Historical Losses of Mangrove Systems in South America from Human-Induced and Natural Impacts

8

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Abstract

Mangrove forests are an intrinsic part of the coastal landscapes of tropical and subtropical South America. Although less well studied than their North American, Southeast Asian and Australian counterparts, they cover large expanses (approximately 11% of global mangrove cover) and perhaps represent a greater proportion of their respective coastline than other ecosystem types. The last century has been witness to a large but ultimately unknowable loss of mangrove forests across the continent through intensified use of coastal zones by humans. Indeed it has been estimated that more than 11% of the mangroves existing in the 1980's have been lost or severely degraded. Additionally, while protection for mangroves in many parts of the world has increased considerably, management in South America remains complex and the lack of regular change indicators complicates status assessments at both national and international levels. This chapter presents a historical and contemporary background to losses of mangrove systems in South America with a focus on those countries that have the most up-to-date and accessible data (i.e., Brazil, Ecuador and the Guineas). The goal was to present what is known about the drivers and degree of historical loss, the current and future threats, and to document efforts at restoring degraded forests. The chapter concludes with advice on how to address important knowledge gaps and facilitate effective management to improve the conservation outcomes for South American mangrove systems.

Keywords

Wetlands · Urbanization · Aquaculture · Modification · Sea-level rise · Climate change

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8.1 Introduction

8.1.1 Ecological Value of Mangroves

Mangrove forests are an important component of nearly all earth's tropical and subtropical coastlines and signal the frontier between terrestrial and marine environments (Alongi 2008). Although historically viewed as unproductive and even unhealthy wastelands, greater research and experience has shown mangroves to be amongst the most important and productive ecosystems on our planet (Fig. 8.1). The three-dimensional structure of these coastal forests provide numerous ecosystem services including; renewable resources for human populations (Alongi 2002), nursery grounds for a multitude of ecologically and commercially important fish and crustacean species (Nagelkerken et al. 2008), a vital role in carbon export and sequestration (Lee et al. 2014; Alongi 2012), offsets to atmospheric CO_2 emissions (Alongi 2002) and an effective means of shoreline protection (Everard et al. 2014). Despite these numerous services, mangrove forests remain at risk due to continued deforestation, land reclamation and pollution. This is especially concerning given that the structure, ecology and genetic diversity of these systems is still not fully understood. Recognizing the importance of conserving mangrove forests across South America is vital given that they are believed to harbor ca. 11% of the planet's remaining cover and because the continent is experiencing continued economic development that can overwhelm the capacity to cope with the challenges of local and global change.

8.1.2 South American Mangrove Systems

The continent of South America comprises twelve independent countries and three dependent territories, with only Bolivia and Paraguay lacking maritime borders. Together, the combined coastline extends for more than 31,000 km

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Fig. 8.1 Mangrove forests provide numerous ecosystem services to coastal environments as well as local human populations. The area of mangroves in South America (ca. 11% of global total; Ward et al. 2016) is not well defined and much of it lacks adequate legal protection (Photo: mangrove forest in Lagoa de Guaraíras, RN, Brazil, Daniel Gorman, 2016)

and includes tropical, subtropical and temperate biomes that fringe the Pacific, Caribbean and Atlantic Oceans (FAO 2007). Across this range, there exists a great diversity of coastal environments including; coral reefs, sandy beaches, mudflats, rocky reef, saltmarshes and mangrove forests (Miloslavich et al. 2010). The total extent of South American coastline covered by mangroves has been estimated at just under 2 million hectares, down from 2.2 million hectares in 1980 (FAO 2007). Because of the vastness and relative isolation of much of the coastline (particularly in the tropical north) large expanses of mangrove forest remain relatively unexplored and unstudied. Indeed, a basic *Web of Science* (database) search spanning the years 1900–2017, showed that the number of studies done on mangrove systems in South-east Asia and Australia was 1.8 and 7.7 times greater respectively, than the number done in South America.

Mangrove forests occur in all but the three coldest countries of Argentina, Chile and Uruguay (Lacerda and Schaeffer-Novelli 1999). This tropical-subtropical distribution is governed by a combination of climatic (i.e., mainly temperature and rainfall) and oceanographic factors (e.g., currents and sea surface temperature) and leads to a noticeably uneven distribution across the continent, with the Atlantic and Caribbean coasts harboring nearly 70% of the total. On the Pacific west coast, upwelling of cold water from the Humboldt current combine with a semi-arid climate and limited freshwater inputs to restrict the southern extension of forests to the Piura River in northern Peru (approximately 5°32′ S; Fig. 8.2). Along the Atlantic east coast, mangroves extend much further south to the Santo Antônio Lagoon, Santa Catarina, Brazil (approximately 28°28′S). This present limit is thought to be defined by the coldest mean monthly temperature of 20 °C and a thermal amplitude of less than 5 °C (Soares et al. 2012).

Across their South American distribution, mangroves occur within relatively sheltered muddy environments that span brackish, estuarine and intertidal zones. The group comprises a range of salt-tolerant trees and other plant species from an array of families. Members are highly adapted to periodic immersion and exposure to high tides, fluctuating salinities, low oxygen concentrations and exhibit a number of features including aerial roots, viviparous seeds and salt exclusion/excretion mechanisms (Tomlinson 1986). Compared to tropical south-east Asia where mangroves reach their greatest diversity (Polidoro et al. 2010), South American mangrove forests comprise only ten species that have different representation across the continent (Table 8.1). Species

Fig. 8.2 South Americas mangrove forests extend from the Pacific north coast of Peru, through the Caribbean and down to the southern Atlantic coastline of Brazil. Data derived from recent estimates for each country based on the model of Hutchison et al. (2014), available through the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) website (www.unep-wcmc.org)

diversity is highest in the tropics and typically declines with increasing latitude (Lacerda and Schaeffer-Novelli 1999).

