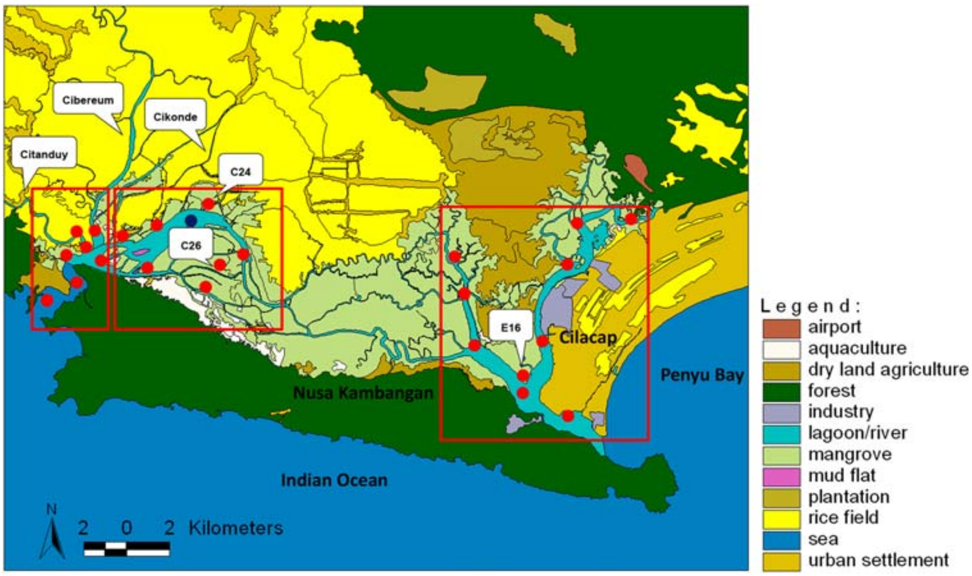

FIGURE 7.3 Map of the Segara Anakan Lagoon in 2006 including land use, major rivers (Citanduy, Cibereum, Cikonde) and the city of Cilacap. The red rectangles denote major geographical areas of work (left to right: W = western, C = central, E = eastern lagoon) as later used. Red dots denote sampling stations in the lagoon and three mangrove stations C24, C26, and E16. The blue dot denotes the location of a sediment core taken in the central lagoon. *Adapted from Jennerjahn et al. (2009).*

western and eastern ends (Yuwono et al., 2007). It has a dominance of river input in its western part, where the Citanduy River discharges into the lagoon, and a dominance of tidal exchange in its eastern part, where freshwater input is very low (Holtermann et al., 2009). The lagoon is fringed by the largest remaining single mangrove forest on the south coast of Java with a total area of approximately 9000 ha (Ardli and Wolff, 2009), the flora of which consists of 15 mangrove tree species and 5 understory genera (Nordhaus et al., 2019). The density, diversity, and aboveground biomass of trees are lower in the central than in the eastern part of the lagoon, mainly as a consequence of environmental degradation due to logging and land use conversion (Hinrichs et al., 2009; Nordhaus et al., 2019). The lagoon has shrunk drastically and became shallower due to heavy sedimentation from rivers, mainly the Citanduy River, in the past 150 years (Yuwono et al., 2007; Lukas, 2014a,b). The land areas adjacent to the lagoon are dominated by settlements and agriculture, mainly cultivation of rice under irrigation, the area of which increased by 62% between 1987 and 2006 to a total of 19,274 ha, which makes up 21% of the Segara Anakan region (Fig. 7.2; Ardli and Wolff, 2009). The 450 km^2 large catchment area of the lagoon comprises a range of land use and land cover types, including irrigated rice agriculture, rainfed agriculture with a diversity of crops, settlements with house gardens, villagers' mixed forests, state forests (mainly comprising monocultures of teak and pine), and plantations (e.g., rubber and cocoa) (Lukas, 2015). The city of Cilacap with a population of about 234,000 (BPS Cilacap, 2018) is located at the eastern end of the lagoon and harbors the largest oil refinery of Indonesia in its port.

The Berau Regency is located in East Kalimantan (118°05′E, 2°25′N; Fig. 7.1). The hydrodynamics of the Berau coastal area are driven by the two rivers Berau and Tabalar in the west and strong currents in the east influenced by the Indonesian Throughflow (ITF) that connects the Pacific and Indian Oceans through the Makassar Strait (Gordon, 2005; Wiryawan et al., 2005). The coast is covered by dense mangrove forests, which are relatively undisturbed. Some areas near the Berau River estuary have been cleared for aquaculture, but these activities are still in an early development stage. The hinterland is covered by tropical rainforest, which has been partly converted into palm oil plantations (Weiss et al., 2016). With a population density of 10 persons per km^2, Berau is one of the least populated of the 300 regencies in Indonesia (BPS Kalimantan Timur, 2017). Its economy is characterized by a heavy dependence on the extraction of minerals and other natural resources, with a massive push of coal mining, logging, and timber plantation development following decentralization in the early 2000s (Keulartz and Zwart, 2004). About 37% of the original mangrove area of Kalimantan has been lost (Ilman et al., 2016). Many remaining areas have lost their ecological connections to adjacent freshwater or terrestrial systems due to agricultural and oil palm plantations that have replaced lowland forests. In 2005, the Berau marine protected area (1321 × 106 ha) was established, which has the second highest coral reef biodiversity in Indonesia and the most extensive remaining mangrove forest in Kalimantan covering an area of 56,000 ha (Siahainenia, 2016).

The Togian Islands are a ca. 120 km long chain of around 60 larger islands in the Bay of Tomini (Fig. 7.1). Since 2004, the area has belonged to the district of Ampana and has been designated a marine protection area in the same year. Although the Bay of Tomini is tucked away from greater flow-through systems and in general shallow, both of which are limiting the exchange of water, the mangrove forests and coral reefs are surprisingly rich in diversity (Wallace, 1999). Major income of the Togian population, which consists of a number of ethnic groups, is the trade of seafood, using the capital small town of Wakai as the hub for exportations, increasingly to China. There is, to a lesser extent, also dive tourism, which unfortunately suffered dramatically due to heavy dynamite and cyanide fishing practices, resulting in severely disturbed reefs with uncertain chances for regeneration. Unlike the underwater situation, the islands still harbor relatively undisturbed coastal mangrove forests, which receive freshwater input by karst runoff and precipitation. There are also mangrove patches found, which grow directly on intact coral reefs, sometimes called "clearwater mangroves" (Weiss et al., 2016).

7.3 Environmental setting and natural resource use

7.3.1 The physical setting

The physical setting is a major determinant of biogeochemical processes and fluxes and the flora and fauna composition in mangrove ecosystems. Precipitation in the SAL watershed is high due to the monsoon climate with maximum rainfall during the wet NW monsoon in austral summer (November–March). The long-term annual average precipitation in the coastal city of Cilacap amounts to 3340 mm $year^{-1}$ but can be as low as 1200 mm $year^{-1}$ during El Niño years (Jennerjahn et al., 2009; Weatherbase, 2019). In Sidareja in the center of the SAL, watershed precipitation amounts to 2770 mm $year^{-1}$ (Weatherbase, 2019). The SAL receives freshwater input from a number of rivers. The Citanduy river contributes >80% of the freshwater in the western part of the lagoon, with an annual average discharge of 227 $m^3\ s^{-1}$ (dry season 171 $m^3\ s^{-1}$, rainy season 283 $m^3\ s^{-1}$), resulting in an annual total of 7.2 km^3 (Ludwig, 1985). Tidal exchange with the Indian Ocean occurs through two channels in the western and eastern parts of the lagoon. The mixed and predominantly semidiurnal tide ranges between 0.4 m during neap tide and 1.9 m during spring tide (Holtermann et al., 2009; White et al., 1989). The residence time of the water in the lagoon is generally short, which is on the order of 0–2 days near the western and eastern outlets and is at maximum 8 days (dry season) and 12 days (wet season) in the central lagoon (Holtermann et al., 2009). It is at the lower end of the range reported for lagoons in Brazil, Taiwan, and around the Mediterranean (Hung and Hung, 2003; Knoppers, 1991; Umgiesser et al., 2014). The sediment dynamics vary largely between the western and eastern parts of the lagoon. While total suspended matter concentration varied around 10 mg L^{-1} in the latter due to the low freshwater input, it can be orders of magnitude higher (>100 to >1000 mg L^{-1}) in the west because of the high input of the Citanduy River during the wet season (Moll, 2011; Yuwono et al., 2007). There, it is much higher than the global average of 500 mg L^{-1} because of the generally high physical and chemical weathering and high river discharge in the SE Asia region (Milliman and Farnsworth, 2011). The hydrodynamics and the sediment dynamics exert major control on the dispersal and accumulation of substances in the lagoon like, for example, sediments, carbon, nutrients and pollutants, and how they can affect flora and fauna and ultimately ecosystem health.

