CHAPTER 16

Invasive Mangroves and Coastal Change on Moloka‘i

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Mangroves are salt-tolerant, woody plants that grow on island shores and along low-relief coastlines throughout the world’s tropical and subtropical oceans (fig. 1). Often found in association with coral reef environments, mangroves form coastal forests that exist in a dynamic equilibrium between the ocean and the land (fig. 2). The term “mangrove” refers to an individual mangrove plant, but is more generally used in an ecological context to describe an entire plant community, including approximately 70 different species of trees and shrubs, that inhabits the brackish land-sea margin along low-latitude coastlines (Duke, 1992). Not native to the Hawaiian Archipelago, mangroves were introduced to Moloka‘i in the early 20th century to help stabilize eroding coastal mudflats on the south coast near Pālā‘au (MacCaughy, 1917; Wester, 1981; Allen, 1998). Their subsequent colonization of the island’s south shore has altered the structure of the coastal margin, influencing a variety of changes to surrounding nearshore habitats and coastal infrastructure.

Figure 1. Red mangrove (*Rhizophora mangle*) juvenile tree growing on the reef flat off Moloka‘i’s south coast near Pālā‘au.

Regarded as land builders and known for their ability to promote sedimentation in coastal settings, mangroves play a valuable role in protecting and stabilizing eroding coastlines worldwide. They are most prolific in sediment-rich areas where freshwater and terrestrial runoff are abundant, such as near the mouths of coastal rivers and streams and in coastal wetlands. Mangroves trap sediment being transported seaward, thereby reducing water turbidity and decreasing the amount of sediment flowing into adjacent coastal ecosystems. Water flow is decreased in the vicinity of the extensive aerial root systems, allowing silt (fine-grained terrigenous sediment) to deposit. The high abundance of microbial communities within mangrove forests also plays an important role in trapping and binding sediment, as fine particles settling out from reduced water velocity are aggregated and mineralized by biological activity (Alongi and McKinnon, 2005).

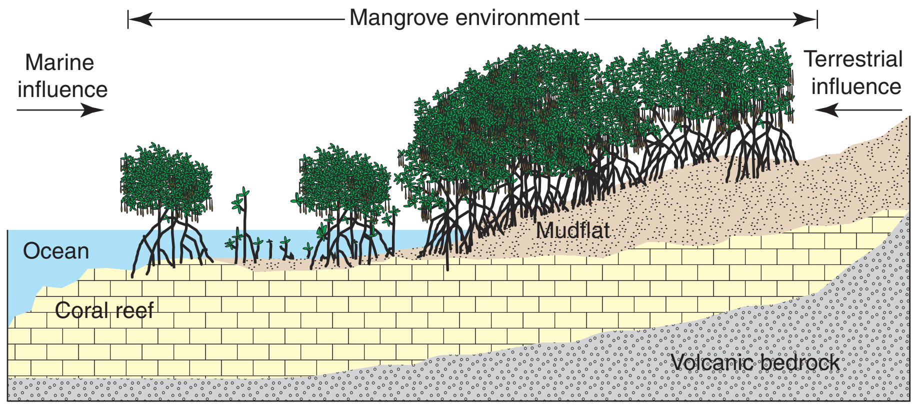

Figure 2. Schematic diagram illustrating the dynamic relation that exists between coral reef and mangrove environments because of the complex interaction of marine and terrestrial processes at the land-sea margin.

Mangroves are unique plants that have evolved special physiological and morphological adaptations which allow them to thrive in the relatively harsh environmental conditions that exist within the intertidal zone. Increased water salinity, the presence of anaerobic substrates, high-energy wave action, and frequent tidal inundation are all factors that contribute to the severe nature of the mangrove environment. Their ability to survive in these relatively adverse conditions sets mangroves apart from other plant species and allows them to occupy a niche within the coastal zone where they have little to no competition among other plants.