Forests reach their greatest levels of development in the stable and humid tropical regions of northern Brazil, Columbia, Venezuela and the Guianas (i.e., Guyana, French Guiana and Suriname) (Fig. 8.2). Within these areas, forests can be many kilometers deep and exhibit strong horizontal zonation from fringing forests to inland river systems and lagoons. Within these systems, forests comprising the red mangrove (*Rhizophora mangle*) can reach heights of 40–50 m, with trunk girths exceeding 1 m in diameter (Lacerda and Schaeffer-Novelli 1999). Well-developed black mangrove forests (*Avicennia germinans*) regularly attain heights of up to 30 m on the coasts of the Guianas and Northern Brazil (Lacerda and Schaeffer-Novelli 1999). About half the mangrove area of the region is found in Brazil, which also has the third largest mangrove area in the world (FAO 2007).

Despite the important role of mangroves in the structure and function of coastal ecosystems, data on their distribution and status in South America is not well described. This has made understanding historical losses and rates of deforestation notoriously difficult (Blanco et al. 2012; Ellison and Farnsworth 1996). While an attempt to compile comprehensive long-term data by country was undertaken by the Food and Agriculture Organization of the United Nations (FAO 2007), this assessment was based on a relatively small number of sites stretching back to the 1980's; and its current relevance is uncertain. More recent assessments of the global status of mangroves, including those in South America, have been derived from LANDSAT imagery (Giri et al. 2011) and through the use of modeling approaches (Fig. 8.3).

Another challenge to assessing the status of South American mangrove systems as a whole (i.e., at the continental scale), has been the realization that much of the scientific research has remained stranded in the grey literature (i.e.,

Table 8.1 Mangrove species represented in South American countries (Table modified from FAO (2007))

Species	Brazil	Colombia	Venezuela	Ecuador	Suriname	Guyana	French Guiana	Peru
Acrostichum aureum		☆		☆	☆			
Avicennia bicolor		☆						
Avicennia germinans	☆	☆	☆	☆	☆	☆	☆	☆
Avicennia schaueriana	☆		☆			☆		
Conocarpus erectus	☆	☆	☆	☆		☆		☆
Laguncularia racemosa	☆	☆	☆	☆	☆	☆	☆	☆
Pelliciera rhizophorae		☆		☆				
Rhizophora harrisonii	☆	☆	☆	☆				☆
Rhizophora mangle	☆	☆	☆	☆	☆	☆	☆	☆
Rhizophora racemosa	☆	☆	☆				☆	
Total no. of species	7	9	7	7	4	5	4	5

☆ = uncertain

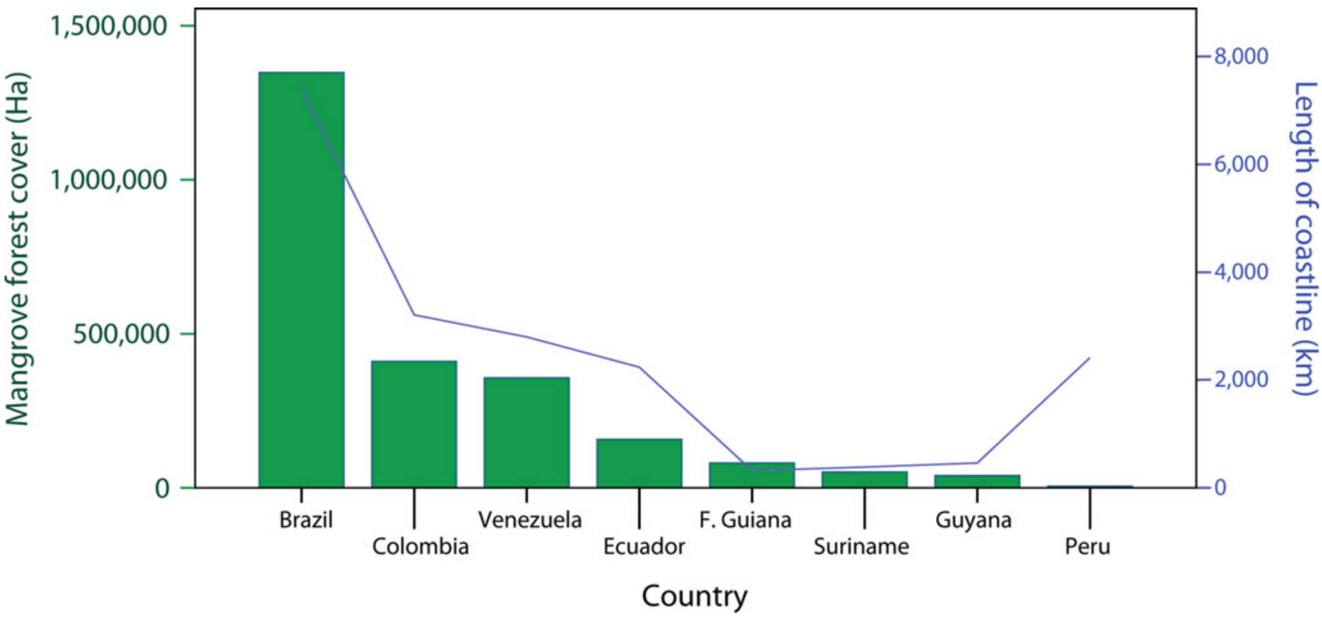

Fig. 8.3 Estimated mangrove forest cover and total length of coastline for South American countries. Bars are the most recent estimates for each country based on the model of Hutchison et al. (2014) available through the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC) website (www.unep-wcmc.org); line represents respective coastline length (CIA 2013)

forestry documents, national or state government reports, theses, etc.) and typically has not been translated into the broader canon of scientific literature (primarily in English). Difficulties in accessing data complicates the derivation of historical trends for mangrove habitats (as it has for other coastal marine systems; Connell et al. 2008). Although the problem is being addressed through efforts at international collaboration, there is still a wealth of data that will become increasingly important to understand current and future trends.

