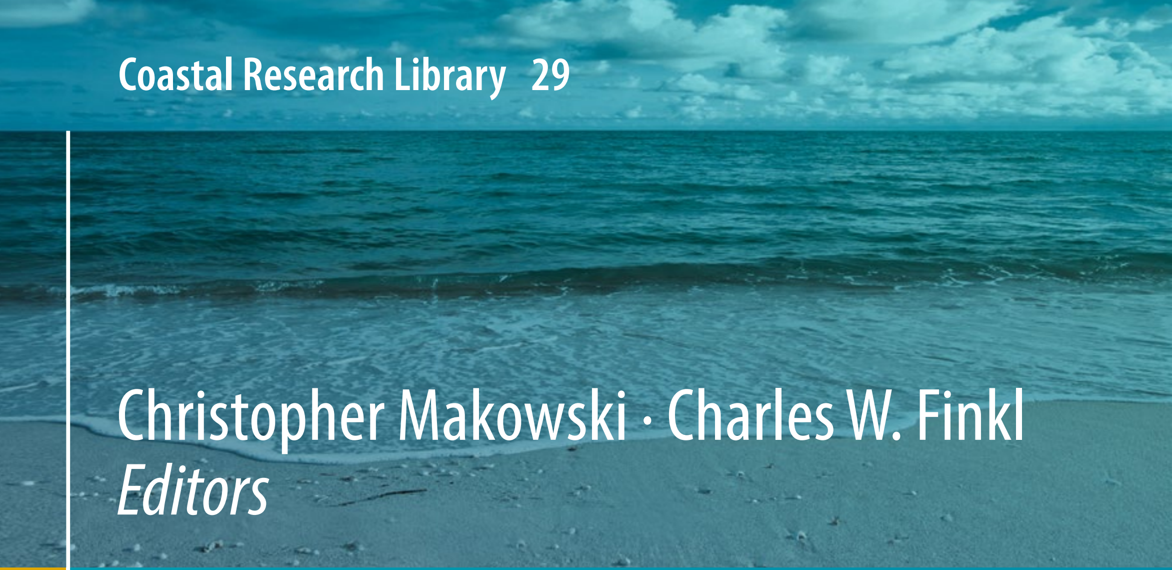

Coastal Research Library 29

Christopher Makowski · Charles W. Finkl
Editors

Impacts of Invasive Species on Coastal Environments

Coasts in Crisis

Springer

Coastal Research Library

Volume 29

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Charles W. Finkl
Department of Geosciences
Florida Atlantic University
Boca Raton, FL, USA

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Editors
Christopher Makowski
Coastal Education and Research Foundation (CERF)
Coconut Creek, FL, USA

Charles W. Finkl
Coastal Education and Research Foundation (CERF)
Asheville, NC, USA

Department of Geosciences
Florida Atlantic University
Boca Raton, FL, USA

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Preface

When examining coastal environments throughout the world, there is usually a delicate balance formed among native vegetative and animal species and the environment itself. This equilibrium helps to sustain the ecosystem as a whole and ensures that the biodiversity of a particular coastal region is preserved. However, an unfortunate imbalance is observed in this modern era where bioinvasions of alien species have infiltrated multiple coastal landscapes. This volume in the *Coastal Research Library* (CRL) focuses on the regional and localized impacts that incur to various coastal environments from nonnative, invasive species. The book has been divided into two main parts: Part I – Regional Impacts from Multiple Coastal Invasive Species; and Part II – Localized Effects of Individual Coastal Invasives. These general subject-area parts are then subdivided into chapters that describe, through either generalized overviews or specific case studies, how invasive flora and fauna create destructive cascades within coastal systems that ultimately end with substantial deleterious impacts on environmental quality. While the following collection of topics provides insight into the common threat that is coastal invasive species, it also pushes to the forefront the undeniable influence of human action, whether through urbanization, industrialization, and commercialization, to enable such detrimental bioinvasions. With so many coastal environments already compromised, it is imperative that protection against invasive species is mandated in order to rehabilitate, preserve, and sustain these delicate littoral zones.