History of Mangroves on Moloka‘i

Although no mangrove species are native to the Hawaiian Islands, 25 species exist naturally elsewhere in the Pacific, with 9 species identified on Guam and 12 on both the Republic of Palau and the Federated States of Micronesia (Ellison, 1999). Because of the relatively young geological age of the Hawaiian Islands and their geographic and oceanographic isolation from large continental land masses, the various mangrove species that evolved and radiated throughout the Indo-Pacific during the Cretaceous Period and have since colonized many island coasts throughout the South Pacific, Atlantic, and Indian Oceans did not naturally disperse to the Hawaiian Islands.

In 1902, however, the Florida red mangrove, *Rhizophora mangle*, was introduced to the south coast of Moloka‘i by the American Sugar Company. Young mangrove trees were planted on the Pālā‘au mudflats to help protect the shoreline and adjacent coral reef environment from the increased agricultural runoff associated with the cultivation of the uplands for sugar cane (Allen, 1998). Since its introduction, *Rhizophora mangle* has become well established on Moloka‘i, migrating eastward along the coastline, colonizing tidal mud flats, shallow embayments, and the rock walls and muddy interiors of coastal fishponds. The species has also spread to other nearby islands in the Hawaiian chain but is most prolific on Moloka‘i. It now dominates the

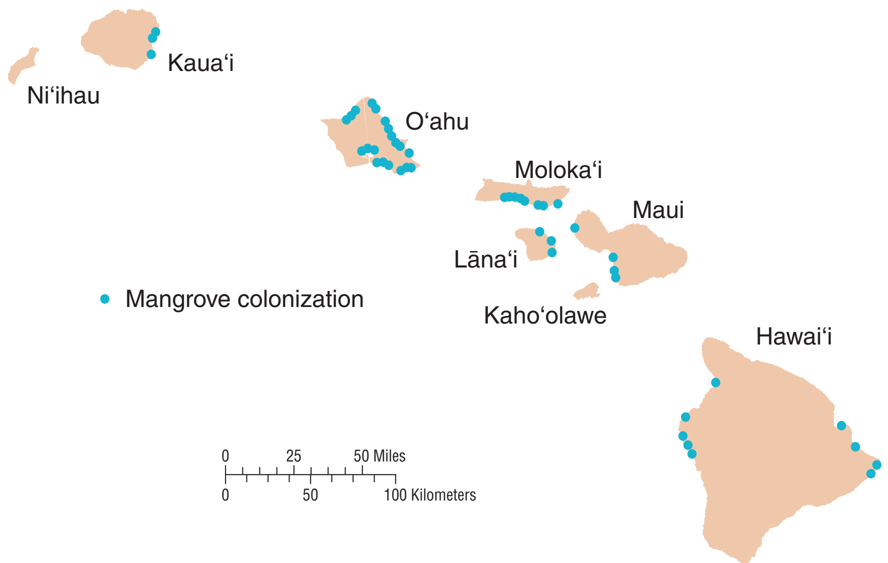

Figure 3. Map showing the approximate sites (blue dots) of known mangrove colonization throughout the eight main Hawaiian Islands. Sites updated from Allen (1998) and Wester (1981).

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Figure 4. Large mature red mangrove tree growing on the reef flat at Pālā‘au. Note the dense matrix of prop roots that extend from the tree's main stem onto the sediment-covered reef flat.

island's south coastline at Pālā‘au, and localized coastal colonies are identified as far as Pauwalu on the island's east end.

In most of the world, native mangrove systems are declining as a result of overharvesting, land reclamation, and aquaculture (Spalding and others, 1997; Alongi, 2002), and large-scale efforts focus on restoring degraded mangroves and preserving remaining natural mangrove forests (Saenger and Siddiqi, 1993; Islam and Wahab, 2005). In Hawai‘i, however, the alien mangrove is not threatened, but is spreading, colonizing coastal property on at least six of the eight main islands (fig. 3; Allen, 1998). The proliferation of introduced mangroves has contributed to loss of habitat for four endemic waterbirds, including the endangered Hawaiian stilt (*Himantopus mexicanus knudseni*), damage to sensitive archaeological sites, premature infilling of historic fishponds, and restructuring of the native coastal wetland ecosystem. Management of *R. mangle* is of concern in many of the national parks and wildlife refuges on the islands, where native habitats, nesting grounds, and important archaeological sites are threatened by encroaching mangroves. These effects of alien mangroves on the native systems have encouraged local agencies to consider and implement alien-species management strategies. Mangrove removal projects have already been initiated in the Kaloko-Honokōhau National Historic Park on the Island of Hawai‘i (Pratt, 1998) and in the Nu‘upia Ponds Wildlife Management Area (NPWMA) within the Kāne‘ohe Bay Marine Corps Base on O‘ahu (Cox and Allen, 1999).

