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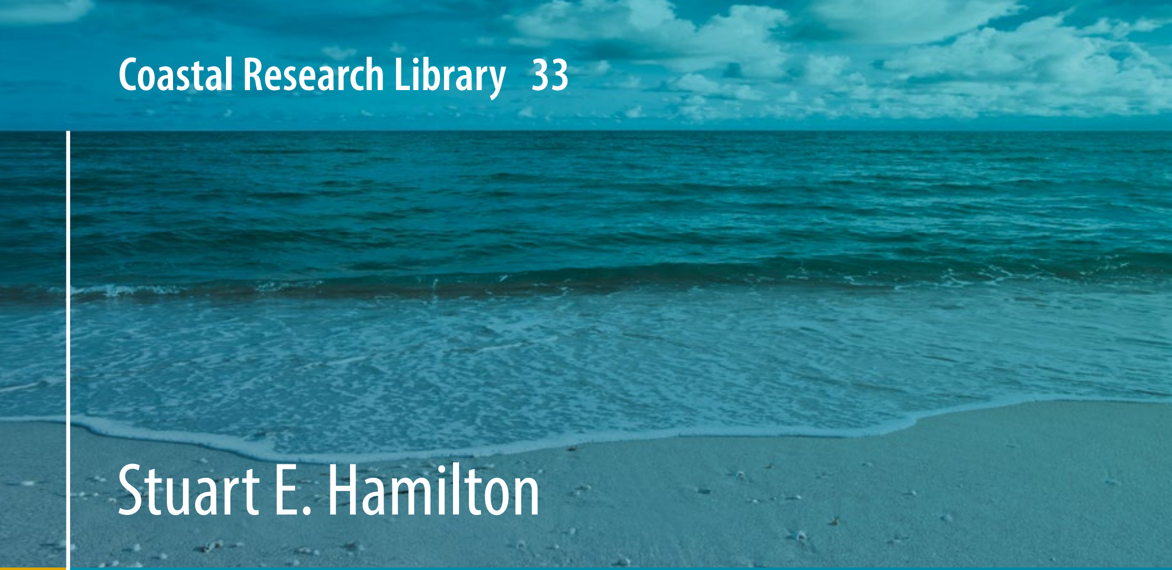

Stuart E. Hamilton

Mangroves and Aquaculture

A Five Decade Remote Sensing Analysis of Ecuador's Estuarine Environments

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Stuart E. Hamilton
Department of Geography and Geoscience
Salisbury University
Salisbury, MD, USA

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While I was in Ecuador conducting research for this book in April 2016, northern Ecuador was struck by a 7.8 magnitude earthquake centered near Cojimies Estuary. I want to dedicate this text to the families of the 676 people who died in the earthquake, the 17,000 that were injured, and the tens of thousands who lost their homes.

Preface

This book has two primary aims:

1. To tell the land use and land cover change story of Ecuador's estuaries from the advent of commercial shrimp aquaculture to the present day
2. To provide a consistent and repeatable remote sensing synthesis methodology that allows for others to conduct such analysis in different regions using different sensors that can be used in both research and instructional settings

This idea for this research began during my first trip to coastal Ecuador in late 2006 and early 2007. During this trip, I traveled up and down the Pacific Ocean coastline between Guayaquil in Guayas Province and San Lorenzo in Esmeraldas. During the long road trips, I saw the magnitude of the landscape changes that had occurred since the advent of commercial aquaculture in this region. I was surprised I did not know about such a massive and recent tropical land cover change. Massive shrimp pond systems dominated the coastal estuaries, while mangrove forests had retreated to a few locations in some isolated locations. Local fisherfolk told me a consistent story of mangrove forest loss and shrimp farm expansion occurring over the prior two or three decades and how now this land cover transition had altered their way of life.