Kalimantan and its coastal areas including the Berau Regency are affected by the Asian-Australian monsoon. The wet season starts in October and extends until May. The dry season spans from July to September, and average annual rainfall in the Berau catchment varies from 2400 to 3350 mm year^{-1}. During the study period, monthly rainfall ranged between 194 mm in September 2015 and 484 mm in November 2015 (World Weather Online, 2019). Porewater salinity was 6.1 at the most northern mangrove site in the Berau Delta, whereas salinity ranged between 24.3 and 35.0 at all other sites (Tripathi, 2016).

The Togian Islands are located in the Bay of Tomini, between 121°37′ and 122°25′ E close to the equator. Roughly 60 larger islands span an area of 120 km in lateral extension. The precipitation is around 1600–1700 mm year^{-1}, which falls more or less equally distributed with a short drier period in August and September. Temperature ranges between 23 and 33°C without any observable seasonality. Climatically, the Togians belong to the "lands below the wind" famed in seafaring, as they lie just between the northern and southern monsoon systems dictating the climate of the rest of Sulawesi (Wallace, 1999).

7.3.2 Water quality, biogeochemistry, and pollution

Dissolved oxygen ranged between 5.4 and 6.2 mg L^{-1} or 70%–90% of oxygen saturation in the SAL and was lower in the Citanduy River (3.9 mg L^{-1}, 50% saturation). Concentrations of the dissolved inorganic nutrients nitrate and phosphate, which to a large extent result from human activities in the hinterland, displayed large spatial and temporal variations. Concentrations were generally higher in the western (up to 35 μM nitrate) than in the eastern part of the lagoon (<10 μM nitrate), and they were higher during the wet (W: 5–35 μM nitrate, E: 3–10 μM nitrate) than during the dry season (W: 0–8 μM nitrate, E: 0–5 μM nitrate; Moll, 2011). The concentrations of chlorophyll *a* as an indicator of biomass of primary producers were also moderate (1–8 μg L^{-1}; Yuwono et al., 2007). It appears that the nutrient inventory of Segara Anakan results from a mixture of anthropogenic and natural sources and processes. Maximum inputs into the western lagoon were supplied by the Citanduy during the rainy season, while tidal exchange with the Indian Ocean dominated in the eastern lagoon, which generally has little freshwater input. Porewater profiles exhibited that losses from recycling processes in the mangrove forests are an additional source of nutrients to the lagoon during the dry season (Jennerjahn et al., 2009). Despite the high freshwater and nutrient input from the agriculture-dominated hinterland, the trophic status of SAL was mostly oligo- to mesotrophic and nutrient pollution on a low to moderate level compared with other lagoons around the globe (Jennerjahn et al., 2009).

In terms of organic pollution, the focus is often on the so-called "dirty dozen," the major persistent organic pollutants originally listed in the Stockholm Convention on

Persistent Organic Pollutants (2018), but it is known there are thousands of other organic contaminants. However, in most cases, little to nothing is known on their potential risk for the environment (Muir and Howard, 2006). With a nontarget screening approach, more than 50 organic contaminants were found in water, sediment, and macrobenthic invertebrates of the SAL in 2008. The level of contamination was low to moderate in all parts of the lagoon except for the eastern lagoon close to the oil refinery, where it was high even on a global scale (Fig. 7.4; Dsikowitzky et al., 2011; Syakti et al., 2013).

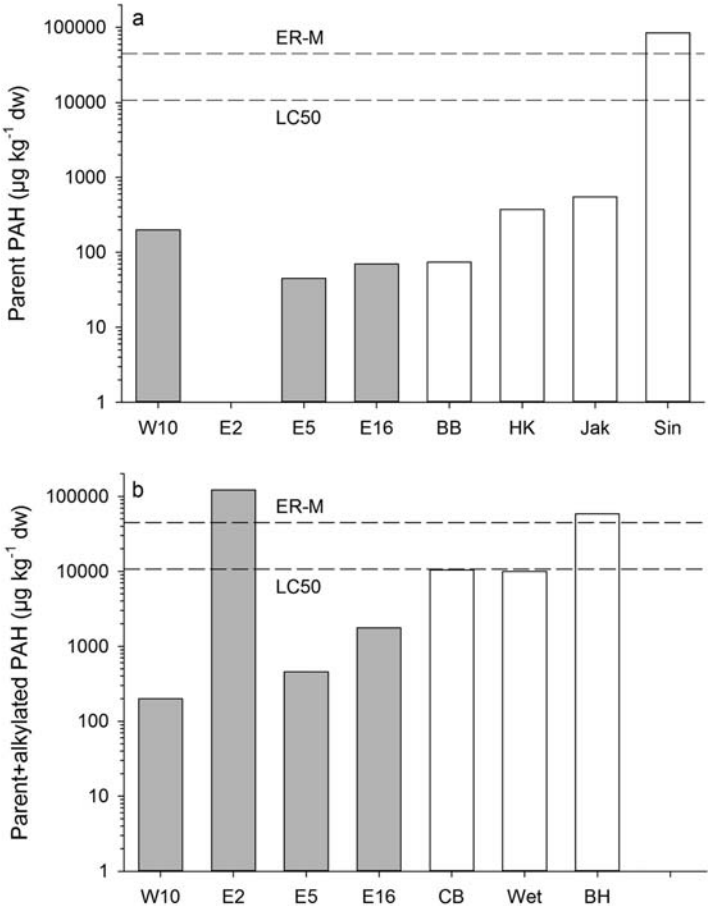

FIGURE 7.4 Concentrations of total parent PAH (A) and of total parent PAH + alkylated PAH (B) in sediments from Segara Anakan (gray bars) and in sediments from other areas (white bars). Note the logarithmic scale for PAH concentrations. Sediment toxicity thresholds: LC50 of oil-polluted sediment as obtained by a standard amphipod bioassay using Rhepoxynius abronius, considering 20 parent PAHs and 19 alkylated PAHs (Page et al., 2002). LC50 is the concentration of a compound that is lethal for 50% of the exposed population. Effects range-median (ER-M) value for toxic effects of marine and estuarine sediments on aquatic organisms, considering 12 parent PAHs and methylnaphthalene (Long et al., 1995). The ER-M indicates the concentration of a compound above which toxic effects are generally observed. (A) BB, Banten Bay, Indonesia; HK, Nature reserve near Hongkong; Jak, Jakarta Bay, Indonesia; Sin, Singapore's coastal environments. (B) CB, Cienfugos Bay, Cuba; Wet, Wetlands, Alberta, Canada; BH, Boston harbor. *Adapted from and for data sources see Dsikowitzky et al. (2011).*

Substances resulting from municipal sewage input were found, but concentrations were low. Moreover, no contaminants were detected which can clearly be assigned to further pollution sources such as agriculture or other industries. Contamination close to the oil refinery mainly consisted of alkylated polycyclic aromatic hydrocarbons (PAHs), while concentrations of the "usual suspects" known from the Stockholm Convention, the parent PAHs were low. As yet not much attention has been paid to alkylated PAHs. However, the sum of parent PAHs together with alkylated PAHs in sediments close to the oil refinery exceeded published toxicity thresholds for aquatic invertebrates (Fig. 7.4). As these compounds are structurally similar, it is likely that alkylated PAHs have a health risk potential similar to that of parent PAHs. Macrobenthic invertebrates from the mangrove forest took up contaminants from different sources in different combinations suggesting a species-specific uptake related to habitat and feeding mode (Dsikowitzky et al., 2011). This, in turn, implies that the biotic responses to organic contaminants are not uniform and health risks for organisms can be manifold. Taking into account that organisms from the lagoon are an important food source for the local population and that some pollutants can become enriched along the food web, the consumption of benthic organisms like, for example, crabs, mussels, and snails may even impose a health risk on humans. However, assessing this risk would require to quantify possible bioaccumulation of contaminants in those organisms, which could not be done in the frame of the SPICE investigations.

The generally low to moderate concentrations of nutrients and organic contaminants are probably mainly related to the short residence time of the water in the SAL and indicate that a large portion of land-derived substances from agriculture, industry and households are rapidly exported to the Indian Ocean.

7.3.3 Carbon sources and storage

While mangrove forest is the dominant land cover in and around the lagoon area and therefore also a major source of carbon for storage and export, the tidal exchange with the Indian Ocean and the river inputs from the hinterland are other quantitatively important sources of carbon. The carbon and nitrogen stable isotope composition of plants and soils from the mangrove forest and from the rice-dominated hinterland as well as of lagoon sediments indicates a W–E gradient in organic matter composition that is mainly related to the land-derived inputs. While rice field soils have an average $\delta^{13}C_{org}$ of −26.1‰ and a $\delta^{15}N$ of 5.3‰, mangrove leaves of the dominant species form the other end of the spectrum with ranges of −30.9 to −27.7‰ for $\delta^{13}C_{org}$ and of −1.0 to 6.2‰ for $\delta^{15}N$ (Moll, 2011). The isotope signatures of sediments from the eastern lagoon are closer to those of the mangrove leaves, while those of sediments from the western and central lagoon are closer to those of rice soils and the Citanduy River (Moll, 2011; Weiss et al., 2016). Sediment cores obtained from an island in the central lagoon that only formed in the second half of the last century and is dominated by mangrove plants display an isotope signature close to that of rice soils and Citanduy sediment and suggest that a large portion of the sediment and carbon deposited there is not of mangrove but of hinterland origin (Fig. 7.5).