Characteristics of Mangroves on Moloka‘i

All mangrove species are considered facultative halophytes, meaning that they can survive in both saltwater and freshwater environments. In native mangrove environments, where multiple species exist and compete for space, the mangrove habitat exhibits species zonation in response to local cross-shore environmental gradients of salinity, substrate composition, and elevation. Each zone is dominated by the mangrove species that is best adapted to survive in the given conditions. On Moloka‘i, however, there is a monospecific distribution of *R. mangle*, a species that is characteristically found at the water's edge, along the turbulent boundary of the intertidal zone. As a result, the species zonation evident in native systems is not observed on Moloka‘i, and *R. mangle* has been able to successfully migrate and colonize outside its traditional niche.

Rhizophora mangle, or red mangroves, are easily distinguished from other mangroves throughout their reproductive cycle by their prominent aerial prop roots, their thick, waxy leaves, and their pencil-shaped fruit or propagules, which grow in dense, low-hanging clusters. These propagules, which include embryonic root structures, germinate while still attached to the parent tree and grow into long greenish-brown seedlings that drop into the water, where they float upright and are dispersed by currents. After an often lengthy water-borne dispersal period (that can be as long as a year), during which they continue to grow and develop, the germinated seedlings eventually encounter land or are stranded on tidal flats, where they plant their roots, grow leaves, and flower (fig. 4). The dense system of prop roots, extending up to a meter above the soil surface, provide stability from wind and waves and are equipped with pores called lenticels that promote respira-

Figure 5. Features of red mangrove (*Rhizophora mangle*) on Moloka‘i's south coast. *A*, Propagules hanging from mature red mangrove tree at the coastal margin near Pālā‘au. *B*, Young mangrove seedlings at various stages of root development colonizing the reef flat just offshore of the Kapuāiwa coconut grove. *C*, Mangrove seedling that has taken root on the reef flat near the Kapuāiwa coconut grove. Notice the aerial prop roots that have begun to grow laterally away from the main stem toward the substrate. *D*, Red mangrove tree establishing a stronghold on the reef flat at Pālā‘au. Note the young seedling in the foreground that has yet to grow any prop roots. The prop roots collect algae and sediment around their base, forming a unique and protected environment for marine microfauna.