Part I contains seven chapters highlighting regional impacts around the world from multiple coastal invasive species. Chapter 1 (Invasive Species Within South Florida Coastal Ecosystems: An Example of a Marginalized Environmental Resource Base), by Christopher Makowski and Charles W. Finkl, discusses how numerous invasive species of vegetation and wildlife have wreaked havoc over the southern Florida peninsula. Descriptions of specific invasive species are given, as well as various countermeasures used in an attempt to neutralize the alien bioinvaders. The authors also explore the notion of humans as the main invasive species in coastal environments. Chapter 2 (Invasive Species in the Sundarbans Coastal Zone (Bangladesh) in Times of Climate Change: Chances and Threats), by

Shafi Noor Islam, Sandra Reinstädtler, and Albrecht Gnauck, presents the impacts and threats of multiple invasive species to the Sundarbans deltaic region. These biological invasions are linked to vulnerabilities in mangrove forests and wetlands throughout the Sundarbans Natural World Heritage Site in Bangladesh. Chapter 3 (Threats to Sandy Shore Habitats in Sri Lanka from Invasive Vegetation), by Wasantha Rathnayake, quantifies how native plant diversity is decreasing while invasive weeds are more abundant along the sandy shorelines of Sri Lanka. Chapter 4 (Alien Species and the Impact on Sand Dunes Along the NE Adriatic Coast), by Urban Šilc, Danijela Stešević, Andrej Rozman, Danka Caković, and Filip Küzmič, continues in a similar vein by examining the results of a multifaceted approach to observe how sand dune plant communities in Montenegro have been affected by invasion of five alien species. Chapter 5 (Manila Bay Ecology and Associated Invasive Species), by Benjamin M. Vallejo Jr., Alexander B. Aloy, Melody Ocampo, Jennifer Conejar-Espedido, and Leanna M. Manubag, takes a look at how the high marine biodiversity of the Philippines' Manila Bay becomes compromised through the biological invasions of fouling organisms. Chapter 6 (Bioinvasion and Environmental Perturbation: Synergistic Impact on Coastal–Mangrove Ecosystems of West Bengal, India), by Susanta Kumar Chakraborty, reports on the prospective consequences of several bioinvasions within the coastal–estuarine network of West Bengal, India, which includes more than 100 deltas in this region. Chapter 7 (Specialized Grooming as a Mechanical Method to Prevent Marine Invasive Species Recruitment and Transport on Ship Hulls), by Kelli Z. Hunsucker, Emily Ralston, Harrison Gardner, and Geoffrey Swain, assesses the ubiquitous impact of biofouling on ship hulls and proposes an innovative countermeasure to thwart invasive species recruitment and transport.

Part II contains seven chapters and focuses on the localized effects generated by an individual invasive species, in particular. Chapter 8 (Feeding Habits of *Pterois volitans*: A Real Threat to Caribbean Coral Reef Biodiversity), by Arturo Acero P., Diana Bustos-Montes, Paula Pabón Quintero, Carlos Julio Polo-Silva, and Adolfo Sanjuan Muñoz, delves into the commercial and ecological threats caused by one invasive marine species, the lionfish, which may single-handedly be responsible for altering the biodiversity of the Caribbean Sea. Chapter 9 (Environmental Impact of Invasion by an African Grass (*Echinochloa pyramidalis*) on Tropical Wetlands: Using Functional Differences as a Control Strategy), by Hugo López Rosas, Eduardo Cejudo, Patricia Moreno-Casasola, Luis Alberto Peralta Peláez, María Elizabeth Hernández, Adolfo Campos Cascaredo, and Gustavo Aguirre León, discusses how one invasive grass species is altering the wetland and dune ecosystems in Mexico by reducing plant biodiversity, changing system hydrology, reducing faunal habitat, and causing vertical accretion of physicochemicals within the soil profiles. The authors also highlight an ongoing control strategy project to curb the bioinvader. Chapter 10 (Environmental Impacts of an Alien Kelp Species (*Undaria pinnatifida*, Laminariales) Along the Patagonian Coasts), by M. Paula Bunicontro, Silvia C. Marcomini, and Graciela N. Casas, focuses on the effects of an invasive kelp species along the Argentinean coast. This submerged aquatic bioinvader not only impacts indigenous populations but may also be responsible for collapsing commercially important benthic community structures and increasing beach erosion. Chapter 11 (Only the Strictest Rules Apply: Investigating Regulation Compliance of Beaches to Minimize Invasive Dog Impacts on Threatened Shorebird Populations), by Grainne S. Maguire, Kelly K. Miller, and Michael A. Weston, explores an unlikely coastal invasive species in domesticated dogs and how to minimize their impact on threatened populations of shorebirds in southern Australia. Chapter 12 (Evaluating How the Group Size of Domestic, Invasive Dogs Affect Coastal Wildlife Responses: The Case of Flight-Initiation Distance (FID) of Birds on Southern Australian Beaches), by S. Guinness, W.F. Van Dongen, P.-J. Guay, R.W. Robinson, and M.A. Weston, is a follow-up to the previous chapter where the flight-initiation distance (FID), a measure of wariness in shorebirds, was correlated to the group size of invasive dog packs on Australian beaches. Chapter 13 (Impact of Invasive Nypa Palm (*Nypa fruticans*) on Mangroves in Coastal Areas of the Niger Delta Region, Nigeria), by Aroloye O. Numbere, investigates one of the major bioinvading threats to mangrove and coastal systems in the Niger Delta area. This alien palm has the potential to adversely change the pedology, hydrology, and overall landscape of the deltaic environment. Chapter 14 (*Acacia* spp.: Invasive Trees Along the Brunei Coast, Borneo), by Shafi Noor Islam, Siti Mazidah Bin Haji Mohamad, and Abul Kalam Azad, probes another invasive flora, this time a non-indigenous genera of tree, that has impacted the forest ecology along the coast of Brunei Darussalam in Borneo.