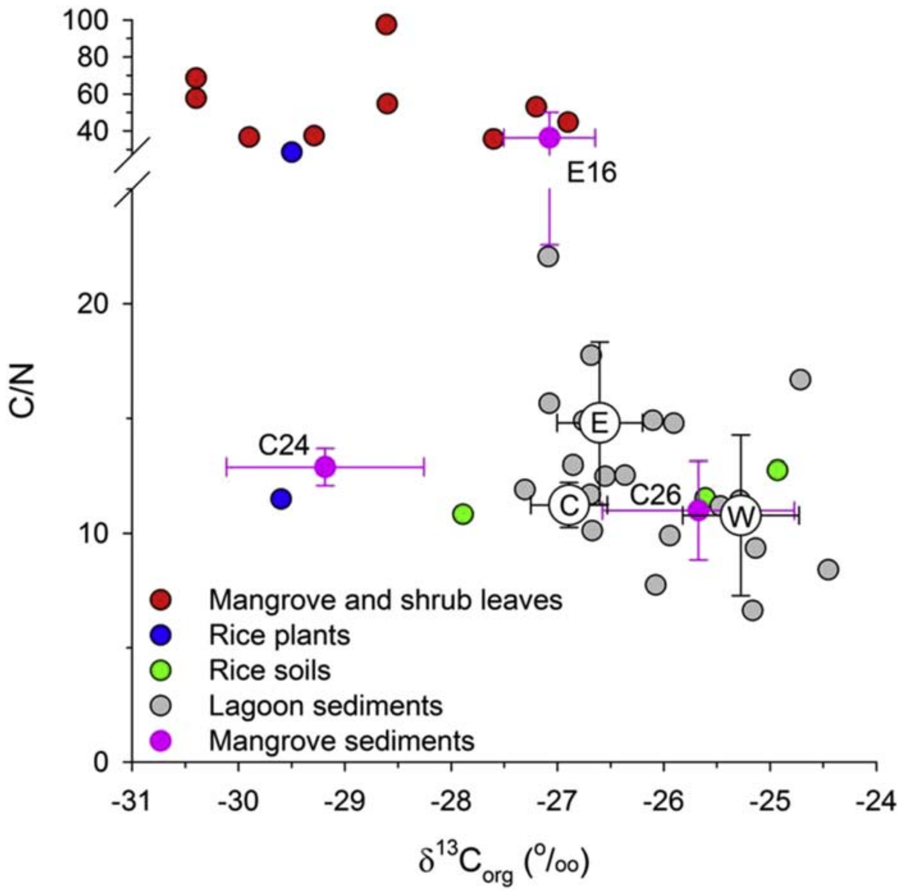

FIGURE 7.5 Biogeochemical properties of Segara Anakan Lagoon (gray circles) and mangrove sediments (pink circles, E16 from eastern lagoon, C24 and C26 from central lagoon) and of potential sources (rice plants and soils, mangrove, and shrub leaves). *Data from Yuwono et al. (2007) and Jennerjahn (unpublished).*

The high relative carbon storage per unit area is an important ecosystem service of mangrove forests. Major part of that carbon is stored in sediments, hence, hydrodynamics and sediment dynamics play an important role. In accordance with the large differences in hydro- and sediment dynamics between the western and central versus the eastern lagoon, carbon stocks and accumulation rates are also very different. Carbon stocks in the upper meter of mangrove sediment including belowground biomass are on the order of 100–200 Mg C ha^{-1} in the western and central lagoon and of 300–600 Mg C ha^{-1} in the eastern lagoon (Kusumaningtyas et al., 2019; Weiss et al., 2016). The aboveground biomass of <20 Mg C ha^{-1} is extremely low compared with other mangrove ecosystems in Indonesia and the global average (Alongi, 2014; Murdiyarso et al., 2015), which is probably mainly due to mangrove degradation caused by wood extraction (Hinrichs et al., 2009; Kusumaningtyas et al., 2019). Low phosphate concentrations and high N/P ratios of dissolved nutrients in combination with intensive soil nutrient recycling in logged areas with increasing pioneer vegetation (Weiss et al., 2016) indicate that P limitation may be an additional factor for the low carbon stocks in the western and central SAL.

In contrast, the carbon accumulation rate (CAR) with an average 658 g C m^{-2} $year^{-1}$ is more than three times higher in the western and central than in the eastern lagoon and among the highest in the world (range ca. 50–1700 g C m^{-2} $year^{-1}$; Kusumaningtyas et al., 2019). There, the autochthonous carbon supply of the mangrove plants is diluted by the high loads of mineral sediments from the hinterland, which results in the fairly low carbon stock. Moreover, the carbon isotope composition and C/N ratios indicate that part of the sedimentary carbon in the mangrove forest originates from the agricultural hinterland (Fig. 7.5; Kusumaningtyas et al., 2019). In the eastern SAL, the CAR is much lower, but still moderate on a global scale. Because of the low freshwater input, there is little dilution with allochthonous sediment input, leading to a high C stock but low CAR. Consequently, the carbon isotope composition and C/N ratios indicate the mainly autochthonous origin of organic matter deposited in the mangrove ecosystem.

The uniqueness of Segara Anakan is also important in terms of carbon storage in lagoon sediments. Mangrove productivity, in combination with the high sediment and carbon delivery from the hinterland, leads to the observed high carbon accumulation rates in mangrove sediments. However, the continuous tidal exchange between mangroves, lagoon, and the Indian Ocean is also responsible for a substantial export of carbon from the mangroves that are accumulating in lagoon sediments. A recent reconstruction of lagoon deposition history reveals that in the past 400 years, climate oscillations and human-induced land use change were responsible for variations in carbon accumulation. In the past century, the CAR in the central lagoon amounted to 153 g C m^{-2} $year^{-1}$, was even higher during the past two decades, and almost half of it was of mangrove origin (Hapsari et al., 2020). In combination with the hinterland input, this indicates that the lagoon itself is also a quantitatively relevant carbon sink.

The formerly described influences on the organic carbon composition of the hinterland were less pronounced in Berau, as the conservational levels of both the Berau catchment and the mangrove forest itself are higher, and as the mangrove forest is larger, while the river catchment is smaller than in the case of the SAL. Organic carbon concentrations in the mangrove sediments of Berau (1.5%–8.5%) were approximately 50% higher than in the SAL (1.1%–4.6%). In terms of organic carbon stocks, a clear gradient from the main river to its oxbows existed, yielding up to twice the carbon stocks of the SAL in sites experiencing lower sedimentation rates (Fig. 7.6; Weiss et al., 2016). C/N ratios were similar to those in the SAL and much lower than in marine mangrove sediments (e.g., Togian Islands), indicating a better potential biodegradability of organic matter in these sediments. Unlike the sediments of marine mangrove forests, those of the estuarine mangroves showed no change of the C/N ratio with depth.

A suitable way to estimate the contribution of leaf and root litter to the organic carbon in sediment is the $\delta^{13}C$ value. It differs between roots and stem of woody mangroves and the invading halophytic herbs, which appear in case of mangrove disturbance.

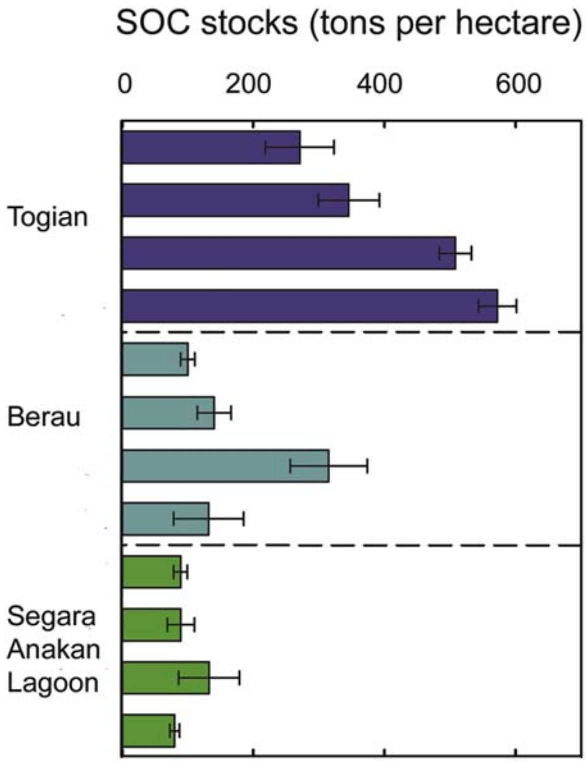

FIGURE 7.6 Comparison of the sediment organic carbon stocks down to a depth of 1 m in the mangrove forests of the Segara Anakan Lagoon, Berau, and the Togians Islands. The bars represent individual cores taken in the three study areas. Error bars denote standard deviation. *Modified from Weiss et al. (2016).*

Consequently, mangrove sediments of Berau and the Togian Islands displayed a range between −30 and −28‰, while values in the SAL ranged between −27.5 and −25.5‰, indicating the higher disturbance level of the latter (Weiss et al., 2016). In terms of $\delta^{15}N$ of soil organic matter, values were similar in the two estuarine mangrove ecosystems, ranging between 3 and 8‰, and indicating a substantial influx of N via litter input to the ecosystem, lacking the clear nitrogen-fixing symbiont signature observed for the Togians (see the following).