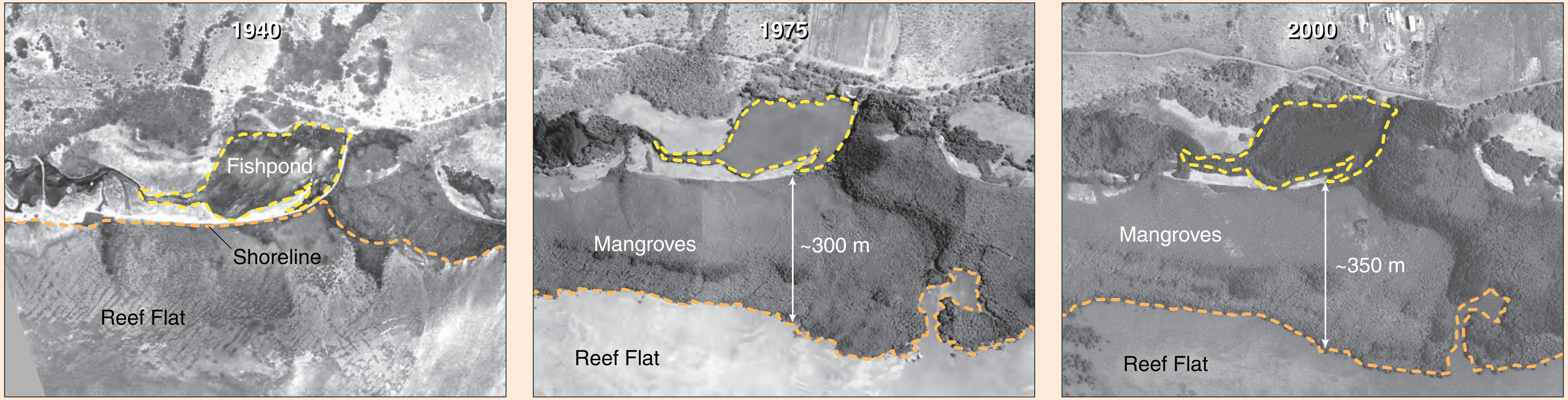


Figure 6. Historical aerial photographs showing the relative location of the shoreline (orange dotted line) to the Kaluaapuhi Fishpond (yellow dotted line) near ‘Umipa‘a in 1940, 1975, and 2000. Note the lack of mangroves on the tidal reef flat in 1940.

tion in anerobic (low-oxygen) soils by diffusing oxygen down to the buried roots when exposed at low tide. Figure 5 shows the features of *R. mangle* trees in various stages of development.

Fishponds are easy targets for mangrove encroachment, providing root support within rock walls and protection from surface currents and northeasterly trade winds. Shoreline change associated with mangroves and fishponds is most evident in the ‘Umipa‘a region, where a number of previously shoreline-bound fishponds (loko ‘ume iki) are now separated from the coastline by hundreds of meters of mangrove forest (fig. 6).

Mangroves and Shoreline Change

To understand how the invasion of *Rhizophora mangle* influenced coastal change on Moloka‘i, rates of shoreline progradation were calculated across various time scales to assess the temporal and spatial variability in mangrove colonization throughout the 20th century. Remote sensing and geographic information systems (GIS) techniques were used to interpret satellite data, aerial photographs, historical maps, and coastal surveys in order to identify the position of the south coast shoreline and to map its seaward migration since the introduction of *R. mangle* in 1902.