8.2 Historical Drivers of Loss

8.2.1 Natural Factors

The coastal wetlands that support mangroves can change in response to a variety of geomorphic, hydrologic and climatic factors (Phillips 1999). Understanding the long-term stability of mangroves, therefore requires an understanding of the background prevalence of natural phenomena such as floods, tsunamis, storms and hurricanes (Alongi 2002). Because these disturbances vary considerably across the South American continent, the risks they pose need to be considered on a regional basis. Hurricanes for example, have been shown to cause significant damage to mangrove forests along the Caribbean coastline of Columbia (Bernal et al. 2016) and Venezuela (Miloslavich et al. 2003) but generally do not occur along the Atlantic or Pacific coastlines. Contrastingly, tsunamis might pose a major, albeit rare, risk to forests occurring along the coastlines of Peru and Ecuador. Studies done on the impacts of the 2004 tsunami in Banda Aceh, suggest ca. 50% losses of trees directly facing the tsunami flow, with the greatest mortality seen in those species lacking prop roots (Yanagisawa et al. 2010). Given that three out of the five mangrove species in Peru fall within this category, there might be cause for concern about the scale of damage from such an event.

The absence of cyclones and tsunamis along the tropical coastlines of the Guianas and northern Brazil, means that storms and especially flooding (from the Orinoco and Amazon river systems) are the principal drivers of natural loss. Flooding for extended periods, can cover aerial roots with water and/or sediments that lead to oxygen deprivation of plant tissues and subsequent changes to leaf function (Naidoo 1983). Further south, along the subtropical coastline of Brazil, low pressure Atlantic storms are generally responsible for the greatest natural losses of mangroves, especially forests that directly fringe the coastline. The actions of wind and waves can break branches, damage foliage and in some cases undermine and uproot entire trees especially at the seaward margin (Smith et al. 1994).

Another risk for mangrove systems in South America is that of inter-annual climate variability driven by El Niño Southern Oscillation (ENSO). El Niño events typically alter rainfall patterns in ways that lead to extreme flooding in some regions but droughts in others. During ENSO years, most of tropical South America receives lower than average rainfall and a decrease in extreme precipitation events (Grimm and Tedeschi 2009). Along the semi-arid coastline of Peru however, strong ENSO events like the one that occurred between 1982 and 1983 have been shown to cause mean sea-level rise of up to 40 cm and increase rainfall by up to ten time the usual. In this way, ENSO events are likely to have considerable, though probably quite regionally specific consequences for mangrove health through changes in salinity, inundation cycles and sediment budgets (Ellison 2000).

8.2.2 Human-Induced Factors

The impacts of human activity on South American mangrove ecosystems have been long and varied. The earliest evidence for exploitation dates back ca. 9000 years to pre-Columbian human groups (Lacerda et al. 1993). These were simple activities however, that involved the traditional use of timber and wood for energy production and in this way the degree of impact was governed by the specific characteristics and size of populations. For coastal communities, there was also a sustained reliance on the food resources generated by mangroves, as evidenced by the large mounds of shells and other organic debris, called "conchales" or "concheros" (Colombia) or "sambaquis" (Brazil). Such archaeological remnants provide important information on the characteristics of these populations including food habits and resource utilization (Prahl et al. 1990).

The earliest contemporary writings of mangroves from South America are attributed to the Portuguese noble Gabriel Soares de Souza in his 1587 work titled *Tratado Descritivo do Brasil* (Treaty of Brazil), in which he describes the physical structure of trees (remarking on their curious roots) and the seemingly endless 'riches of the sea' by which he refers to the productivity of oysters associated with these same roots. European colonization intensified the pressure on mangrove ecosystems principally as a result of the development of ports and settlements to facilitate the exchange of people and goods with European centres and the African continent (i.e., the slave trade). The earliest recorded regulation relating to the use of mangroves in South America, was a law imposed on Brazil in 1706 by King Jose of Portugal who made it illegal to fell mangrove trees under financial penalty (or even a 3 month jail sentence), without first harvesting the bark (Hamilton and Snedaker 1984). Although it would be nice to imagine this as an early example of environmentally sound management, it was instead driven by the concerns of leather merchants eager to guarantee the supply of high quality material for their tanneries. The supply of tannins was important for the production of parchment for manuscripts, books and diplomas, with the South American supply becoming increasingly important as Portuguese colonial power declined in Asia.

Fast-forward to the early twentieth Century, and the general attitude towards mangrove ecosystems had changed little. Mangroves and wetlands were still widely viewed as wastelands or useless swamps and were neglected and abused well up until the late 1960s (Lugo and Snedaker 1974). Even later when their importance began to be realized through studies done in the Caribbean and North America (Golley et al. 1962; Odum 1971), attitudes toward mangrove forests in South America changed only slowly and mainly through the activities of NGO's such as UNESCO and FAO who implemented programs of research, conservation and management (Lacerda and Schaeffer-Novelli 1999). Unfortunately, this period coincided with a period of socio-economic crisis across Latin America that drove a large segment of the population into poverty and placed increasing pressure on the environment. As a result, large areas of mangrove forest were lost during the latter part of the twentieth century through a combination of demographic and economic factors linked to coastal population growth and the urgent need to generate economic opportunities (Duke et al. 2007). Table 8.2 provides a summary of the main drivers of exploitation and loss of South American mangrove forests.