This volume offers wide-ranging examples of how invasive species impact many diverse coastal environments. Chapters selected for this book selectively show that native populations of plants and animals are under constant threat of bioinvasions along the coasts of the following regions: North and South America, Australia, Southeast Asia, Bangladesh, West Africa, India, Philippines, Sri Lanka, and the Caribbean Sea. The underlining theme of this publication is to create awareness of the global impacts caused by coastal invasive species and to instill a responsibility among people that humans may in fact be the quintessential bioinvader on planet Earth. Only then can people begin to repair the damage they have unleashed in the form of exotic, alien species along the coasts. Through the dissemination of this book, researchers, managers, and the public alike can begin to collectively work together to identify the root of the problem when it comes to invasive species and to no longer put our coasts in crisis.

Coconut Creek, FL, USA Christopher Makowski
Asheville, NC, USA Charles W. Finkl
Boca Raton, FL, USA

Contents

Part I
Regional Impacts from Multiple Coastal Invasive Species

Chapter 1
Invasive Species Within South Florida Coastal Ecosystems: An Example of a Marginalized Environmental Resource Base

Christopher Makowski and Charles W. Finkl

Abstract Bioinvasions from exotic flora and fauna are a constant threat to the ecological balance that allows coastal ecosystems to maintain homeostasis. Throughout the world, invasive species are responsible for a multitude of impacts upon the coastal zone, some of which include outcompetetion and displacement of native species, biochemical degradation of water resources, destabilization of the soil, overexertion of carrying capacity limits, and the overall collapse of indigenous flora-fauna boundaries. South Florida is a prime example where the successful establishment and dispersal of numerous invasive species has occurred through human disruption and interference of the natural coastal ecosystems. This chapter focuses on five species of invasive vegetation (i.e., Australian pine [*Casuarina equisetifolia*], Brazilian pepper [*Schinus terebinthifolius*], broadleaf paperbark tree [*Melaleuca quinquenervia*], water hyacinth [*Eichhornia crassipes*], hydrilla [*Hydrilla verticillata*]) and five species of invasive wildlife (i.e., red lionfish [*Pterois volitans*], marine cane toad [*Bufo marinus*], red imported fire ant [*Solenopsis invicta*], Nile monitor [*Varanus niloticus*], Burmese python [*Python molurus bivittatus*]) that have contributed to the profound ecological breakdown of a vulnerable coastal region. By reviewing how different invasive species marginalize the environmental resource base of South Florida, a spotlight is then shone on how invasions can destroy coastal biodiversity worldwide, as well as expose the role of humans, not only as the main introducing factor of alien species, but perhaps as the most invasive of all species on planet Earth.

C. Makowski (✉)
Coastal Education and Research Foundation (CERF), Coconut Creek, FL, USA
e-mail: cmakowski@cerf-jcr.com; http://www.cerf-jcr.org

C. W. Finkl
Coastal Education and Research Foundation (CERF), Asheville, NC, USA

Department of Geosciences, Florida Atlantic University, Boca Raton, FL, USA

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1.1 Introduction

Ecosystems throughout the world maintain a certain order in the specific types of native flora and fauna species found within them as a means to sustain a harmonistic balance in nature. This delicate balance, in terms of geologic time, may span entire eras before a shift or transition occurs. Studies have shown that it is usually an outside factor that gives rise to a change in the species composition of ecosystems. One famous example is the postulated K-T Mass Extinction Event, where approximately 65 million years ago, more than three-fourths of all the plant and animal species living on Earth became extinct. Named for the boundary between the Cretaceous (K) and Tertiary (T) time periods, Alvarez et al. (1980) hypothesized that an extraterrestrial meteorite impact was the main cause for such a shift in the types of organisms that were then found on the planet. Extraordinary amounts of the metal iridium in the rocks that were laid down at the time of the K-T boundary (Alvarez et al. 1982) lend credence to the theory that a punctuated outside force could be responsible for such a disruption in the composition of native plants and animals.