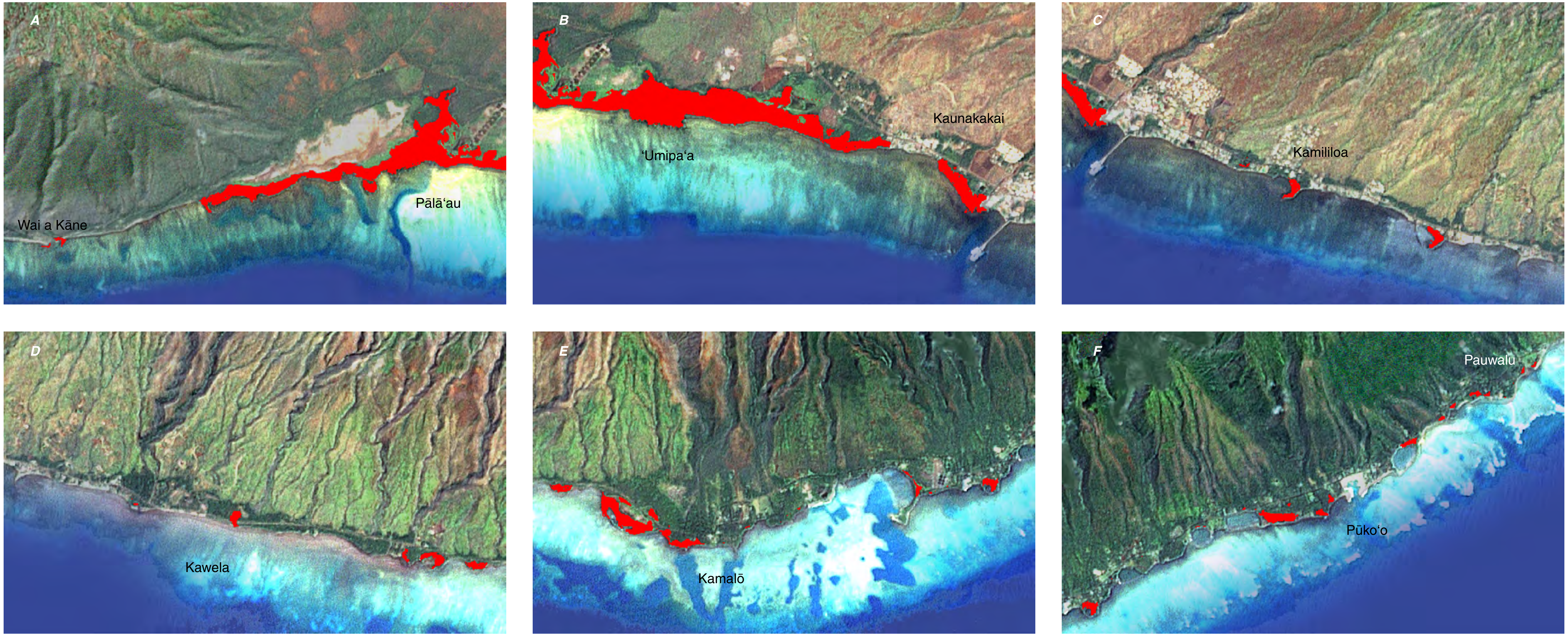
Historical maps and aerial photography offer a perspective into the past that can be digitally recreated in a GIS environment to assess spatio-temporal patterns of change in coastal systems. Topographic coastal surveys (T-sheets), published by the National Oceanic and Atmospheric Administration’s (NOAA) Coastal Services Center (and previously by NOAA’s National Ocean Service), are the oldest reliable representation of the shoreline, providing a valuable point of reference for defining historical coastal features and shoreline positions. Quantification of coastal change involves the acquisition and digitization of these historical resources, their rectification and/or georegistration, digital extraction of shoreline position, and the calculation and interpretation of change rates. Additionally, satellite data and aerial imagery were processed to extract species coverage and distribution information for assessing the spatial extent of *Rhizophora mangle* as observed from space and airborne imaging sensors.

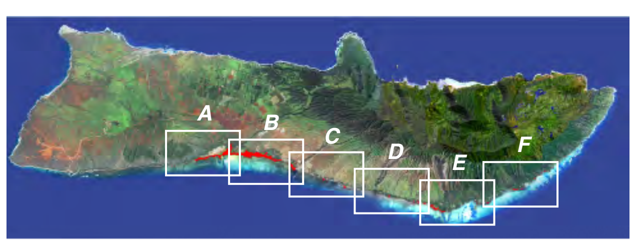
In the year 2000, mangroves occupied 2.4 km^2 of coastal land on Moloka‘i, with the Pālā‘au and ‘Umipa‘a regions exhibiting the most extensive coverage of dense mangrove canopy. The western portion of the island’s south coast exhibits greater overall coverage, whereas mangroves in the east preferentially colonized in coastal fishponds. The geographic boundaries of mangrove habitat alongshore are from Wai a Kāne in the west to Pauwalu in the east (fig. 7).

The distribution of *R. mangle* may be both naturally and anthropogenically influenced. The red mangrove prefers muddy, protected settings for colonization, but it is likely that mangrove colonization has been prevented on some suitable substrates by clearing of the propagules as they begin to encroach onto private property. In support of this, anecdotal evidence through discussion with local residents indicates that at least some fishponds are routinely cleared of mangrove pods to maintain operability and prevent overgrowth and excess sedimentation.

Mangrove propagules are dispersed into the water column and are transported by winds and surface currents, influencing the coverage of mangroves along the south coast of Moloka‘i. With predominantly east-to-west surface flow and northeasterly trade winds, material and seedlings deposited at the coast are generally transported westward (see Ogston and others, this vol., chap. 20, for further discussion about surface flow and transport). This may account for the greater mangrove coverage at the west end of the island. Additionally, observations at the Kaunakakai Wharf show a substantial accumulation of pods along the east side of the causeway, suggesting that further westward transport is blocked by the presence of this long structure that extends across the shallow reef flat.