It has been estimated that more than 11% of the total expanse of mangrove forests in South America were cleared between 1980 and 2005 (data derived from; FAO 2007), however when added to historical losses, this figure is likely to be much greater. It is also important to note that losses were not uniform across countries (Fig. 8.4), with estimates showing that Peru lost by far the greatest proportion of its

Table 8.2 Summary of the historical drivers of mangrove loss across South America with stars indicating the degree of complicity

Category	Agent of change	Loss
Resource exploitation	Bark tannin	☆☆
	Wood for construction	☆☆
	Charcoal	☆☆
	Traditional use/harvesting	☆
	Animal fodder	☆
	Medicines and food (e.g., fish, shellfish)	☆
Competition for space	Conversion for food production	☆☆☆
	Industrial development	☆☆☆
	Conversion to salt production	☆☆
	Urban development (e.g., condominiums)	☆☆
	Infrastructure (e.g., ports, harbors, airports)	☆☆
Human modification	Diversion of freshwater resources	☆☆☆
	Land fill, solid waste disposal	☆☆
	Eutrophication (sewage and agriculture)	☆☆
	Pollution (chemical, organic and oil spills)	☆
Management failure	Inappropriate planning policies	☆☆☆
	Failure to recognize ecosystem value	☆☆☆
	Illegal land encroachment	☆☆
	Failure of community involvement	☆☆
	Land ownership and access	☆
	Inadequate enforcement	☆

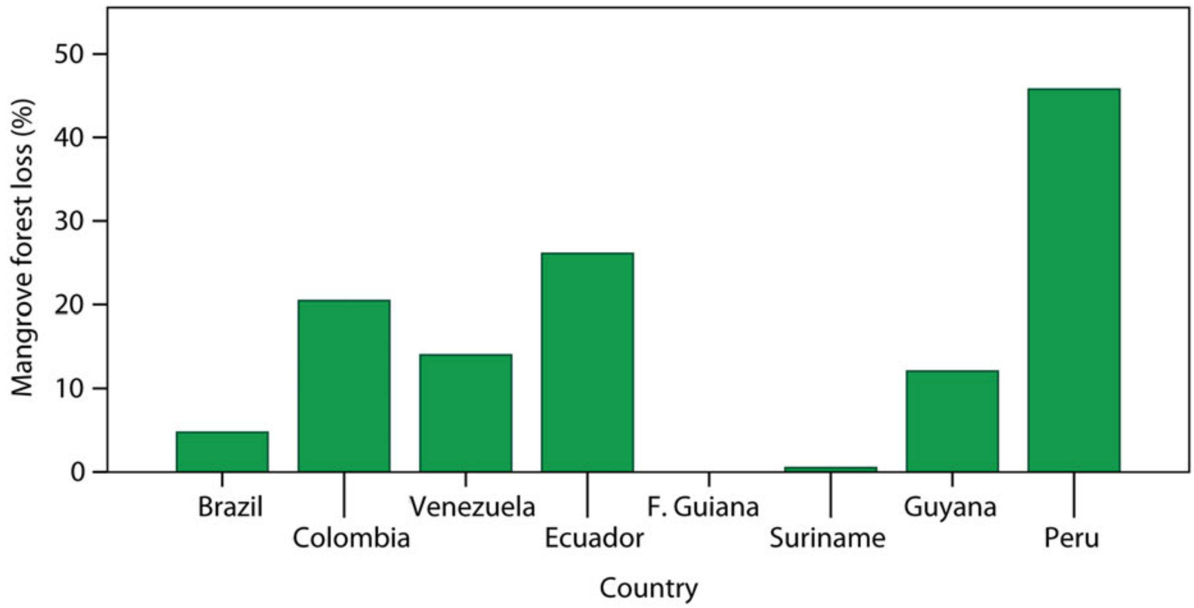

Fig. 8.4 Estimated loss of mangrove forest by South American country. Data from the Food and Agriculture Organization of the United Nations (FAO 2007)

original forests, followed by Ecuador and Columbia, Venezuela, Guyana and Brazil, and finally the lowest rates seen for Suriname and French Guiana.

8.2.3 Resource Exploitation

Although the traditional use of mangrove resources in South America is thought to be less than that which occurred in southeast Asia (Hong and San 1993), expanding coastal populations, particularly following European colonization, led to over-harvesting and a decline in natural resources in certain areas. Exploitation of mangroves for timber, charcoal, bark tannin, animal fodder and traditional medicines have all negatively impacted South American mangrove forests in a similar way to many other regions (Alongi 2002). Beginning in the sixteenth century, mangrove timber was exported from Colombia to Peru and reached in excess of 6000 poles per year by the seventeenth century (Lacerda et al. 1993). Likewise, in 1677 thousands of mangrove poles were exported to Cuba from the Pacific coast of Colombia (Prahl et al. 1990). Commerce in bark was also intense, with Ecuador for example, exporting more than 600 tons per year to neighboring countries between 1879 and 1906 (Lacerda et al. 1993). In Venezuela, extractive logging of *Rhizophora mangle* in the western part of the country for power utility poles, similarly led to marked declines in mangrove population numbers (Hamilton and Snedaker 1984). In Colombia mangrove resources have traditionally been used for construction, firewood, poles, coal, piles, pulp, to obtain tannin, and for fishing gear, cattle pens, etc. (Sánchez-Páez et al. 1997).

8.2.4 Conversion and Development

Conversion of coastal wetlands as a result of economic development and urbanization, has undoubtedly been the greatest driver of mangrove loss in South America over the past 30 years (FAO 2007; Hamilton 2013). This was driven by the imperative for economic opportunities and a need to increase food production for rapidly growing populations. Because they occur in coastal areas that provide direct access to saltwater, forests were regularly converted to provide habitat for shrimp, clams and other seafood products (Fig. 8.5a; Valiela et al. 2001). Nearly 50% of Ecuador's mangroves were converted between 1980 and 2000 as a result of shrimp farm development (Lacerda et al. 2002). In fact, the industry grew to become one of the countries three largest exports (second only to oil and just before bananas). Construction of ponds at first involved reclaiming coastal saltmarsh, but it soon started encroaching on adjacent mangrove forests. The outcome of this devastation soon became manifest in marked declines in the catches of commercially important prawns that directly relied on these mangroves as a nursery (Turner 1977). This matches the ample evidence for a direct relationship between mangrove area and offshore shrimp and fish catches in many regions (e.g., Philippines, Malaysia, Indonesia, and Australia; Primavera 1997). A similar proportion of the Tumbes mangrove forest in Peru was cleared for mariculture production between 1945 and 1985.