Due to the lacking allochthonous sediment input and therefore the missing dilution effect of suspended mineral debris, the sediments of the Togian mangroves had the highest organic carbon concentrations among the three study regions (17.3%–26.2%; Weiss et al., 2016). Based on the comparison of the upper meter, the Togian mangrove sediments sequestered by far the most organic carbon of the three study regions (Fig. 7.6). This is most likely attributable to the very high C/N ratio of 25–60, impeding microbial turnover. The low N content in the marine mangrove sediments of the Togian Islands seems to be a result of the lacking nitrogen input estuarine mangroves receive from their agriculture-dominated hinterland. The low $\delta^{15}N$ value of 0–1‰ of the Togian mangrove sediments indicates fixation by microbial root symbionts as the main entrance gate of nitrogen to the ecosystem.

In the context of evaluating the factors controlling carbon sequestration in mangroves, a strong interplay between N and P supply of mangroves was found (Weiss et al., 2016). There is a strong gradient in P content of mangrove biomass toward the sea, especially of the root biomass, with the highest stocks close to the sea, which was also observed in other regions (Castañeda-Moya et al., 2013; Adame et al., 2014). Likewise, nitrogen supply is the lower the further away a mangrove is growing from the N-bearing waters of the river estuaries, resulting in litter of wide range of C/N ratios and hampering microbial degradation in case of the seaward mangroves. As a result, mangroves invest increasing fluxes of photoassimilates into nitrogen fixation by symbionts under these conditions. As an outcome, it appears that water-extractable P (the sum of P offered by exchange processes with the soil matrix and the microbial recycling activity) is a major control of carbon stocks across the observed mangrove types (Fig. 7.7). It indicates that carbon stocks generally are determined by the distance to the sea (the source of P) and to the next river (the source of nonsymbiotic N), i.e., the larger the distance the lower the carbon stock (Weiss et al., 2016). This illustrates that restoration of mangrove forests also contributes substantially to carbon sequestration, besides its obvious advantages in coastal protection, as seaward mangroves without direct access to easy available N

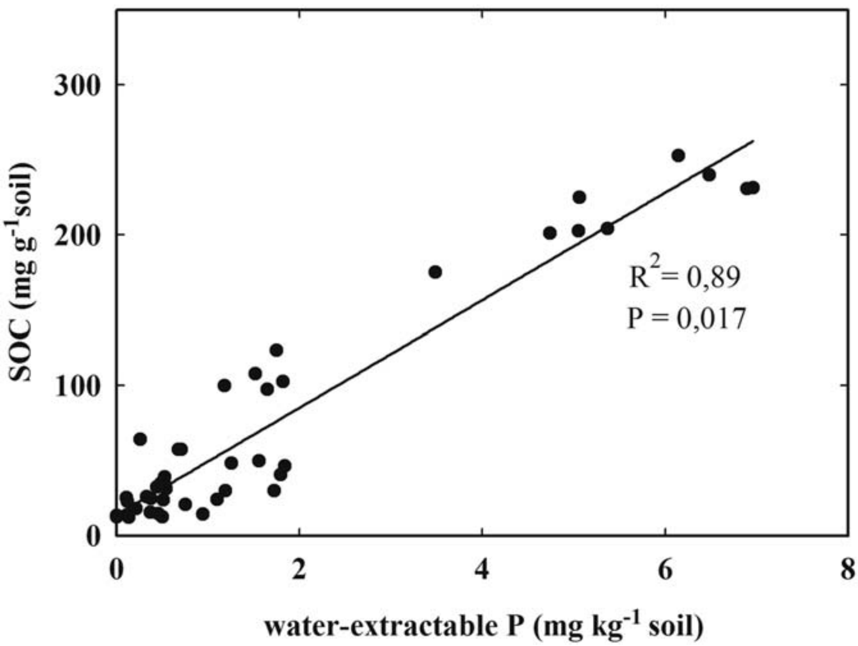

FIGURE 7.7 A close correlation between water-extractable P and sediment organic carbon exists across the mangroves in the Segara Anakan Lagoon, the Berau River estuary, and the Togian Islands, thus holding true for estuarine and marine mangroves both. *From Weiss et al. (2016).*

sources appear to have a high potential for building up carbon-rich soils. A recent "Blue Carbon" study in the Perancak estuary on Bali found carbon sequestration in soils of a mangrove forest 10 years after restoration on abandoned aquaculture ponds almost as high as in soils of a nearby undisturbed mangrove forest (Sidik et al., 2019).

Carbon stocks and accumulation rates display a large variability, but they are generally high on a global scale even when considering the Segara Anakan mangrove forest a "degraded" one (Figs. 7.8 and 7.9). The large discrepancies between the carbon stock and the carbon accumulation rate in some areas (Kusumaningtyas et al., 2019) highlight the large differences in the underlying processes and the relevance of both measurements to assess the "Blue Carbon" storage potential and its relevance for PES and REDD schemes. Indonesian mangrove forests occur in all environmental settings, which display large differences in the input and accumulation of autochthonous versus

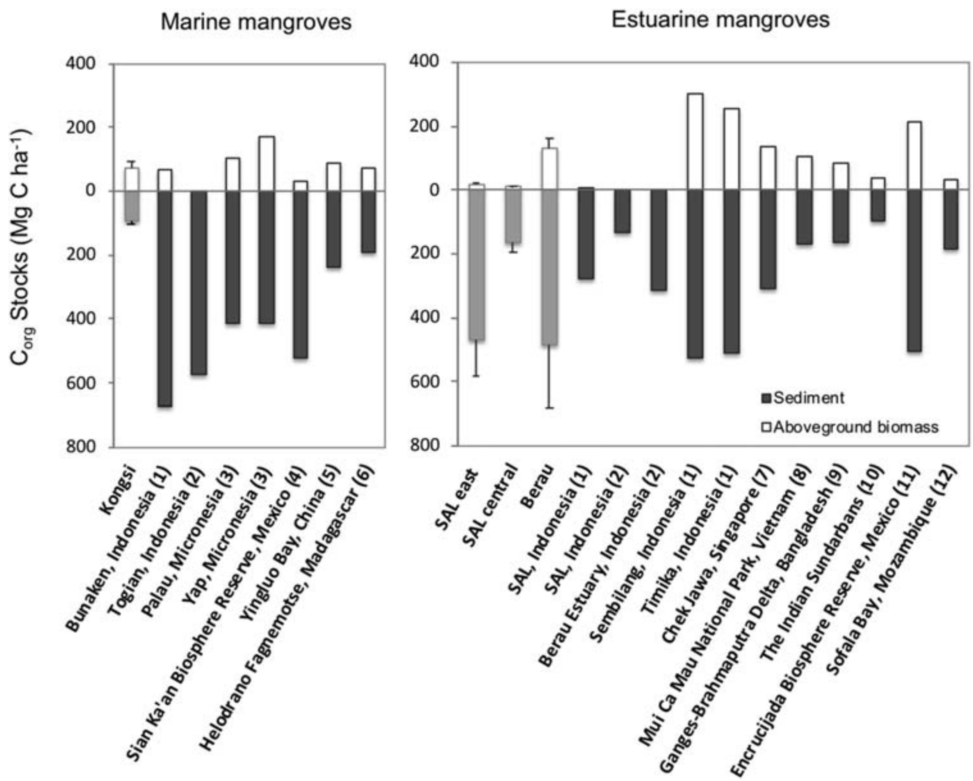

FIGURE 7.8 Global-scale comparison of carbon stocks (aboveground biomass and sediment including belowground biomass to 1 m depth) in marine and estuarine mangroves from several sites. Data source: 1—Murdiyarso et al. (2015); 2—Weiss et al. (2016); 3—Kauffman et al. (2011); 4—Adame et al. (2013); 5—Wang et al. (2013); 6—Benson et al. (2017); 7—Phang et al. (2015); 8—Tue et al. (2014); 9—Donato et al. (2011); 10—Ray et al. (2011); 11—Adame et al. (2015); 12—Sitoe et al. (2014). Boxes in light gray denote sites in the study areas of Kusumaningtyas et al. (2019; Kongsi Island; Segara Ananan: SAL east, SAL central; Berau: Berau Delta). *From Kusumaningtyas et al. (2019).*