On my return to the USA, I reviewed the academic and broader literature and could only find a limited accounting of what had occurred in this region as it pertained to mangrove loss and shrimp farm expansion. What I did find was a call to arms to tell the story from others interested in this topic. During this time, I had been considering applying to a doctoral program but had yet to find a topic that genuinely motivated me, but upon visiting Ecuador one more time and completing my literature review, I was sure this would be that topic, so I applied to Ph.D. programs with an outline of my dissertation already written. I wanted to tell the land use and land cover change story of Ecuador's coastal estuaries since the arrival of shrimp aquaculture.

I graduated with a Ph.D. about 5 years later with a dissertation entitled, "The Impact of Shrimp Farming on Mangrove Ecosystems and Local Livelihoods Along the Pacific Coast of Ecuador." Although proud of the dissertation, I immediately felt it only told a small portion of the complete story I had been researching. I began to flesh out more of the story in other venues. I was fortunate that others found the research worthwhile and a raft of publications followed including pieces in *Nature Climate Change*, *Annals of the Association of American Geographers*, *PLOS One*, *Global Ecology and Biogeography*, *Bosque*, and *Proceedings of the National Academy of Sciences of the United States of America* and a chapter in the Coastal Research Library, to which this book belongs. All these manuscripts told interesting, but isolated, portions of the bigger story. This initial mangrove and shrimp farm research agenda additionally provided me both fellowship and further research opportunities in Ecuador to continue researching the topic. As my mangrove research expanded over time, the desire to revisit the entire coastline of Ecuador and attempt to write the definitive text grew stronger. Despite the journal articles, presentations, and book chapter publications, the feeling that the full story was not being told persisted within me, and I began to realize that a comprehensive monograph was likely the only means to get the full story out to other academics and hopefully both the public and policy-makers.

From 2006 to present, I continued expanding on my research into mangrove loss and shrimp farm expansion and visited Ecuador every year for almost a decade, including living on the coast in both 2005 and 2016. Among other activities, I participated on a working shrimp farm, hiked through remote mangrove forests, and visited a shrimp hatchery. While in Ecuador, I visited the remaining mangrove forests that I had been unable to reach prior. From 2006 to 2016, I conducted interviews with fishing syndicates, held meetings with local researchers, conducted ethnographic research, and held PPGIS workshops all along the coast. Sarah Collins took the lead on the livelihood research while I kept expanded the land cover and land use theme of the research. Ramon Cedeno Loor took me under his wing and arranged for visits to ever more remote mangrove forests and meetings with more stakeholders. With the help of many students, I processed more land cover data from ever more resolute Earth observing systems and incorporated these data into my ever-growing spatial databases. By early 2016, the book was ready to be written as I finished my fellowship in Bahia de Caráquez, Ecuador.

From 2016 to 2018, the text was written and revised, and Springer accepted the book as part of their Coastal Research Library series. The book attempts to give as complete as possible account of the land cover and land use change that occurred in Ecuador's estuaries from the advent of commercial aquaculture to present. The book covers each estuary in Ecuador to allow for local, regional, provincial, and national results to be derived. In addition to telling the Ecuador story, the book presents a methodology of remotely sensed data synthesis that can be applied to other regions and other land cover types globally.

The first chapter of the book is dedicated to mangrove forests. It introduces mangrove forests and examines mangrove biology including mangrove adaptive mechanisms that allow them to exist in saline and anaerobic environments, their evolution, their current distribution, their paleodistribution including the mangrove anomaly, their historic and current coverage area estimates, their traditional uses, their species composition, their support of fisheries, their management regime, and their role in climate change. The chapter examines each of these topics at the global scale, at the Ecuadorian national scale, and when possible at the local scale. The chapter is written for coastal researchers who not are either biologists or botanists but desire to gain a foothold in mangrove research and understand the role of mangrove forests.