Fig. 8.5 Large areas of mangrove forest have been lost across South America because of a multitude of factors including; (**a**) conversion of wetlands for mariculture (photo: João Lara Mesquita, Mar Sem Fim, 2015), (**b**) urban development (photo: Portal da Copa ME, 2013), (**c**) altered hydrography (photo: Aaron Machado, Australian Marine Wildlife Research & Rescue Organisation, 2007), (**d**) anthropogenic inputs (photo: US Department of Agriculture, 2006), (**e**) widespread dumping of industrial and residential waste, and (**f**) entanglement by marine debris (photo: Daniel Gorman, 2017)

More recently in northeastern Brazil, a similar cycle occurred with a boom in the Pacific shrimp *Litopenaeus vannamei* mariculture (Lacerda et al. 2002; Maia et al. 2006) of which ca. 15% of the area is thought to have been converted from mangrove forests (Ferreira and Lacerda 2016). In addition to the direct devastation caused by these operations, there can also be long-term chronic effects for remaining forest caused by the nutrient-rich effluents produced by these activities (Suarez-Abelenda et al. 2014).

In addition to mariculture, there are a range of other activities that have caused substantial losses or degradation of mangrove forests in South America. One of these is the harvesting of salt from coastal impoundments or ponds, which, in addition to direct clearing often increases the salinity of adjacent water bodies (Silva et al. 2003). In Colombia significant growth in cattle ranching, banana farming and an expansion of the logging industry have likewise impacted mangroves, particularly those in the important area of Urabá. There have also been losses through the exploitation of fishing resources and the establishment of coconut crops.

Coastal population growth and expansion of the tourism industry during the 1980's were other significant drivers of forest loss in many parts of South America (Fig. 8.5b; Barbier and Cox 2003). These activities can have both direct effects (i.e., clearing) as well indirect consequences for forest health, brought about by the novel conditions created by humans (e.g., watershed contaminants; Peters et al. 1997). The desire for residential developments (e.g., condominiums), tourism infrastructure (e.g., hotels and marinas) and the development of ports, harbors, airports and coastal mining activities led to significant and ongoing losses of forests across the continent. In Brazil for example, mangrove losses associated with the larger population centers of Rio de Janeiro, Santos and Florianopolis have been considerable. It has been suggested, that of the forests existing around the Ilha Grande Bay (State of Rio de Janeiro, Brazil) in the 1980's, almost 80% were reclaimed for industry, residential developments and marinas (Lacerda and Schaeffer-Novelli 1999).

8.2.5 Human Modification of the Abiotic Environment

Although more subtle and often unambiguous, mangrove ecosystems have regularly suffered the effects of human modification of the abiotic environment (Fig. 8.5c). Changes to the structure and composition of forests have been associated with modifications to tidal and salinity regime, as well as changes to hydrology (i.e., freshwater inputs) and geomorphic processes (Cunha-Lignon et al. 2009; Marchand et al. 2004). Diversion of freshwater for irrigation has been recognised as a major threat to mangroves in a number of countries (e.g., Colombia, Restrepo and Kettner 2012; Peru, Burdette 2017; and Brazil, Schaeffer-Novelli et al. 2016). Mangrove communities are more susceptible to disease and pests when they are stressed by changes to salinity, inundation cycles, sedimentation and soil chemistry. Another related issue has to do with the widespread alteration of river flow through the construction of dams. In South America, 22 of the 38 large river systems currently dammed are considered to be either strongly or moderately effected (Nilsson et al. 2005), with the resulting changes to the downstream transport of sediments and freshwater likely to affect mangrove communities.

Other drivers can be more subtle, indirect and sub-lethal. For instance, the encroachment of human populations into coastal areas typically increases the wastes dumped into mangroves and adjacent coastal waterways (Figs. 8.5d and e; Mani-Peres et al. 2016). Although mangroves can assimilate some excess nutrients, this capacity is unknown for most systems and is likely to depend on the nature of discharge and the characteristics of the receiving system (Trott and Alongi 2000). Mangrove plants exhibit reduced growth when exposed to dissolved heavy metals, particularly when concentrations greatly exceed those of pristine mangrove soils (Yim and Tam 1999). In Colombia, large mangrove losses have been directly attributed to contamination of water with domestic and industrial wastes and in particular accidental spills of hydrocarbons (Guevara-Mancera et al. 1998). Studies of oil spills in the Caribbean have shown that mangroves exhibit increased mutation rates and long (approximately 20 years) recovery times after repeated exposure (Burns et al. 1993; Klekowski et al. 1994). Along the Colombian-Ecuadorian border, more than 10,000 people are engaged in gold prospecting, an activity that threatens downstream mangrove systems with mercury pollution, changes to sediment transport and freshwater flow.

Another emerging threat for the survival of mangrove forests, is the increasing volume of marine debris that enters coastal wetlands (Debrot et al. 2013). The risks posed by these materials are twofold, firstly entanglement by items such as plastic bags can lead to the mortality of juvenile plants (Fig. 8.5f; Gorman and Turra 2016) and secondly, accumulation on and around pneumatophores can suffocate adult trees. In this way, marine debris can act to reduce the health of existing forests while at the same time reducing the degree of successful recruitment. Given the enormous scale of this emerging problem, it is likely that the full implications of marine debris for mangrove forests are yet to be realized (Derraik 2002).