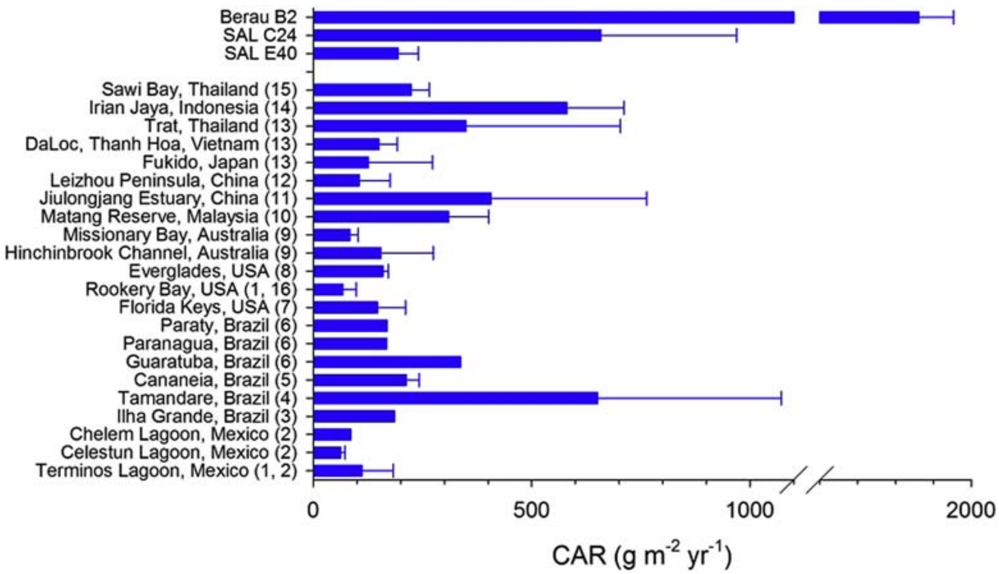

FIGURE 7.9 Global-scale comparison of carbon accumulation rates in our study areas (Berau: B2; Segara Anakan: SAL C24, SAL C26) with other sites. Data sources: 1—Lynch (1989); 2—Gonneea et al. (2004); 3—Sanders et al. (2008); 4—Sanders et al. (2010a); 5—Sanders et al. (2010b); 6—Sanders et al. (2010c); 7—Callaway et al. (1997); 8—Smoak et al. (2013); 9—Brunskill et al. (2002); 10—Alongi et al. (2004); 11—Alongi et al. (2005); 12—Yang et al. (2014); 13—Tateda et al. (2005); 14—Brunskill et al. (2004); 15—Alongi et al. (2001); 16—Cahoon and Lynch, unpublished data in Chmura et al. (2003). *From Kusumaningtyas et al. (2019).*

allochthonous carbon and mineral sediments. In this context, carbon stocks allow to assess the potential of CO_2 being released upon degradation of the ecosystem (e.g., Murdiyarso et al., 2015; Weiss et al., 2016), but they do not provide information on the actual carbon sequestration rate of the ecosystem. In contrast, carbon accumulation rates allow to quantify the amount of CO_2 sequestered at present and also in the past. Therefore, those are the more relevant numbers for calculating the climate change mitigation potential (Kusumaningtyas et al., 2019). As yet, however, there is very little information on the CAR of Indonesian mangrove ecosystems available.

7.3.4 Flora and fauna

Mangrove vegetation and macrobenthic invertebrates were studied over a period of 10 years during which a considerable decline of biodiversity was recorded (Nordhaus et al., 2019). In 2005, 21 true mangrove tree species were identified, and the community was dominated by *Aegiceras corniculatum*, *Avicennia alba*, *Ceriops tagal*, *Rhizophora apiculata*, *Sonneratia caseolaris*, and the palm *Nypa fruticans* (Hinrichs et al., 2009). Species richness declined to 15 in 2015, and mean and maximum tree diameter and mean density declined for almost all species. Stand basal area and aboveground biomass (6.3 cm^2 m^{-2} and 18.4 t dm ha^{-1} in 2015, respectively) as well as the density of *Avicennia* spp., *Sonneratia* spp., *Ceriops* spp., *Aegiceras corniculatum*, and *Bruguiera* spp.

decreased significantly over the 10 years. By contrast, an increase of *Rhizophora apiculata* abundance and biomass occurred in the eastern area of the lagoon as a result of reforestation and natural regeneration (Nordhaus et al., 2019).

Large areas of the western and central parts of the lagoon are overgrown by the herbaceous plant *Acanthus* spp., which was favored by tree logging in combination with the high freshwater input through rivers (Hinrichs et al., 2009). In 2015, this area had a significantly lower tree density, stand basal area, species number, habitat complexity, and aboveground biomass than the eastern area of the lagoon. The forest in the central lagoon can be classified as severely degraded (Nordhaus et al., 2019).

The community of macrobenthic invertebrates is diverse and composed of 49 species of brachyuran crabs, 45 gastropod species, 10 bivalve species, and 19 polychaete species (Geist et al., 2012; Güldener, 2013; Nordhaus et al., 2009; Pamungkas, 2015). Species numbers of crabs and gastropods are lying at the higher end of the worldwide range. In contrast, biomass of benthic invertebrates is low compared with other Indo-West Pacific mangrove forests (Geist et al., 2012). Dominant species are *Perisesarma darwinense* (Sesarmidae), *Metaplax elegans* (Camptandriidae), *Ilyoplax strigicarpus* (Dotillidae), *Uca bellator*, and *Uca coarctata* (Ocypodidae). The community composition differed significantly between the central and the eastern parts of the lagoon due to environmental conditions, including differing pore water salinity, sediment grain size distribution, and vegetation composition (Geist et al., 2012; Nordhaus et al., 2009; Nordhaus et al., 2011). Concurrent with the decline in tree species richness, density, and aboveground biomass, species richness of crabs declined considerably between 2005 and 2015 (Nordhaus et al., 2019; Rose, 2015, p. 121). Several new invertebrate species were detected of which the meiobenthic species *Echinoderes applicitus* (Kinorhyncha) and the polychaetes species *Polymastigos javaensis* have already been described (Ostmann et al., 2012; Pamungkas, 2015).

The mangrove forest of the Berau Delta was composed of 13 tree species and one fern species (*Acrostichum speciosum*). The most frequent tree species were *Rhizophora apiculata* und *Bruguiera parviflora*. The forest was in a good condition at almost all sites with tree heights between 10 and 25 m. Two of the 10 sites were located near shrimp ponds for which large mangrove areas had been cut (Tripathi, 2016). A total of 42 crab and 37 gastropod species were identified. The crab communities were dominated by *Ilyoplax dentatus* (Dotillidae), followed by *Clistocoeloma merguiense* (Sesarmidae) and *Paracleistostoma laciniatum* (Camptandriidae). The most abundant gastropods were *Assiminea reticula*, *Melampus* spp., and *Laemodonta* spp. Mean crab and gastropod densities were 47.4 ± 36.7 m^{-2} and 8.6 ± 6.0 m^{-2}, respectively (Tripathi, 2016). Some crab species were only recorded with one or two individuals, indicating them as rare species. The number of crab species was high, but that of gastropods was low compared with other mangrove forests in the Indo-West Pacific region.

The mangrove forest in the Togian Islands is dominated by *Rhizophora apiculata* and *Bruguiera parviflora*, similar to the sites in the Berau regency. *Rhizophora stylosa* and *R. mucronata* are mixed in, if broader coastal shelves are colonized (Weiss et al., 2016).

Toward the sea, *R. apiculata* forms almost pure stands directly limiting the seagrass ecosystem in front. Mangrove trees can reach up to 15 m height in the hinterland of the mangrove forest, but they are typically 6–8 m high under the influence of the wash of the waves. Crab and gastropod diversity appeared to be high but are not quantitatively evaluated so far.

7.3.5 Population and natural resource use in the Segara Anakan region

Segara Anakan is home to some 14,000 people living in three villages (*desa*) and a number of associated settlements (*dusun*). The villages are characterized by a nuclear structure and home to a mostly Javanese population, who were originally fisherfolk. Newer settlements often have a linear structure and developed together with the establishment of rice farming. Many of their inhabitants are migrants and often belong to the ethnic group of Sundanese from West Java, who profited from the formation of new land caused by sediment deposits. The settlement history of the lagoon is strongly linked to Java's colonial past. Written sources document the existence of 11 villages in 1706, but the spread of piracy throughout the entire Indonesian archipelago also reached Segara Anakan at the beginning of the 19th century. Its population suffered from terrible attacks by raiders acquiring slaves. In 1812, Segara Anakan's inhabitants had been either carried off or escaped inland. Resettlement started with the building of guardhouses to prevent the pirates from coming back. These guardhouses were built on stilts in the water, making them excellent places for fishing. Additional houses were soon built, and the guard stations eventually developed into fishing villages, the so-called *kampung laut* or sea villages (Schwerdtner Mañez, 2010). Segara Anakan's Javanese inhabitants still trace their origins back to a royal order assigning them to be the guardians of the coast (Reichel et al., 2009) and identify themselves as descendants of fisherfolk.

Sedimentation of the lagoon and overfishing have undermined the economic viability of fishing over the past decades. Today, fishing is largely a part-time activity, combined with the cultivation of irrigated rice, and the growing of other plants including soy beans and cassava. Fruits and vegetables are grown for subsistence needs and sold on a small-scale basis to local markets. In addition, a number of tree plantations established by lagoon residents deliver wood for paper production and other uses. In addition to agricultural expansion, aquaculture development has been a driver of mangrove conversion. Aquaculture ponds were established by external investors in the frame of the ADB-funded *Segara Anakan Conservation and Development Project*, implemented 1996–2005. These ponds were soon plundered by residents, who did not benefit from the development. The ponds have been abandoned or used mainly by immigrant Sundanese residents thereafter (Reichel et al., 2009). Another substantial mangrove area in the central part of the lagoon has gradually been converted to aquaculture by smaller-scale investors moving into the lagoon from the north coast of West Java.