While the K-T Event proved to cause an ancient global shift of plant and animal species, much more common localized disruptions to native flora and fauna can be seen today with the onset of human interventions. Within the field of biogeography, a particular species is referred to as native, endemic, or indigenous to a specific ecosystem if their presence there is only the result of natural processes. Non-native, exotic, or alien species, however, are those organisms that have been introduced to a new ecosystem through direct anthropogenic influences. And finally, invasive species, by definition, are those non-natives whose presence will most likely cause economic or environmental damage to the ecosystem, with the potential to inflict harm to human health.

There has been a struggle to combat invasive species within many of the world's coastal ecosystems. With the advent of human transportation technological advancements, it has become apparent that invasive species could be easily introduced to foreign ecosystems simply by 'hitching a ride' in the cargo hold of an airplane or the ballast of a ship. What proved to be even more unforgiving was the hubris of humans to 'play God' by systematically introducing exotic species into a particular coastal ecosystem in order to disrupt the natural order of things for their own gain. Sometimes one alien species is introduced to offset a previously introduced non-native species that has turned invasive. Unfortunately, in a lot of those circumstances, both introduced exotic species ultimately turn out to be invasive within a coastal region. As a consequence, the introduction of invasive species, along with both pollution and habitat loss, are now considered the top three environmental threats in the modern era (Perrings 2005).

The coastal plain of South Florida (Fig. 1.1) is a prime example of how human interventions have completely transformed an ecosystem of natural harmony into one that is constantly under duress from invasive flora and fauna species (Tables 1.1, 1.2, and 1.3). The delicate balance of any coastal ecosystem allows for many species of native plants and animals to flourish, however, due to the wide-spread release of invasive species in South Florida, that balance has been critically disrupted. Invasive plants, such as the Australian pine (*Casuarina equisetifolia*), Brazilian pepper (*Schinus terebinthifolia*), and broadleaf paperbark tree (*Melaleuca quinquenervia*) (Austin 1978; D'Antonio and Meyerson 2002; Doren et al. 2009a, b), as well as invasive animals, such as lionfish (*Pterois volitans*), Nile monitors (*Varanus*

Fig. 1.1 Satellite imagery, combined with ocean floor composite renderings, showing the geographical location of South Florida in relation to the rest of the state. The red outline demarcates the southern limits of Florida from the northern limits and includes such features as the Florida Everglades, Lake Okeechobee, the Florida Keys, Biscayne Bay, Florida Bay, the Florida Reef Tract, and the Miami-metropolitan conurbation. (Credit: Google Earth)

niloticus), and Burmese pythons (*Python molurus bivittatus*), displace or eradicate native species and threaten to disrupt the entire ecosystem balance (LeSchiava et al. 2013). The purpose of this chapter is to review some of the main invasive species of plants and animals that continue to disturb and out-compete the indigenous species populations of South Florida. Through such an evaluation, one can begin to see a different type of extinction event occurring, albeit on a much smaller scale, where human outside forces cause a major shift in the species composition of a particular coastal area.

1.2 Invasive Flora

*1.2.1 Australian Pine Tree (*Casuarina equisetifolia*)*

One of the main invasive alien species plaguing South Florida is the Australian pine tree, *Casuarina equisetifolia*, which in fact, is not a pine tree at all. It is actually classified as a deciduous dicot angiosperm tree that mistakenly resembles the appearance of a typical conifer tree. *C. equisetifolia* can grow on average between 20 and 46 m in height, at a rate of 1.5–3.0 m per year, and has a maximum lifespan ranging from 40–50 years (Elfers 1988a, b; Swearingen 1997) (Fig. 1.2). Distinct features of the Australian pine include a single straight, rough-barked trunk with an open, irregular crown of branches, cone-like fruits that are small and round, and wispy needle-like branchlets (Fig. 1.3), that may or may not contain small non-descript brown flowers (Snyder 1992; Swearingen 1997; Langeland and Craddock Burks 1998).

While Australian pines are known to reproduce sexually via seed dispersal, this invasive species also has the ability to replicate vegetatively through the sprouting of new clonal trunks from existing rootstock. Usually, small, inconspicuous flowers are wind pollinated throughout a coastal area, with each of the oval cone-like fruits (i.e., nutlets) containing approximately 12 rows of seeds when they mature. Australian pines are capable of flowering for extended periods of time, even year-round occasionally, and individual trees can produce thousands of seeds a year, making them a very difficult species to control (Morton 1980; Elfers 1988a, b) (Fig. 1.4).