The second chapter of the book provides a review of shrimp aquaculture. It provides a background on shrimp farming and wider aquacultural practices. The chapter is again written for none aquaculture experts to gain the required knowledge of shrimp aquaculture to conduct such analysis as this in other regions. This chapter covers the biology of shrimp including the complex lifecycle of *Penaeus vannamei* in both the wild environment and farmed systems. Additionally, it covers the operation and management of shrimp farms, the legal framework of aquaculture in Ecuador, and the importance of Ecuador's estuaries and mangrove forests to both farmed and wild shrimps. Again, the chapter transitions from global to Ecuador to local in scale.

The third chapter of the book delineates the study sites and subdivides the coastline of Ecuador into logical estuarine units for analysis. It is dedicated to the local situation. The chapter provides information on each of the study sites including the climatic conditions of each of the estuaries, the environmental regime present in each estuary, the protected status of each estuary, the biodiversity associated with each estuary, and the socioeconomic condition of the residents who reside near the estuary. It not only attempts to provide the reader with the statistics, facts, and boundaries for each estuary but also attempts to additionally provide information on the milieu of the residents of the estuaries including information on the lifestyle, livelihoods, and culture of each estuarine community.

The fourth chapter is dedicated to the methodology with a significant portion of the chapter describing remote sensing of the Ecuadorian estuaries from pre-1970 to present. It presents a consistent and widely applicable remote sensing methodology that allow for repeating this study in Ecuador and more importantly to duplicate this study in other regions. It reviews the Earth observing instruments used, the feature delineation approaches taken, the GIS tools applied in the method of change detection, and how the differing Earth observing systems and other data were combined into a singular spatiotemporal analysis. The data required to repeat this approach is provided in the accompanying Dataverse.

The fifth chapter presents the results of the study. The results are presented at the estuarine level and then summarized to the national level. The first set of results presented document the changes in areal extent of mangrove forests and shrimp farms across all study sites. The second set of results examines the displacement of one land cover type by another. The results also present the spatiotemporal land cover changes and the sub-estuary and estuary scale. Finally, the estuary results examine the patterns revealed in the remote sensing analysis that validate the oral histories provided by local stakeholders. The data required to repeat this approach is provided in the accompanying Dataverse.

Finally, the sixth chapter of the book is a brief discussion that identifies future research needs and identifies data gaps, presents some potential policy ideas for consideration, and discusses the broader implications of this study at multiple scales. The discussion also describes the pros and cons of the methodological framework presented and suggests additional regions that may benefit from a similar approach.

The accompanying Dataverse provides all data in GIS and tabular formats. This includes all input data, all output data, and other data required for data processing. The URL is https://dataverse.harvard.edu/dataverse/MFACRL.

Salisbury, MD, USA Stuart E. Hamilton

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Contents

Acronyms

AC	Agulhas Current
ACEP	Atlantic, Caribbean, and Eastern Pacific
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BC	Brazilian Current
BeC	Benguela Current
BMN	Baculoviral Midgut Gland Necrosis
BOD	Biological Oxygen Demand
CE	Chone Estuary
CI	Confidence Interval
CJ	Cojimies
CLIRSEN	Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos
CM	Cayapas-Mataje
DAC	Development Assistance Committee
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
EAC	East Australian Current
EOS	Earth Observing System
ESA	European Space Agency
ETM+	Landsat Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization of the United Nations
FARC	Revolutionary Armed Forces of Colombia
FCR	Feed Conversion Ratio
FDI	Foreign Direct Investment
FUNDECOL	Fundación para la Defensa Ecológica
GDP	Gross Domestic Product
GFC	Global Forest Cover
GG	Gulf of Guayaquil
GIS	Geographic Information System
GLCF	Global Land Cover Facility