The cumulative effects of urbanization and changes to the abiotic environment can have major consequences for coastal wetlands. The mangroves of Guanabara Bay (Rio de Janeiro) for example, which are thought to have exceeded 50 km^2 at the beginning of the century, have been largely degraded through the modification of creeks and river banks, oil spills, solid waste dumping and decreased freshwater inputs, so that now less than 15 km^2 can be considered as relatively pristine. Along the coastline of São Paulo (Brazil) remnant mangrove stands have been heavily impacted through land reclamation, solid waste disposal, industrial and domestic effluents, chemical, organic contamination and oil spills from nearby ports and oil terminals (see the following case study of Araçá Bay).

8.2.6 Management Failure

The degradation of many coastal ecosystems has been exacerbated by the slow recognition that they need and deserve to be actively conserved (Lotze et al. 2006). Economic imperatives have historically outweighed consideration of the full suite of services provided by healthy wetlands and mangroves (IUCN 2016). Because of this, large and often inappropriate developments have regularly been approved across much of South America, resulting in substantial forest areas being destroyed, degraded or fragmented. Indeed, there is a direct negative relationship between areas of remaining forests and the level of primary sector (i.e., agricultural) activity (Barbier and Cox 2003). Most of the estimated 50,000 ha of forest cleared in Brazil over the past 25 years occurred along the more populous southern coastline, despite the greater areas of mangrove occurring in the north (Rovai et al. 2012). The severity of loss is also a function of the level of environmental protection, the accessibility of mangrove areas, and other institutional considerations (such as political stability), that vary widely both within as well as across countries.

An example of inept management in Brazil is given by the case study of Araçá Bay; a small but diverse coastal inlet located on the developed coastline of São Paulo (for a complete background see: Amaral et al. 2010). The changes to this bay clearly show how the cumulative effects of inappropriate development, pollution and socio-economic factors can lead to the degradation and possible extinction of mangrove ecosystems in certain areas. The bay, which lies in the shadow of Latin America's largest petroleum shipping terminal, contains some of the last stands of mangroves along this section of subtropical coastline (Amaral et al. 2016). Economic imperatives led to the reclamation of ca. 50% of the original bay for the construction of a port facility (beginning circa 1936; Francisco and Carvalho 2003). In addition to the direct effects on habitats, there were also major changes to the hydrodynamics of the area, which altered patterns of sediment accretion and erosion. Population growth necessitated the installation of a sewage outfall in 1990 (Mani-Peres et al. 2016), which rather than being sited offshore to avoid plumes entering the bay (Gorman et al. 2017), was inappropriately placed at its southern entrance. This led to increased inputs of organic contaminants and other pollutants and created persistent problems of eutrophication and anoxia (Gubitoso et al. 2008). These impacts combined with the widespread dumping of rubbish, residential and industrial wastes have resulted in losses of up to 65% of the historical mangrove area present in the 1960's (Fig. 8.6). What is particularly troubling about this case, is that certain sectors of industry and government are still trying to push ahead with further port amplification in the name of 'public good', which given the age of the remaining trees and critically low levels of recruitment, would likely lead to the extinction of mangroves from the area.

8.3 Current and Future Threats

Mangrove ecosystems are expected to face unprecedented challenges over the coming decades (Duke et al. 2007). While perhaps more subtle than some of the historical drivers of change, future threats are likely to be pervasive and highly consequential for species that are tightly coupled to both atmospheric and oceanographic processes (Schaeffer-Novelli et al. 2016). There is broad scientific consensus that continued human development and population growth will alter the global climate over the next hundred years, with major consequences for mangrove ecosystems, including those of South America (Ward et al. 2016). Large-scale phenomena such as sea-level rise, global warming, increased frequency of hurricanes and storms and changes to precipitation patterns, will act in concert with a range of more localized human impacts to further test the ability of mangroves to persist (Table 8.3).

8.3.1 Sea-Level Rise

Sea-level rise is widely considered to be the most serious threat to mangrove ecosystems globally (Field 1995; Gilman et al. 2008). Forests occurring in low-lying tropical and sub-tropical regions might be expected to show some of the earliest indications of change. There is concern that areas in the northeast of South America may be susceptible to the anticipated long-term trends in sea-level rise (e.g., notably the Guianas; Anthony and Gratiot 2012). The coastline of Guyana in particular, lies between 0.5 and 1.0 m below high spring tide level and because of historical destruction of the mangrove fringe, now needs to be protected by a continuous 238 km long sea defense system consisting of walls and embankments (Evans 1998). Although the effects of sea-level rise have so far been negligible when compared to some of the historical drivers of loss (outlined previously), it is likely that any effects will intensify over the coming decades (Church and White 2011, but compare Houston and Dean 2011). The risk to mangrove communities is that

Fig. 8.6 Photos showing the extent of mangroves in Araçá Bay during the 1960's (top panel) with polygons highlighting subsequent areas of loss (Cultural Heritage Department Collection São Sebastião), and the present degraded condition of remnant stands (bottom panel) that has resulted from the cumulative effects of multiple human-induced stressors (Daniel Gorman 2017)

Table 8.3 Summary of the current and future threats facing mangrove forests across South America and the world

Category	Agent of change	Threat level
Sea-level rise	Inundation and drowning	☆☆☆
Global warming	Range shifts, altered productivity	☆☆☆
Freshwater diversion	Salinity fluctuations	☆☆
	Reduced sediment replenishment	
Changing climate	Increased frequency of hurricanes and severe storms	☆☆☆
	Changes to precipitation (both increases and decreases)	☆☆
	Flooding and erosion	☆☆
Coastal urbanization	Direct clearing for urban development	☆
	Land conversion for condominiums ('sea change')	☆☆
	Construction of marinas and tourism facilities	☆☆
Economic development	Development of ports, roads and large-scale infrastructure	☆☆
	Mariculture and resource harvesting	☆☆
	Pollution and marine debris	☆☆
Genetic isolation	Loss of genetic diversity	☆
Atmospheric CO_2	Changes in physiology and productivity	☆
Biological agents	Diseases and invasion	☆

because they are typically slow growing, some populations will be unable to adapt to changes in sediment elevation, accretion, erosion, soil composition and compaction (review Gilman et al. 2008). Indeed, the consequences could be considerable, particularly in areas where rising sea level combines with reduced sediment delivery owing to anthropogenic activities such as the damming of rivers (Lovelock et al. 2015). There is recent evidence however, that well-planned restoration efforts can ensure that forests will not only keep pace and persist under medium sea-level rise, but may actually expand to increase the carbon storage capacity of these systems (Krauss et al. 2017).