Within South Florida, *C. equisetifolia* are known as a Category I exotic species. This designation indicates that Australian pines have become so abundant within a particular region that entire native plant community structures are being altered and ecological functions of specific ecosystems are being negatively affected (Schmid et al. 2008; Wheeler et al. 2011). The native range of *C. equisetifolia* includes southern Asia, Malaysia, Australia, and Oceania (i.e., the islands of the Pacific between Asia and the Americas). However, the current worldwide-introduced range includes the Caribbean Territories (which include Puerto Rico and the Bahamas), Hawaii, and coastal Florida. Specifically in Florida, this invasive species ranges from north-central regions of the state southward through the Florida Keys (Wheeler et al. 2011; FLEPPC 2017).

Fig. 1.2 Australian pine trees (*Casuarina equisetifolia*) growing as part of the foredune canopy adjacent to Boca Raton beaches in South Florida. As a non-native, invasive species, *C. equisetifolia* outcompetes the indigenous vegetation below it by shielding a lot of the essential sunlight resources. (Credit: Chris Makowski)

Fig. 1.3 Distinct wispy needle-like branchlets growing from the Australian pine tree. This unique feature often has *C. equisetifolia* mislabeled as a conifer pine tree, when in fact they are deciduous dicot angiosperm trees. (Credit: Chris Makowski)

Fig. 1.4 Two juvenile Australian pine trees establishing themselves in the foreground as part of an upper dune ecosystem in South Florida. This invasive species can reproduce vegetatively through the sprouting of new clonal trunks from existing rootstock. Once exotic trees become established among the native species, management against this type of bioinvasion proves to be very difficult. For example, if these young *C. equisetifolia* individuals continue to grow, they have the potential of producing thousands of germinating seeds per year. (Credit: Chris Makowski)

The history of the Australian pine in South Florida began in 1898, when the species was intentionally introduced as both an ornamental tree and as a windbreak buffer to border agricultural groves (Morton 1980). The trees were also utilized as support in a lot of ditch and canal stabilization projects, as engineers channelized much of the Everglades in the early twentieth Century (Snyder 1992; Swearingen 1997) (Fig. 1.5). However, the species proved to be unsuitable for these purposes, as their shallow and wide-spreading root systems disrupted residential lawns and pavement areas, and ultimately made the tree susceptible to being overblown in strong wind storms (e.g., tropical storms and hurricanes). *C. equisetifolia* also grows too tall for the roots to support its own weight, especially in the sandy-rich soils along South Florida's coasts. Furthermore, not only was this species ill-suited for commercial purposes, but it quickly became evident that Australian pines were a highly-invasive species capable of high fecundity in disturbed and nutrient-poor coastal areas. *C. equisetifolia* grows at a faster rate than most indigenous species and typically form monospecific stands that can produce a dense canopy that shades out competing flora. These invaders also form a thick layer of dropped branchlets (i.e.,

Fig. 1.5 Drainage canal within the southeastern section of the Florida Everglades, where *C. equisetifolia*, an exotic invasive species, has colonized along the waterway's margins. Once thought to be a good stable tree to reinforce these canals, Australian pine trees proved to be unsuitable for this purpose due to their shallow, wide-spreading root system. The trees commonly grow too tall for its own roots to support it, thereby making this invasive foliage more of a nuisance than a benefit. (Credit: Charles W. Finkl)

needles) and fruits that blanket the ground below, which eliminates available regolith for native plants to germinate and grow. Additionally, the roots of *C. equisetifolia* harbor nitrogen-fixing microbial assemblages that allow the host tree to colonize and thrive in low nutrient soil conditions that many other native species cannot tolerate (Swearingen 1997).

Despite an ongoing statewide ban on cultivation, Australian pines are now widely established throughout South Florida and they continue to thrive as an invasive species in a variety of open coastal habitats, such as coastal strands, sand and shell beaches, and dune fields (Snyder 1992). They are usually the dominant species when in direct competition with native Florida vegetation and can prompt permanent ecological alteration of an ecosystem through the rapid displacement of indigenous flora. This loss of native vegetation (i.e., food and shelter resources) to an ecosystem has a cascade effect that can reduce the species diversity of mammals, birds, and other native coastal animals. In addition, competitive displacement of coastal mangrove stands by *C. equisetifolia* can eliminate a lot of the nursery habitat needed for recreational and commercial fishing, as well as the loss of critical nesting and roosting habitat for many waterbird species. To make matters worse, the fact that Australian pines are highly unstable during storms introduces the high potential of obstruction hazards in the form of fallen trees, which can then encumber keystone and endangered species, such as gopher tortoises (*Gopherus polyphemus*) and sea turtles, respectively (Elfers 1988a, b). These fallen trees can also increase erosion rates along beach and dune systems and further compromise the South Florida coastal region.