GS	Gulf Stream
HAB	Harmful Algal Bloom
HC	Peruvian/Humboldt Current
IFC	International Finance Corporation
IGM	Instituto Geografico Militar
IHHNV	Infectious Hypodermal and Hematopoietic Necrosis
IMF	International Monetary Fund
ISME	International Society for Mangrove Ecosystems
ITTO	International Tropical Timber Organization
IUCN	International Union for Conservation of Nature
IWP	Indo-West-Pacific
KC	Kuroshio Current
LULC	Land Use and Land Cover
MAE	Ministerio del Ambiente del Ecuador
MFW	Mangrove Forests of the World
MHHW	Mean Higher High Water
MLC	Maximum Likelihood Classification
MS	Muisne
MSS	Multispectral Scanner 1
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NGO	Nongovernmental Organization
NOAA	National Oceanographic and Atmospheric Administration
OECD	Organisation for Economic Co-operation and Development
OLI	Operational Line Imager
PBDE	Polybrominated Diphenyl Ethers
PCB	Polychlorinated Biphenyls
PCDD	Polychlorinated Dibenzodioxins
PCDF	Polychlorinated Dibenzofurans
PMRC	Coastal Resources Management Program
PPGIS	Public Participation Geographic Information Systems
PSAD	Provisional South American Datum
RBV	Return Beam Vidicon
REMCAN	Reserva Ecológica Manglares Cayapas Mataje
REye	RapidEye
RMSE	Root-Mean-Square Error
SLC	Scan Line Corrector
SNAP	Sistema Nacional de Áreas Protegidas del Ecuador
SPOT	Satellite Pour l'Observation de la Terre
SWIR	Short-Wave Infrared
TIR	Thermal Infrared
TM	Landsat Thematic Mapper
TOA	Top of Atmosphere
TSV	Taura Syndrome Virus
UAV	Unmanned Aerial Vehicle

UN	United Nations
USAID	United States Agency for International Development
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VHR	Very High-Resolution Satellite-Based Optical Imagery
VNIR	Visible and Near-Infrared
WDPA	World Database on Protected Areas
WGS	World Geodetic System
WRS	World Reference System
WSSV	White Spot Syndrome Virus
ZEM	Special Area Management Plan

Chapter 1
Botany of Mangroves

To the land animal or plant, the sea is a hostile environment. High salinity, wave action, and fluctuating water levels present problems that are rarely experienced in terrestrial or freshwater habitats.

(Hogarth 2007 P. 1)

Abstract Despite such harsh environmental conditions, mangroves have colonized the nearshore environment of much of the global tropical coastline. In doing so, mangrove forests have converted what is otherwise often barren coastlines into one of the most productive ecosystems on the planet. Measured regarding human livelihoods, carbon processing, fisheries support, erosion control, or biodiversity; mangrove forests are one of the most productive ecosystems on the planet, yet they mangrove forests are historically one of the most underappreciated and misunderstood land cover types. This chapter examines the botany of mangroves. Section 1.1 describes the biology of mangroves with a focus on those present in Ecuador. Section 1.2 examines the dominant Ecuadorian mangrove that is *Rhizophora mangle* which is currently undergoing a taxonomic reclassification to *Rhizophora samoensis*. Section 1.3 delineates the global and Ecuadorian distribution of mangrove species. Section 1.4 examines current and past estimates of mangrove forest area for both global mangrove forests and Ecuadorian mangrove forests. Section 1.5 examines the role of mangrove forests in supporting the wider ecosystem that they inhabit. Section 1.6 focusses upon the role of mangrove forests in supporting wild fish fisheries and Sect 1.7 on the manner in which mangrove forests provided important livelihood options and other goods and services to the people that reside nearby. Section 1.8 elucidates on the role of mangrove forests in mitigating global climate change and recent advances in this critical arena.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-22240-6_1) contains supplementary material, which is available to authorized users.