8.3.2 Global Warming

Because the distribution of mangroves along both sides of the South American continent is strongly influenced by climate and temperature (e.g., Soares et al. 2012), the consequences of global warming may have unpredictable effects for these systems. While mangroves are not expected to be adversely affected by changes to sea surface temperature (Field 1995), this may be location and species specific (depending on local currents and upwelling). In terms of air temperature, most species demonstrate increased rates of productivity up to temperatures of 25 °C, so it is possible that forests in some regions may actually benefit from warming. Prolonged exposure to higher temperatures however, can lead to lower rates of leaf formation and the cessation of photosynthetic activity. An interesting aspect of global warming with respect mangroves in South America, is the likelihood of a southern extension of the current distribution limit. This links with an increasing body of work that implicates warming ocean currents, and the consequent tropicalization of temperate seas, as a driver of species range-shifts in the marine realm (Molinos et al. 2017). Warming of temperate parts of the Brazilian and Peruvian coastlines could facilitate the southward migration of mangroves, though this will depend on a number of additional factors.

8.3.3 Extreme Weather Phenomenon

Storms and extreme weather events can significantly influence the productivity and health of mangrove ecosystems. Indeed, large storms have resulted in mass mortality in ten Caribbean mangrove forests over the last 50 years (Jimenez et al. 1985). While mangroves are typically resilient to regular storm events (Alongi 2002), any increase in the frequency and/or magnitude of extreme events (as predicted by the IPCC 2014) would be likely to magnify the scale of direct storm damage (e.g., defoliation and tree mortality; Gilman et al. 2008) and exacerbate flooding, coastal erosion, saline intrusion and changes to sediment dynamics. Similarly, changes to precipitation patterns may have additional and regionally variable consequences. Decreased precipitation can restrict productivity, decrease growth and seedling survival and favor regime-shifts to more salt tolerant species (Ellison 2000). In contrast, increased precipitation, as has been predicted for large parts of the tropical north of South America (Barreiro 2010), may increase mangrove area, diversity and growth rates (Field 1995).

8.3.4 Continued Exploitation

Mangrove resources in South America will continue to be exploited both directly and indirectly. In addition to the political and scientific dimensions, there are the social issues linked to good or bad catchment management that will influence conservation outcomes (Barletta et al. 2010). The levels of social and economic development of countries and their different regions are a key determinant of wetland health and conservation options. Many coastal communities still rely on mangrove resources for their livelihood, collecting timber and wood for fuel in many parts of Brazil, Colombia, Ecuador, Guyana, Peru and Venezuela. Mangrove forests will also need to incorporate new and changing uses. A recent example, is the expansion of a new method of harvesting crabs in Brazil called *redinha*, which is causing renewed damage to mangrove forests (Nascimento et al. 2011). The approach involves cutting a section of mangrove root, which is used one time to set a snare. The increasing economic return on crabs means that this incremental damage to mangroves is certain to continue. On a larger-scale, are the challenges of providing clean power generation and sufficient food for the populations of South American countries. Continued clearance of coastal wetland for agricultural production and changes to hydrological cycles for power generation are likely to have major effects. The proposed construction of 30 major dams in the Brazilian Amazon alone (Fearnside 2014) raises the likelihood of major impacts on the extensive areas of downstream mangrove forest in the Amazon delta (Latrubesse et al. 2017).

8.3.5 Other Factors

There are a range of other factors likely to influence the sustainability of mangrove forests in unpredictable ways. The combined effects of enhanced atmospheric CO_2 and increased nutrient availability on the growth of mangroves is still largely unknown (but see, Reef et al. 2016), although there is some evidence that not all species will respond in a similar way, which could lead to changes in species composition. Another often overlooked aspect of mangrove health relates to genetic diversity and its implications for the ability of forests to cope with future environmental change. Understanding how genetic diversity varies for populations at their current distributional range limit can provide valuable insights into how species may contend with changing environmental and demographic factors (Arnaud-Haond et al. 2006). Genetic connectivity can also be a means of assessing re-colonization pathways from refuge populations (Kennedy et al. 2016) and can therefore help to inform management about the likelihood of dispersal. Although disease and other biotic factors have not historically been major causes of mangrove loss (Jimenez et al. 1985) they may become factors that can effect forests that have been weakened by changes in the physical environment.

8.4 Managing Forests for the Future

Given the diversity of threats facing mangrove ecosystems across South America, conservation will become an increasingly important and pressing issue. Economic and social pressures are likely to intensify as the continent becomes more integrated with the global economy. Safeguarding remaining forests will require a range of responses from governments and local communities (Ward et al. 2016). Priority should be given to improving scientific understanding to better anticipate current and future trends and to undertake programs to reverse past losses and build resilience. There is also a growing impetus for 'blue carbon' initiatives which have the goal of preventing further CO_2 emissions (e.g., Brazilian mangroves have the fourth largest potential for emissions under senarios of continued deforestation; Atwood et al. 2017), while at the same time protecting and restoring these habitats to take advantage of their huge potential to sequester carbon in the context of combating climate change (Mcleod et al. 2011).