Shoreline change rates are highly variable both alongshore and over time. From 1915 to 2000, mangrove progradation in regions of the south coast accounted for shoreline change rates in excess of 14 m (45.9 ft) per year (fig. 8). Long-term trends of shoreline change rates show an overall decrease in progradation from west to east, which appears to be related to the distribution of coastal fishponds alongshore. Interval rates for the Pālā‘au and ‘Umipa‘a regions suggest that there was an early period of rapid mangrove expansion that occurred from 1915 to 1940, during which a majority of the currently existing mangrove habitat was established (fig 9). Maximum rates calculated over this period are found in Pālā‘au, where shoreline progradation rates exceeded 44 m (144.4 ft) per year. Interval change trends





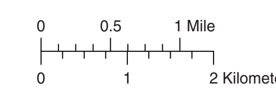


Figure 7. Maps showing the distribution of *Rhizophora mangle* (shown in red) on the south coast of Moloka‘i in the year 2000. The left image is a composite of Landsat 7 data showing the mangrove distribution for the entire south coast of Moloka‘i, with rectangles outlining the extents of the six insets presented above (*A–F*). Each red pixel represents an area 10 m by 10 m (32.8 ft by 32.8 ft) that is predominantly occupied by the red mangrove. The total coverage for *R. mangle* in the year 2000 was approximately 240 hectares (2.4 km^2).