Segara Anakan's mangroves have certainly always been used for different purposes. This included logging to obtain wood for construction and firewood. Charcoal production has also a long history, as evident from historical photographs. Between the 1870s and 1930s, fuelwood and charcoal production increased to an industrial level because of its use in sugar factories and for the operation of railways (De Haan, 1931). These industrial uses exceeded local residents' timber demands for houses and fishing stakes by far and contributed to extensive wood extraction, rendering first management attempts of the colonial forest administration ineffective (De Haan, 1931). Today, brickworks are an important buyer of charcoal, and increases in gas prices have contributed to a rising demand from households (Schwerdtner Mañez, Ring, Krause and Glaser, 2014). In addition to charcoal production and fuelwood collection, mangroves are used as a source of fodder. They are also important for the catching of crabs (*Scylla* spp.) and the collection of shellfish. In addition to local natural resource uses, off-farm employments and remittances have become an increasingly important source of livelihood for lagoon residents.

7.4 Environmental change in the Segara Anakan Lagoon region: causes, drivers, and impacts

The drivers of environmental change are manifold. Besides (1) climate change-related sea level rise, warming, and changes in atmospheric moisture transport, they include (2) human interventions, for example, through land use change and natural resource extraction and (3) extreme events, which can be a combination of both natural processes and human interventions, such as earthquakes, landslides, tsunamis, and a changing frequency and intensity of tropical storms (Jennerjahn and Mitchell, 2013). Most of these are relevant in Indonesia, except for the tropical storms, which are of minor relevance because of Indonesia's location in the equatorial calm zone. Indonesia has naturally high river fluxes of dissolved and particulate matter and sediments into the coastal zone; it harbors a large marine biodiversity; and in many parts, it has a dense coastal population that strongly relies on coastal natural resources. This, in turn, makes the coastal regions highly vulnerable to the outcomes of environmental change.

The island of Java is an extreme considering its magnitude of and its vulnerability to environmental change because of its exposure to natural events such as volcano eruptions and landslides, intensive land and natural resources use, and extremely high population densities of >1000 inhabitants per km^2. The environmental status and ecosystem services of the SAL are related to a large range of factors, shaping land, and natural resource use, including conflicts over resource access and control, political–economic structures, and development and management interventions in both the lagoon itself and its catchment area.

7.4.1 Decline of marine species and fisheries

Historical documents picture Segara Anakan as a diverse and species-rich environment. Dolphins, turtles, and crocodiles were common sights, and a "splendidly developed" mangrove forest grew at its shores (Beumee, 1929). Until the early 20th century, the Common Windowpane oyster (*Placuna placenta*) was an important resource collected for both consumption and its pearls (Schwerdtner Mañez, 2010). Local fisherfolk was also famous for *terasi* production, a paste made from fermented shrimp.

Impacts of environmental changes were documented nearly a century ago, when the decrease in lagoon size and depth began to affect fishing. Contemporary publications reported the disappearance of larger species and related income losses for fishers who were considered comparatively wealthy before (e.g., Schaafsma, 1927). In addition to fewer valuable species, family-owned fishing grounds got lost as former water area turned into mudflats. These fishing grounds had traditionally been used to set fixed nets, and losing them required the owners to change their gear, or to find alternative income sources. Decreasing depth was the change most mentioned by local fishermen. Decreasing salinity has also been found to be relevant, as it most likely reduces the quantity of marine fish entering the lagoon (Dudley, 2000). Another aspect is the shifting of currents resulting from changes in the water body, which has an influence on the setting of nets, such as *apong*. The tidal bag nets called *apong* are perhaps the most relevant gear change. They were introduced in the 1960s by fishermen who had been working on trawlers. Characterized by a small mesh size and set in tidal channels, *apong* nets are extremely effective and catch also juvenile species. Especially the catching of juvenile has caused conflicts between fishers operating in the lagoon and others operating in the ocean, who argue that the lagoon fishing activities decrease their catches (Dudley, 2000; Schwerdtner Mañez et al., 2014).

Livelihood diversification became the main strategy to adapt to the environmental changes. Fishers started rice farming on the new land, either part-time in combination with fishing or as a sole income strategy. Trading, sand or clay extraction, the construction of fish ponds, or employment for others became alternative sources of income. Still, fishing remained the primary income source of 90% of the population until the 1980s. After that, a vast transformation from fishing to farming took place (Olive, 1997). Research in SPICE revealed that only few full-time fishers remain, which explains the low number of interviewees. Out of 30 interviewed fishers, 19 reported species disappearances. Caught species are very small, and overall catches are low. Besides several finfish species, a number of shrimp species are caught, including *Metapenaeus elegans*, *Penaeus merguiensis, P. indicus* (Dudley, 2000), and crabs (*Scylla* spp.; I. Nordhaus, personal observation). In contrast to common narratives, fishing no longer is the most important livelihood strategy of Segara Anakan's inhabitants. It is, however, an important activity in terms of additional income, subsistence, and self-identification.

7.4.2 Sedimentation and its causes

Riverine sediment input has drastically reduced the size and depth of the SAL. However, despite predictions of its total infilling in the 1990s (White et al., 1989), the lagoon still exists. These predictions were based on unrealistically high sediment inputs of

5–10 × 10^6 t $year^{-1}$ (PRC-ECI, 1987, p. 351) or even 17 × 10^6 t $year^{-1}$ (Napitulu and Ramu, 1980). Our own estimates based on bathymetric and hydrographic measuring campaigns and modeling result in an annual sediment input from the hinterland of 1.09 × 10^6 t $year^{-1}$, only 13% of which are deposited in the lagoon. The rest is directly exported into the Indian Ocean, 0.84 × 10^6 t $year^{-1}$ through the western channel and 0.12 × 10^6 t $year^{-1}$ through the eastern channel (Jennerjahn and Winter, unpublished data). Our investigations were conducted after a large-scale dredging program, which removed 9.3 million m^3 of sediments from an area of 512 ha mainly in the central SAL in 2002–05 (Asian Development Bank, 2006). The dredging had only a temporary effect on the sedimentation process, which accelerated in the late 19th and throughout much of the 20th century. The water surface area of the lagoon decreased from almost 9000 ha in 1857/60 to slightly more than 2000 ha in 2013 (Fig. 7.10; Lukas, 2014a, 2017a).

While seen as desirable in the context of state-led agricultural reclamation plans until the late 1970s, sedimentation has been regarded mainly as a threat by governmental representatives, consultants, scholars, and fishers since the 1980s (Lukas and Flitner, 2019). Substantial investments into watershed management in the frame of both internationally funded projects and national programs have since aimed at reducing river sediment loads and lagoon sedimentation, yet with limited success.

In line with simplistic assumptions about the causes of high river sediment loads in the whole of Java, these management interventions focused on reducing soil erosion on upland farmers' private agricultural plots through field terracing and tree planting. The knowledge of other sediment sources and their causes remained scarce. No watershed-wide analysis was undertaken for the area prior to SPICE. The assumption that farmers' private plots represent the single-most important sediment source provided a clear-cut narrative for political intervention and rendered inquiries into other causes of high river sediment loads seemingly unnecessary (Lukas, 2015).

Watershed-wide mapping of land use and sediment sources, combined with analyses of satellite images and historical maps, and social-scientific research methods in the frame of SPICE has shown that farmers' private agricultural plots are in fact only one of numerous sediment sources. In addition, there are a broad range of other historical and contemporary drivers of lagoon sedimentation that have been neglected to date (Lukas, 2015, Fig. 7.10). Among the most important of these drivers are conflicts over land and forest resources. Satellite image analysis and watershed-wide mapping identified some state forest and plantation lands as hot spots of land cover change and soil erosion (Lukas, 2015). Historically rooted conflicts over the access to and control of land and forest resources are a major cause of land cover change and soil erosion in these areas (Lukas, 2014b, 2015, 2017b). State forest management practices, involving large-scale clear cuts, also on steep slopes and in close proximity to water courses, are an additional cause of land cover change, erosion, and high river sediment loads (Lukas, 2015, 2017a).