There remains a clear lack of up-to-date information, in some cases at the level of entire countries (e.g., Venezuela), describing the distribution and status of forests. Typically change indicators are presented at a continental scale (e.g., Spalding et al. 1997) or focused on specific countries (e.g., Brazil as reported in; Giri et al. 2011) with fewer assessments from some of the other individual countries (other than that of; FAO 2007). Indeed, comparing past estimates of mangrove covers across South America with those derived using recent modeling approaches (Hutchison et al. 2014) reveal major inconsistencies for certain countries (e.g., both significant overestimates as well as underestimates). Concern over such uncertainty is warranted if the estimates are correct that South America harbors ca.11% of the globes remaining forests. In this context, remote sensing may provide the spatio-temporal information necessary for regular assessments of the distribution, status and any changes to mangrove populations (Kuenzer et al. 2011; Nascimento et al. 2013).

Another requirement is the improved integration of data across institutional, national and international boundaries. Much of what is known remains held by governments and universities and dissemination has not kept pace with the needs of conservation and management (Macintosh and Ashton 2002). In particular, there is a lack of understanding about the ecology, biology and taxonomy of wetland ecosystems in the more remote Amazon basins despite these areas being acknowledged as strongholds for mangroves both at a continental and global scale. There is a need for immediate efforts to continue fostering international collaborations between scientists, engineers, economists and social scientists to identify priority issues and strategies.

8.4.1 Building Resilience and Resistance

One effective means of addressing past losses of mangrove ecosystems is through the active restoration of areas that were previously degraded (Kaly and Jones 1998). This is particularly relevant for the large expanses of coastal wetland that were degraded through mariculture activities and which now lay abandoned. While self-recuperation of mangrove habitats can occur simply by preventing new impacts to allow natural recovery (Field 1996), outcomes can be improved substantially when supported by active measures such as hydrological restoration (Lewis and Gilmore 2007). Guyana represents a good example of successful restoration initiatives in South America (Anthony and Gratiot 2012). The successful collaboration between the Guyana Mangrove Restoration Project

Fig. 8.7 Restoration and augmentation of mangrove habitats can help to build the resilience of wetlands threatened by local and global change. Upper plate shows the successful outcome of a large-scale *Avicennia germinans* revegetation program along the coastline of Guyana (photo: Ian Brierley, CATS, 2012), lower plate shows small-scale revegetation plots that can restore the species richness and abundance of mangrove associated faunal communities over relatively short periods (Photo: *Avicennia schaueriana* revegetation plots in Araçá Bay, Daniel Gorman, 2015)

and the European Union led to the planting between 2010 and 2012 of more than 330,000 *Avicennia germinans* seedlings across nearly 6 km of previously exposed coastline (Fig. 8.7 upper plate; Machin, 2013). In Brazil, similar mangrove restoration efforts have mitigated some of the historical losses that occured over the last three decades (ca. 5% Ferreira and Lacerda 2016). Although revegetation initiatives are often done primarily for the purposes of shoreline fortification (Gedan et al. 2011), they have also been shown as an effective means of restoring the diversity and abundance of associated faunal communities over relatively short periods (Fig. 8.7 lower plate; Gorman and Turra 2016).

There is a clear imperative to build the resilience of mangrove ecosystems to future environmental change (Mcleod and Salm 2006). Adaption measures can help to offset anticipated losses of forests and improve their resistance and resilience to both local and global change (Gilman et al. 2008). For example, mangroves are likely to be able to adapt to sea-level rise if it occurs slowly enough (Ellison and Stoddart 1991) and if there is available space for inland expansion. This will require the setting aside of land-ward buffer zones free of other activities to permit the unhindered migration of mangroves under such scenarios. Efforts will also be required to ensure sediment delivery that is sufficient to maintain rates of vertical accretion and permit the accumulation of organic matter which plays a crucial role in the surface elevation gains required for successful adaptation (Lovelock et al. 2015).

Another hope for the continued persistence of mangroves in South America is that some populations will expand southward into higher latitudes. There is evidence that certain species are already proliferating and extended the their pole-ward range limit on at least five continents (Saintilan et al. 2014). In Brazil, studies on the thermal tolerance of *Avicennia germinans* suggest that this species could expand southwards under established global warming scenarios (Soares et al. 2012). Given the long and continuous coastline on both the western (Pacific) and eastern (Atlantic) sides of South America, mangrove forests could expand considerably given suitable estuarine conditions. The introduction of mangrove forests into areas where they did not previously occur may be an effective, or even necessary way of compensating for ongoing losses within other parts of their current distribution.

Fig. 8.8 Given the multitude of threats facing South Americas mangrove ecosystems; effective governance and community engagement will be vital to ensure the continued provision of ecosystem services by these valuable natural ecosystems (Photo: Daniel Gorman)

8.5 Conclusions

The last century has been witness to a large but ultimately unknowable loss of mangrove forests across the continent of South America. The losses that can be reliably estimated (i.e., since the 1980's) suggest that much of this was driven by the intensified use of coastal zones by humans in terms of resource extraction (fuel and wood), competition for space (aquaculture and coastal development) and changes to the abiotic characteristics of coastal wetlands (e.g., sedimentation, eutrophication, and pollution). The failure of management to acknowledge these losses along with a preoccupation with economic development has led to major loss, degradation and fragmentation of these importance ecosystems to the detriment of the many ecosystem services they provide (e.g., shoreline protection, nurseries for commercial species, etc.). To conclude on a positive note, the large areas of mangrove forest (particularly in the North of Brazil and the Guianas) and their remoteness offer substantial conservation opportunities. There is a clear imperative for immediate human action to safeguard South American mangrove systems so that future generations are not deprived of the services offered by these unique and important environments (Duke et al. 2007) (Fig. 8.8).

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