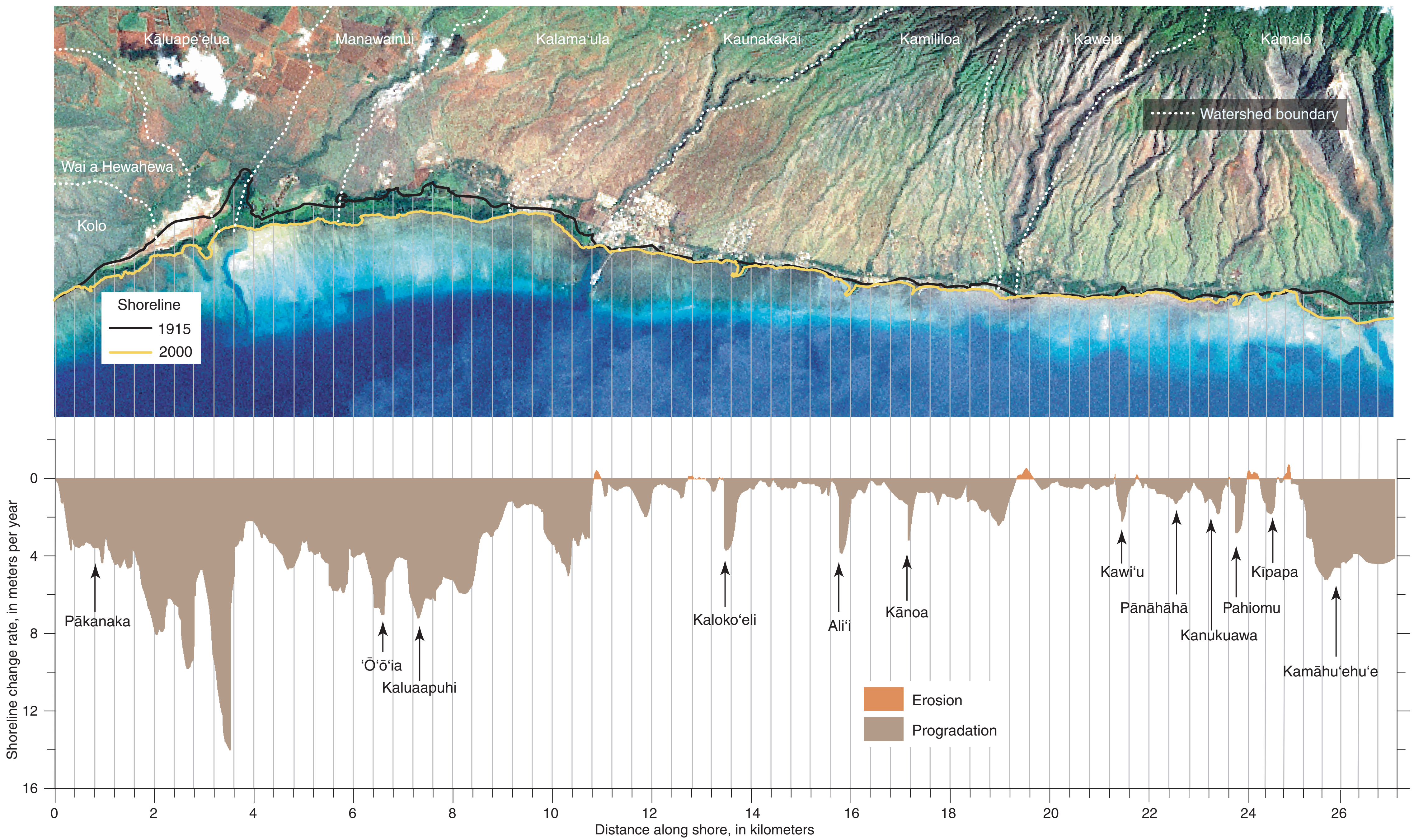


Figure 8. Landsat composite image of a 27-km (16.7 mi) section of coastline of southeastern Moloka‘i from the Pākanaka Fishpond (west) to the Kamalō Harbor (east), showing the position of the shoreline in 1915 and 2000. Below the image is a histogram of long-term shoreline change rates (1915–2000) along this stretch of coast. White dotted lines on the image represent boundaries of coastal watersheds named along the margin of the image (watershed boundaries from Hawai‘i State GIS Program, http://www.state.hi.us/dbedt/gis/, last accessed April 29, 2008). The arrows on the plot identify the locations of coastal fishponds alongshore.