Other important sediment sources include slope cuts to enlarge agricultural fields in valley floors (a practice called *ngaguguntur*), agriculture in riparian zones, and erosion in settlements and on roads, trails, and embankments (Lukas, 2017a). In addition, various

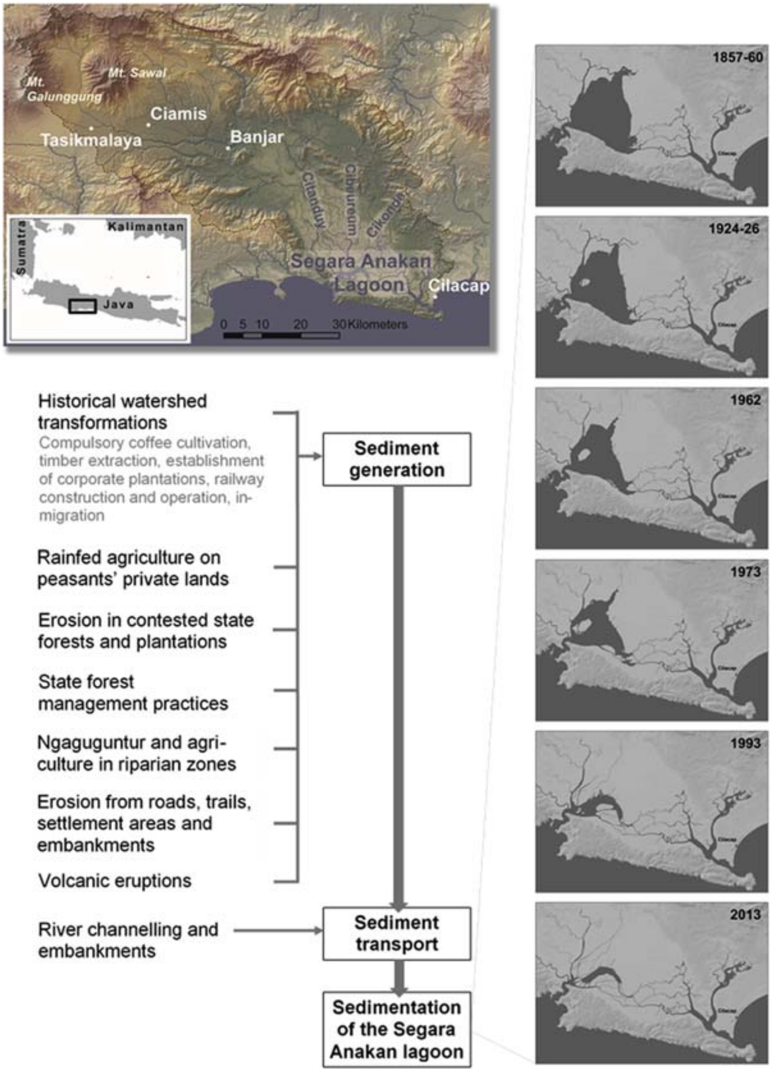

FIGURE 7.10 The Segara Anakan Lagoon has rapidly shrunk due to sediment input from the Citanduy, Cibeureum, and Cikonde Rivers. This is the result of a broad range of drivers that have increased sediment generation and transport. *From Lukas (2017a).*

historical land use and watershed modifications, including coffee cultivation under colonial rule, timber extractions, establishment of corporate plantations, railway construction, and the rapid opening up of new agricultural land in the late 19th and early 20th century, appear to have contributed to lagoon sedimentation (Lukas, 2017a). Volcanic eruptions of Mount Galunggung have also temporarily contributed to river sediment loads (Lukas, 2017a). In addition, the straightening and embankment of the lagoon's tributaries and agricultural reclamation of the floodplains of the lower river basin in the frame of government and donor-funded interventions have accelerated lagoon sedimentation, particularly since the 1960/70s (Lukas, 2017a).

Sedimentation of the SAL is hence the result of a broad range of causes. The focus of debates and management interventions on only one of these factors, i.e., erosion on upland farmers' private agricultural plots, and the neglect of numerous other sediment sources, has further limited the effectiveness of watershed management (Lukas, 2015). Political entanglements of watershed management with politics of forest access and control have contributed to this narrow focus of debates and interventions (Lukas, 2015; Lukas and Flitner, 2019).

7.4.3 Reclamation of land and conflicts over new land

Sedimentation of the SAL has had profound effects on social–ecological conditions and resource uses, has triggered conflicts, and has been the target of government-led management interventions. As with watershed management, many interventions targeting the SAL have been based on narrow assumptions and a limited understanding of realities on the ground (Heyde, 2016; Heyde et al., 2017). Furthermore, like in the lagoon's catchment area, tenure contestation also limits the scope for sustainable environmental management. While sedimentation has been seen as a threat by government representatives and academics since the early 1980s, local residents and newcomers to the SAL have used various strategies to reclaim muddy emergent land and transform it for agricultural use, homes, and other village infrastructure (Heyde, 2016). As fishing livelihoods became increasingly insecure due to sedimentation and subsequent loss of fishing grounds, people started to turn to farming (Heyde, 2016; Olive, 1997). Their small-scale reclamation initiatives have hastened the transition from water to land. As described in more detail by Heyde (2016), over time people have used at least three different microreclamation approaches: (1) transporting soil to build up land for homes and village infrastructure, (2) constructing dikes to block saltwater intrusion into agricultural fields, and (3) intentional channeling of riverine sediment into low-lying fields to enhance agricultural potential.

Early attempts by residents to assert rights to emergent land in the lagoon were at times met with heavy-handed responses from state authorities, including eviction attempts. More recently, conflict has been less overt. For example, the unclear legal status of emergent land in Indonesia has resulted in claims based on different interpretations of the law, including whether emergent land should be designated (1) as part of the national forest estate, or (2) under the jurisdiction of local residents who had traditional rights (*hak ulayat*) to open water areas that were transformed to land (Heyde, 2016). Since the mid-2000s, the state forest corporation has twice tried in the lagoon to establish village-level institutions associated with the Joint Community Forest Management program. These attempts reflect the corporation's belief that they have authority over large areas of emergent land. In both cases, the institutions were rejected by local residents (Heyde, 2016). Rights to farm emergent land were initially granted by village governments and later recognized by the district, although not in the form of full ownership (certification) (Heyde, 2016). In the early 2000s, a cadastral survey was conducted in the western part of the lagoon, following which homes and their yards became eligible for certification. At the time of field research in early 2015, ownership of agricultural land was not allowed (Heyde, 2016). Additionally, over time, people's claims to emergent land have been strengthened as users have increasingly been incorporated into the local taxation system.

The failure to resolve tenure issues points to a persistent lack of trust and weak coordination between actors in the lagoon, including the state forest corporation, various district government agencies, and local residents. There is no forum for coordination of state agencies and little opportunity for engagement by nonstate actors, such as local residents (Heyde, 2016).

Large contradictions between the perspectives and interests of local residents on the one hand and state agencies on the other hand are also evident in the large-scale construction of ponds for shrimp production that started in 1996 in the frame of the ADB-funded Segara Anakan Conservation and Management Project. External town-based investors rather than local lagoon residents managed and benefited from the development. For local fishers and farmers, the shrimp pond development caused hardships due to the loss of mangrove trees and the degradation of soil quality in their rice fields. As a consequence, the ponds were plundered and abandoned in 2001 (Reichel et al., 2009). Unfortunately, the conversion of mangrove forests to shrimp ponds was irreversible. Restoration and manual replanting efforts would not readily regenerate the mangroves (Djohan, 2014). Although aquaculture was supposed to be an alternative source of income for the coastal community, the shrimp production in fact led to ecological and social problems in the Segara Anakan ecosystem and community.

7.5 Threats to mangrove forests and their ecosystem services in Indonesia

Recent estimates show that mangrove deforestation rates in Southeast Asia in the period 2000–2012 with an average loss rate of 0.18% per year were lower than previously thought (Richards and Friess, 2016). However, mangrove loss in Indonesia is substantial. Almost half of the lost mangrove habitat is converted to aquaculture, about one-sixth to oil palm plantations. Major recent losses occurred on the islands of Sumatra, Kalimantan, and Sulawesi with conversion to oil palm plantations being the major land use change on Sumatra, while aquaculture is the dominant conversion in other parts of Indonesia (Richards and Friess, 2016).

The conversion to other land uses for economic reasons does not only mean a loss of natural habitat in the coastal zone but also entails a loss of important ecosystem services. Although these have a "value" that is not directly marketable and therefore is hardly considered by political decisions in our economy-driven world, the loss of ecosystem services can have consequences that also result in economic losses. Therefore, attempts have been made to put a value on ecosystem services from coastal wetlands. A much-noticed study resulted in a value of 10,000 USD ha^{-1} $year^{-1}$ for mangroves (Costanza et al., 1997). In another study, the annual economic values of mangroves, estimated by the cost of the products and services they provide, have been estimated to be 200,000–900,000 USD ha^{-1} $year^{-1}$ (Wells et al., 2006). Mangroves can also be provided with an economic value based on the cost to replace the products and services that they provide, or the cost to restore or enhance mangroves that have been eliminated or degraded. The range of reported costs for mangrove restoration is 225 to 216,000 USD ha^{-1}, not including the cost of the land (Lewis, 2005). However, not all ecosystem services provided can be given a "price," there are others, in particular on a local scale, which have an important value in sustaining the livelihoods of people, for example, the collection of wood for use as fuel for cooking though not having a high direct economic value (Huxham et al., 2015).