*1.2.2 Brazilian Pepper Tree (***Schinus terebinthifolius***)*

Often referred to as an evergreen shrub or small tree, the Brazilian pepper tree (*Schinus terebinthifolius*) is an aggressive, rapidly colonizing invader of natural communities and disturbed habits in South Florida (Ewe and Sternberg 2003; Ewe 2004). This non-native species grows on average 3–7 m tall and forms odd-pinnately compound leaves that are alternately arranged on branches (Fig. 1.6). When crushed, these leaves emit an odor that has been distinctly described as peppery or turpentine-like (Tomlinson 1980; Ferriter 1997). Specifically on female trees, flowering is followed by the production of bright red, fleshy, spherical fruits, often referred to as berries or drupes, each approximately 5–6 mm in diameter and containing a single seed (Ferriter 1997) (Fig. 1.7). Fruit production typically occurs from November to February, at which time the branches of female trees are heavily laden with the red drupes, while male trees remain bare. The survivorship of the naturally established seedlings is very high, ranging from 66–100%, and the ripe fruits can be retained on a single tree for up to 8 months. The tenacity of *S. terebinthifolius* makes it an especially difficult species to compete with, as its seedlings seem to survive for a

Fig. 1.6 Newly formed leaves growing from an invasive Brazilian pepper tree (*Schinus terebinthifolius*). The odd-pinnately compound leaves, along with intermitted spherical fruits, are indicative of the non-native flora. When crushed, the leaves of *S. terebinthifolius* give off a distinct aroma similar to turpentine. (Credit: Chris Makowski)

Fig. 1.7 The bright red berries (also known as drupes) growing from the Brazilian pepper tree are characteristic of female trees during the Northern Hemisphere's winter months (November–February). The survivorship of the newly formed fruits can be very high, making *S. terebinthifolius* a very hardy invasive species that is difficult to control. (Credit: Chris Makowski)

very long time in the dense shade of older canopy growth, where they typically develop (Ewel et al. 1982; Elfers 1988b; Ferriter 1997).

Brazilian pepper uses a variety of strategies to invade and displace native vegetation along the coast (Habeck et al. 1994; Randall 2000; Hight et al. 2002, 2003; Cuda et al. 2006). For example, *S. terebinthifolius* is believed to have allelopathic properties which aid in altering the Chl α concentration of indigenous flora, thus hindering their growth (Morgan and Overholt 2005; Hargraves 2008). Additionally, these invaders form dense monospecific stands that ultimately shade out and reduce the biological diversity of native plants and animals within the affected areas (Ewe and Sternberg 2003; Cuda et al. 2006; Donnelly and Walters 2008). Specifically in Florida, it has become one of the most widespread and problematic invasive plants, infesting approximately 280,000 ha within various ecosystems (Ewe 2004; Cuda et al. 2006; Ewe and Sternberg 2003) (Fig. 1.8). Aqueous extracts have confirmed that Brazilian pepper negatively affects the growth of two South Florida native plants, *Bromus alba* and *Rivina humilis* (Morgan and Overholt 2005), and threatens numerous mangrove swamp community species found in the Everglades, such as *Jacquemontia reclinata* and *Remirea maritime* (Doren and Jones 1997; Cuda et al. 2006). Furthermore, *S. terebinthifolius* has been found to reduce the density and species diversity of native bird populations when compared to uninvaded native pinelands and forest-edge habitats, and can even alter natural forest fire regimes because of its resultant increased shade production (Curnutt 1989; Cuda et al. 2006). Lastly, it has been postulated that Brazilian pepper can trigger a negative cascade effect on primary production, biodiversity, and the overall ecological community structure from species-specific impacts on microalgae, which usually occur at the land-sea ecotonal interface (Hight et al. 2003).

Adverse impacts to humans have also been the result of *S. terebinthifolius* exposure. Because it is a relative of poison ivy (*Toxicodendron radicans*), Brazilian pepper induces allergic skin reactions on contact (Lampe and Fagerstrom 1968; Tomlinson 1980). In fact, the concentration of volatile, aromatic monoterpenes and alkyl phenols is

Fig. 1.8 The Brazilian pepper tree commonly grows among other vegetation and begins to outcompete indigenous species for resources. One strategy that *S. terebinthifolius* uses is to alter the Chl α concentration of indigenous flora through allelopathic properties, thus inhibiting the growth of native species. (Credit: Chris Makowski)

at such a high level, individuals sitting beneath *S. terebinthifolius* trees have exhibited respiratory problems, such as sneezing, sinus congestion, chest pains, and acute headaches (Morton 1969, 1978; Ferriter 1997). Cuda et al. (2006) also showed the tripterpenes found in the fruits of Brazilian pepper can result in irritation of the throat, gastroenteritis, diarrhea, and vomiting in humans.