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Keywords Mangrove forests · Mangroves · *Rhizophora mangle* · *Rhizophora samoensis* · Blue carbon · Mangrove economy · Mangrove forest cover · Mangrove anomaly

1.1 Mangrove Forest Biology

Mangrove, mangrove forest, mangrove forest trees, and mangal are used interchangeably in the geographic literature to describe the tree, plant, and shrub vegetation that exists in and around the tropics. Mangrove forests are most often located at the ocean and land interface, within secluded swamps, and at the mouths of rivers in estuarine environments. The term mangal usually represents the entire flora present in a mangrove forest swamp, and the term mangrove forest refers to those species within mangal that are taxonomically now classified as mangrove forest (Macnae 1968). Although somewhat redundant, this appears to be the most consistent use of this terminology in the botanical literature. Mangrove itself is likely a compound of the Portuguese word *mangue,* from the now extinct indigenous Taino language of the Bahamas and the Greater Antilles, and of the English term *grove.* An alternate but less accepted origin is that mangrove is an adjustment of the Malayan *manage-manggi* term which is still used in eastern Indonesia, although no longer in Malaysia, to describe the local *Avicennia* species (Bakhuizen van den Brink 1921).

There is now general agreement on the species that are considered mangroves, although new species and hybrids are still being classified. The rationale behind the grouping differs from the typical practice of basing biological taxa on common ancestry. The ambiguous mangrove forest grouping is likely because mangroves have not evolved from a single or even a handful of species, but have converged into similarity due to adaptations from inhabiting similar environments. Hence, mangrove forest taxonomy utilizes the environmental conditions of the flora habitat to delineate what species constitute mangrove forests. As such, species labeled as mangrove forest do not necessarily belong to the same taxa; for example, the seven species of mangrove forest within Ecuador belong to five different families and only two species of Ecuadorian mangrove forest belong to the same genus. Classification of mangrove species is thus in many ways a circular process, since the term mangrove forest is generally applied to plant species with specific adaptations that inhabit tropical tidal swamps, yet tidal swamps close to the tropics are often typically defined by the fact that they have mangrove forest present within them (Tomlinson 1986; Hogarth 1999, 2007; Hogarth 2015). Additionally, diverse flora often exists on the terrestrial fringe of intertidal swamps but are omitted from the general classification of mangrove forest because these species have a more dominant presence in terrestrial environments and taxa.

Several common characteristics generally exist in many species referred to as mangrove: (i) A physical adaption to the anaerobic and waterlogged environment; (ii) an adaptive mechanism for living in highly saline water and highly saline soils; (iii) taxonomic isolation from terrestrial relatives, (iv) geographic fidelity, (v) and the presence of a vivipary/crypto-vivipary embryonic structure. We examine each of these in more detail below.

(i) The primary mangrove forest adaptation that allows them to flourish in both waterlogged and anaerobic soils is adaptive root structures. At least four different mangrove forest root adaptations have been noted, and these are termed as pneumatophores, prop or stilt roots, kneed roots, and plank roots (Kelvin et al. 2001). Many species of mangroves roots allow for efficient respiration through hundreds of tiny pores known as lenticels that remain above the water level or close to the water level during high tides (Yáñez-Espinosa and Flores 2011). For example, the *Rhizophora mangle* in Ecuador has stilt roots that are often many meters above the waterlogged and saline soils below (Fig. 1.1).

(ii) Mangroves' adaptive mechanisms for existing in highly saline environments vary across species but can broadly be classified into three overlapping categories. First, many mangrove species roots are effective at filtering out much of the salt water before it enters the plant. Such root processing is likely via a process of ultrafiltration that blocks the uptake of almost all of the salt ions present (Kelvin et al. 2001). Second, many mangroves store excess salt in old bark or their leaves; they then litter or shed bark regularly to rid themselves of the accumulated excess salt. Third, many mangroves have evolved the ability to secrete salt through glands in the leaves. Finally, many mangroves are adept

Fig. 1.1 Rhizophora mangle Stilt Roots in Chone Estuary, Manabi, Ecuador
These *Rhizophora mangle* stilt roots extend about 5 m above the highly saline and waterlogged soils. These are atypically large examples and are found in northern Ecuador. The Mean Higher High Water (MHHW) approximately corresponds to the highest prop root in the picture