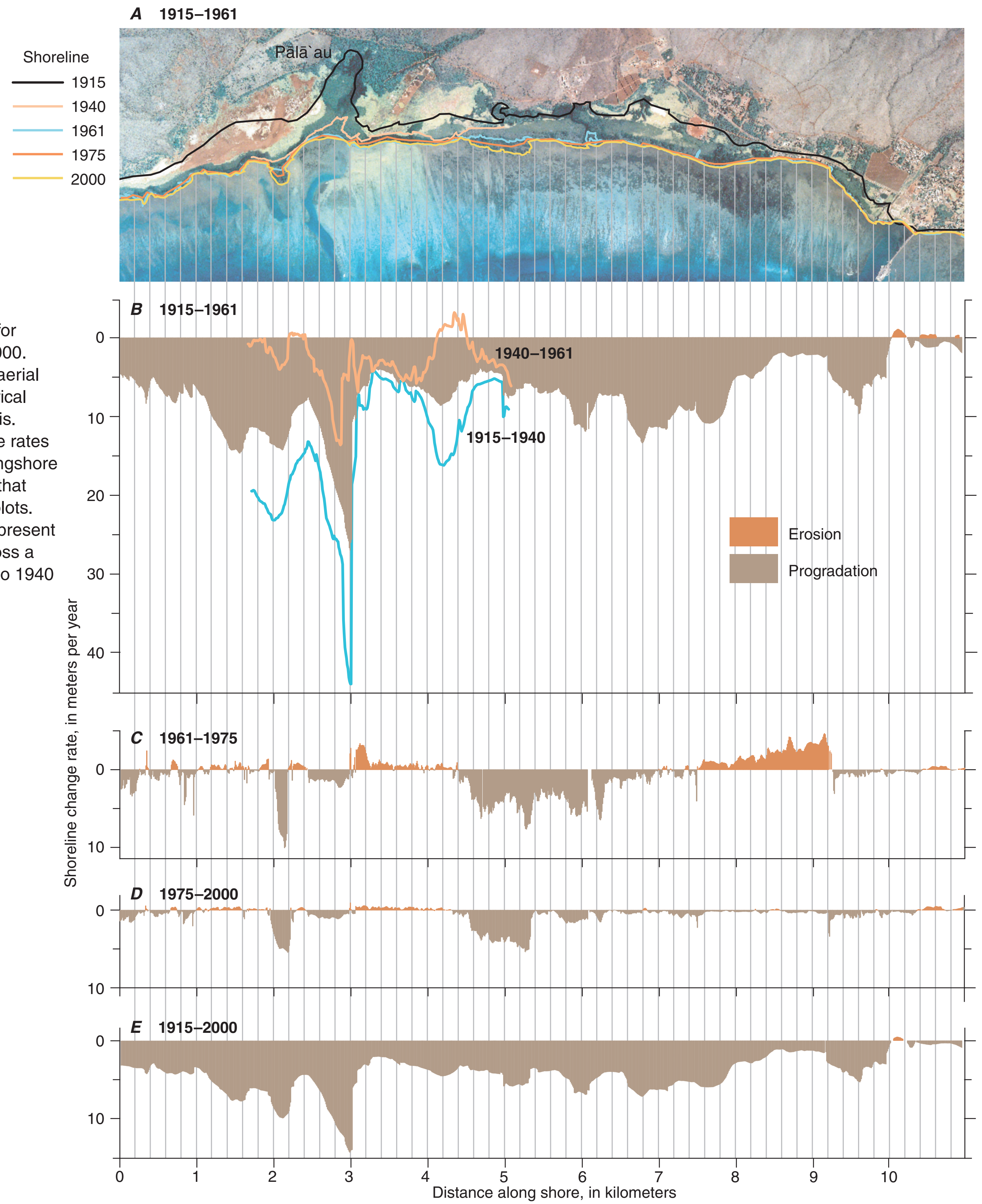


Figure 9. Shoreline change rates for the Pālā‘au region from 1915 to 2000. *A*, Orthophotomosaic of the 2000 aerial imagery overlaid with the five historical shorelines used for change analysis. *B*–*E*, Plots of the end-point change rates measured at 10-m increments alongshore in the defined time intervals. Note that the vertical scale varies between plots. The blue and orange lines on *B* represent the end-point rates calculated across a limited area of Pālā‘au from 1915 to 1940 and 1940 to 1961, respectively.

show an overall decrease in shoreline progradation rates and an increase in rates of erosion of mangrove habitat (fig. 9). From 1915 to 1961, a majority of the shoreline showed progradation, with a maximum rate of 27 m (88.6 ft) per year near the channel at Pālā‘au. Erosional trends were more evident between 1961 and 1975, when approximately 35 percent of the shoreline studied showed varying rates of retreat as great as 4 m (13.1 ft) per year. Average rates of change decayed exponentially through time, starting high in the early 20th century at 4.1 m (13.4 ft) and decreasing to modern rates of less than 0.1 m (0.3 ft) per year.

Summary

No mangroves were present on the Hawaiian Islands before their introduction (the species *Rhizophora mangle*) in 1902. Since that time, shoreline change along the leeward (south) coast has been dominated by seaward growth and progradation at specific locations, most notably the Pālā‘au and ‘Umipa‘a regions of the south-central coastline. Over the 20th century, *R. mangle* has colonized vast areas of the coastal interface, leading to seaward progradation of the shoreline across the reef flat, filling ancient fishponds, and encroaching onto private beachfront property. These effects are typical of invasive species, which often have devastating impacts on native habitats and species’ distributions, phenomena that are often exacerbated on remote islands with already low species diversity.

The invasive mangroves on Moloka‘i have both positive and negative feedbacks on the dynamics of the coastal system. They reduce the area of wetland habitat important for endemic waterbirds and encroach onto the reef flat, coastal beaches, and fishponds, yet at the same time they stabilize coastal land, create new fishery and aviary habitat, and inhibit cross-shore sediment transport onto the reef. With so many intertwined potential effects on the coastal system, understanding how the patterns of this invasive species migration, colonization, and habitat conversion proceed is an essential part of developing effective alien- species policy and coastal management practices.

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