In order to control the spread of this invasive species, a variety of biological control agents have been investigated or released. Among the most effective include the Brazilian pepper thrip (*Pseudophilothrips ichini*), the Brazilian pepper leafroller (*Episimus utilis*), the Brazilian pepper sawfly (*Heteroperreyia hubrichi*), the torymid wasp (*Megastigmus transvaalensis*), and a variety of different fungal pathogens (Wheeler et al. 2001; Cuda et al. 2006; Cleary 2007). In the case of *M. transvaalensis*, the wasp attacks the seeds of *S. terebinthifolius* and damages them to prevent germination. Wheeler et al. (2001) found that in Florida, *M. transvaalensis* damaged up to 31% of Brazilian pepper drupes in the major winter fruiting period and 76% in the minor spring fruiting phase. Additionally, an array of fungal agents, such as *Sphaeropsis tumefaciens*, *Rhizoctonia solani*, and

Chrondostereum purpureum, are all known to infect *S. terebinthifolius* in different capacities and may also prove to be useful biological controls (Cuda et al. 2006).

1.2.3 *Broadleaf Paperbark Tree (*Melaleuca quinquenervia*)*

In South Florida, the broadleaf paperbark tree (*Melaleuca quinquenervia*), commonly known as melaleuca, is a rapidly-growing, hardy invasive tree, whose native range includes Australia, New Guinea, and the Solomon Islands (Langeland and Craddock Burks 1998). With a distinctive peeling paper-like white bark (Fig. 1.9), melaleuca can grow up to 33 m, at a rate of approximately 1–2 m per year (FLEPPC 2017). Branches occur at irregular intervals off the main trunk and support long (10–15 cm) evergreen leaves that are known to release a distinct aromatic smell when crushed (Langeland and Craddock Burks 1998) (Fig. 1.10). The flowers are small and white, and arranged with multiple stamens, while the fruits are small, round woody capsules containing approximately 200–300 seeds each (Austin 1978; FLEPPC 2017).

Fig. 1.9 *Melaleuca quinquenervia*, also known as the broadleaf paperbark tree, gets its name from the distinctive paper-like white bark that peels from the trunk. The lighter color of the bark made this invasive tree appealing as an ornamental species, prompting the transport of specimens from Australia, where they are native, to South Florida. (Credit: Ianaré Sévi)

Fig. 1.10 Branches of the broadleaf paperbark tree occur at irregular intervals and support evergreen leaves that emit an aromatic scent when crushed. This invasive species is capable of producing woody capsules that contain up to 300 seeds each. When the branches are disturbed (i.e., broken or cut), a rapid release of the seeds occurs ensuring a wide dispersal of the non-native tree. (Credit: Homer Edward Price)

Melaleuca quinquenervia primarily propagates by sexual seed production and is capable of flowering within 2–3 years of germination (Meskimen 1962; Laroche 1994). In South Florida, the species can propagate as many as five times a year, with blooms primarily occurring during the months of November through January. Flowering is known to be asynchronous among both the trees and the flowers of a single specimen (FLEPPC 2017). Large *M. quinquenervia* specimens can have a very high reproductive potential and up to 20 million seeds per year are known to be stored in the seed capsules of a single tree (Laroche 1994). Before the seeds are dispersed into the environment, seed capsules must first be dried out; however, seeds can remain viable within the seed capsules for up to 10 years (Meskimen 1962; Langeland and Craddock Burks 1998). Physical damage to the tree (e.g., broken or cut branches, whole tree falls, exposure to a hot-burning wildfire) will trigger the rapid release of seeds from capsules, which culminates in the shedding of all seeds within a few days (Woodall 1982; Flowers 1991; Stocker and Hupp 2008).

In Florida, *M. quinquenervia* is restricted to the southern half of the state, with counties at the very southern end of the state being most vulnerable. Melaleuca is considered one of the most prominent non-native plant species presently invading the natural areas of South Florida (Center and Dray 1986; Hofstetter 1991). The species had invaded more than 200,000 hectares in South Florida by 1994, including significant areas within Everglades National Park, a World Heritage Site and International Biosphere Reserve (Mazzotti et al. 1981; Langeland and Craddock Burks 1998; FLEPPC 2017).