The ecosystem services of Indonesia's mangrove forests will change during this century because of climate change and associated sea level rise, but probably much more by other human interventions (Huxham et al., 2017; Jennerjahn et al., 2017). Our studies show that the supply of many of those mangrove ecosystem services are at risk, in particular in the strongly altered SAL and its surroundings (Table 7.1). There, mangrove conversions and unsustainable natural resource uses threaten the supply of the "provisioning" and the "supporting" ecosystem services. As yet, this is less relevant in Berau and on the Togian Islands, but the largely expanding oil palm plantations and aquaculture ponds at the expense of mangrove forests on Kalimantan already endanger ecosystem service supply in Berau. The supply of the "regulating" ecosystem service is to some extent endangered in the SAL but is mainly uncritical, because of high freshwater supply, the generally high river fluxes of dissolved and particulate substances, and the short residence time of the water in these coastal areas (Holtermann et al., 2009; Jennerjahn et al., 2009; Milliman and Farnsworth, 2011).

The direct value of mangroves of Berau was calculated as 296 USD ha^{-1} $year^{-1}$, the indirect value as 726 USD ha^{-1} $year^{-1}$, and the option and existence value as 15 and 358 USD ha^{-1} $year^{-1}$, respectively (Wiryawan and Mous, 2003). However, Kalimantan is the region of Indonesia for which the highest mangrove loss is forecasted for the next two decades mainly due to conversion into aquaculture ponds, followed by plantations (Ilman et al., 2016). The construction of aquaculture facilities is considered the main reason for the loss of mangrove areas on the east and west coast of Kalimantan (Karstens and Lukas, 2014; Richards and Friess, 2016); palm oil plantations replace mangroves on the west and south coast (Richards and Friess, 2016). Conservation efforts have remained minimal, and only a few mangrove areas are included in protected areas. For instance, the 4150 km^2 large Tanjung Puting National Park in south central Kalimantan has been recognized as a UNESCO biosphere reserve (Spalding et al., 2010). Yet, the example of large-scale conversions of legally protected mangrove forests to aquaculture in the Kapuas estuary in West Kalimantan by nonlocal investors backed by fisheries authorities

Table 1 Mangrove ecosystem service supply at risk in Indonesia, in the Segara Anakan Lagoon (SAL), Java, in Berau, Kalimantan, and on the Togian Islands, Sulawesi. This table shows how resource exploitation and environmental change impair the future provision of mangrove ecosystem services. Ecosystem services of mangrove ecosystems defined by the UNEP World Conservation Monitoring Center (Wells et al., 2006; second column) are grouped in the four categories defined by the Millennium Ecosystem Assessment (2005; first column). Red — at high risk, yellow — at moderate risk, green — at no risk, grey — not applicable/not investigated.

Category	Mangrove ecosystem service	SAL	Berau	Togian
Provisioning	Subsistence and commercial fisheries	Red	Green	Green
	Habitat	Red	Yellow	Green
	Honey	Grey	Grey	Grey
	Fuelwood	Red	Yellow	Green
	Building materials	Red	Yellow	Green
	Traditional medicines	Grey	Grey	Grey
Regulating	Protection of beaches and coastlines from storm surges, waves and floods	Grey	Grey	Grey
	Reduction of beach and soil erosion	Yellow	Green	Grey
	Stabilization of land by trapping sediments	Green	Green	Grey
	Water quality maintenance (N and pollutant filter)	Yellow	Yellow	Green
	Climate regulation (C sequestration)	Yellow	Green	Green
Cultural	Tourism and recreation	Grey	Yellow	Green
	Spiritual – sacred sites	Grey	Grey	Grey
Supporting	Cycling of nutrients	Yellow	Green	Green
	Nursery habitats	Red	Green	Green
	Biodiversity	Red	Yellow	Green

and state representatives demonstrates the weak enforcement of environmental law and the environmentally destructive power of corrupt political–economic networks (Karstens and Lukas, 2014a,b).

7.6 Management programs

For centuries, the natural resources and hence socioeconomic goods and services of the mangrove-fringed SAL and other mangrove ecosystems in Indonesia have been in use, but they have been increasingly threatened by conversion, degradation through unsustainable use, pollution from industry and households, and sedimentation.

The social–ecological changes in the rapidly shrinking SAL have been the subject of political and scholarly debates and of state-led management interventions for decades. Yet, rather than the ecological value of the lagoon and its mangrove forests, it was political instability and agricultural development plans that directed political attention to the lagoon and its adjacent river basin between the 1950 and 1970s (Lukas and Flitner, 2019). At that time, the lagoon and the adjacent mangrove and swamp forests were regarded as unproductive areas that were to be reclaimed for agriculture. State-initiated land swaps related to violent displacements of people in the uplands north of the lagoon and agricultural development projects pushed large-scale conversions of mangrove and swamp forests between the 1960s and 1980/90s (Lukas, 2014b; Lukas and Flitner, 2019). The declaration of the Citanduy River as national priority area for development and its selection as site for the implementation of the first US—Indonesian development project in 1969 set in motion decades of state-led interventions in the river basin, the SAL, and its watershed (Heyde, 2016; Lukas and Flitner, 2019).

In line with changing development paradigms, political interests, and material necessities created by the first projects, the focus of these interventions started to shift from agricultural reclamation to watershed and lagoon management in the late 1970s and early 1980s. Lagoon sedimentation, which was first seen as desirable and which the agricultural reclamation projects unintentionally accelerated, became a threat to the new agricultural irrigation schemes upstream, the in- and offshore fisheries, the lagoon ecosystem, and the livelihoods of lagoon residents (Lukas and Flitner, 2019). Substantial national and international funds have since been spent for upland conservation and lagoon management (Heyde, 2016; Lukas, 2015; Lukas and Flitner, 2019). Yet, the effects of these management interventions are regarded as limited. Lagoon sedimentation continues to be seen as threat by some residents, governmental representatives, and academics, while other residents hasten the transition from water to land through microreclamation strategies (Heyde, 2016). Limited knowledge of and misleading narratives about the causes of sedimentation and conflicts over land and forest resources have limited the effectiveness of sediment mitigation strategies (Lukas, 2014b, 2015, 2017a,b). River diversions to reduce sediment input and lagoon dredging only partly materialized, led to social conflicts and had only temporary effects (Heyde et al., 2017; Reichel et al., 2009). Conflicts over the control of emerging land and mangrove forests and unclear, competing jurisdictions basically thwart mangrove management and reforestation (Heyde, 2016). Furthermore, lacking trust and communication between actors, and mismatches between state-led planning and realities on the ground undermine natural resources management in both the lagoon and its watershed (Heyde, 2016; Lukas, 2017b). Based on an analysis of these issues, Heyde et al. (2017) concluded with six recommendations that should be considered to strengthen development and environmental policies in the Segara Anakan region (see Text Box 2).

More than a decade of SPICE research has resulted in robust scientific results that allowed (1) to identify cause—effect relationships in terms of environmental and socio-political issues and respective responses of the social—ecological system, (2) to quantify carbon storage and pollution (nutrients, organic contaminants) at least partly, (3) to identify knowledge gaps for future research directions, and (4) to give recommendations for policy and society (see Text Boxes 1 and 2). These recommendations as well as other results of SPICE research have been communicated to government representatives across political levels from villages to national ministries, as well as to civil society organizations. To share and discuss research results with policy-makers and civil society and to open a discussion about corresponding policy and management implications, J. Heyde and M. Lukas conducted a science-policy workshop in Cilacap in January 2016. This workshop brought together representatives of lagoon, river and watershed management authorities, forest and fisheries management authorities, agricultural and land registration agencies, district and village governments, community groups, and environmental and land rights organizations. Representatives of lagoon management authorities were also invited to the SPICE workshops held at Universitas Jenderal Soedirman, Purwokerto.

Knowledge gaps and directions of future research

- The filtering capacity of mangrove ecosystems for anthropogenic nutrients needs to be quantified to assess the risk of coastal eutrophication.
- Carbon accumulation in mangrove sediments needs to be quantified to assess Indonesia's natural carbon sinks and the potential for REDD+ schemes.
- To assess the sediment filling and the potential disappearance of the lagoon, sediment dynamics must be understood better and fluxes be quantified.
- Careful participatory mapping of competing land and resource claims and participatory design and implementation of conflict resolution mechanisms and community-based resource management approaches are the key to enhanced natural resource management in the SAL and its hinterland.

Implications/recommendations for policy and society

- Further education to raise stakeholder awareness of the value of mangrove ecosystem services and the vulnerability to overexploitation of resources is required.
- To keep the ecologically and economically important mangrove ecosystem services, logging and land conversion of mangrove forests need to be stopped.
- Because of the high competition for traditional livelihood designs heavily relying on natural resource extraction, alternative livelihood options need to be developed, for example, in the tourism, service, and finishing of goods sectors.
- Planning of initiatives to reduce river sediment loads needs to consider a broader range of sediment sources than has historically been the case.
- Conflicts between farmers and state agencies and plantation companies over land and forest resources in the watershed need to be addressed.
- Lagoon sedimentation should be regarded as a transformation of the ecosystem to which society can adapt, rather than as a threat that must be combated at any cost.
- The spatial plan for the lagoon needs to be updated to take into account claims to and usage of emergent land, and the changing environmental services of the lagoon.
- Coordination between state agencies involved in lagoon management needs to be strengthened.
- Payments for environmental services should not be prioritized as a means of addressing issues of soil erosion in the watershed and of lagoon sedimentation and degradation.

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