The history of melaleuca invasion in South Florida includes multiple introduction events throughout the early twentieth century. Among the first sites recorded were Broward and Lee Counties, where melaleuca seeds were transported from Australia and planted as a landscape ornamental tree and a source of wood. The popularity of melaleuca as an ornamental species, especially as a windbreak for many properties and along fencerows, further facilitated the spread of this invasive species. As recently as 1970, *M. quinquenervia* continued to be recommended as "one of Florida's best landscape trees" (Langeland and Craddock Burks 1998). Additionally, melaleuca was planted as soil stabilizers along canal levees bordering the southern end of Lake Okeechobee and throughout the Big Cypress National Preserve. Seeds were also intentionally scattered from airplanes over the Everglades throughout the 1930s to facilitate the rapid establishment of melaleuca forests (Austin 1978). This led to the environmentally-mediated spread of melaleuca deep into the interior of the Florida Everglades, which was facilitated by propagule transport via wind and water (FLEPPC 2017). A problem arises at the explosive speed by which melaleuca spreads and comes to dominate new areas (Hofstetter 1991). As little as 25 years is required for a 2.5 km^2 area to progress from 5% to 95% infestation of melaleuca (Laroche and Ferriter 1992). This poses a serious threat to the ongoing Everglades restoration and preservation efforts, and continues to threaten South Florida's other natural areas (FLEPPC 2017). Almost a century later from those first introductions, the general distribution of melaleuca in South Florida still remains uncontained (Mazzotti et al. 2001).

Though melaleuca appears to have some positive economic benefits in Florida as a plant utilized by commercially-managed honeybees, the negative impacts of this coastal invasive species are of far greater consequence. For example, a cost-benefit analysis for South Florida determined that melaleuca could contribute an estimated annual benefit of approximately USD $15 million for the beekeeping and pollination service industries, however, an estimated loss of around USD $168.6 million/year would be suffered by the eco-tourism industry in the event of complete infestation by melaleuca throughout the Everglades and other South Florida wetland areas (Diamond et al. 1991).

When competing with indigenous plants, melaleuca is principally an invader of disturbed sites, where it proves to be opportunistic in those Florida habitats exhibiting a high degree of clearing or development (Ewel et al. 1976) (Fig. 1.11). Canal banks, managed pineland margins, pine savannas, sawgrass prairie marshes, and cypress marshes are among the South Florida ecosystems susceptible to *M. quinquenervia* (Richardson 1977; DiStefano and Fisher 1983; Myers 1983; Duever et al. 1986; Laroche and Ferriter 1992). Once it becomes established, melaleuca can form dense monotypic stands capable of displacing large amounts of native plants (Richardson 1977). In fact, the World Conservation Union's Invasive Species Specialist Group (ISSG) lists melaleuca as among "100 of the world's worst invasive alien species" and recognizes them as major drivers of ecosystem disruption.

Fig. 1.11 A common stand of melaleuca trees growing along the disturbed fringes of Interstate 75, also known as Alligator Alley, in South Florida. These invasive trees have proven very opportunistic within human-induced areas of disturbance or development. Melaleuca's ability to become rapidly established prevents many measures of control to be effective. (Credit: Forest & Kim Starr)

*1.2.4 Water Hyacinth (*Eichhornia crassipes*)*

The water hyacinth, *Eichhornia crassipes*, is an invasive non-native plant commonly found as floating dense mats in South Florida freshwater habitats. Originally native to the Brazilian Amazon Basin, the water hyacinth produces distinctive lavender-colored flowers (Fig. 1.12) and a thin walled, capsule-like fruit that can contain up to 400 seeds (Gopal 1987; Langeland and Craddock Burks 1998). This invasive is able to remain buoyant in the water through the use of bulbous, or inflated, petiole stalks and has long feathery roots that hang suspended in the water column.

Water hyacinth flourishes in freshwater ecosystems and is even capable of growing in low-salinity coastal lagoon habitats; for example, along the coastal margins of the Everglades. In fact, over 55 tropical and subtropical countries, including the southern portion of the United States, have reported *E. crassipes* as a noxious weed (Holm et al. 1977; Langeland and Craddock Burks 1998; Ramey 2001). However, increased salinity is a limiting factor in the distribution of the invasive plant. Experimental studies by de Casabianca and Laugier (1995) showed there was an inverse relationship between increased salinity and water hyacinth plant yield. Their results showed that at salinities above 6 ppt, either no plant production occurred or cankerous plants developed. Furthermore, at salinities above 8 ppt, irreversible physiological damage to the vegetation occurred (de Casabianca and Laugier 1995).

Vegetative reproduction of the water hyacinth usually occurs *via* the breaking off of clonal individuals. The stolons (i.e., the horizontal shoots capable of forming new

Fig. 1.12 Distinctive lavender flowers with an orange-yellow flame pattern on the top petal is a trademark feature of water hyacinth (*Eichhornia crassipes*). This invasive plant remains buoyant through the use of inflated, petiole stalks, keeping the pollenating parts of the flower above water. (Credit: USDA)

shoots) are easily broken by wind or wave action and dispersed, whereas, the floating clonal mats of *E. crassipes* are readily transported intact through wind or water movement (Barrett 1980; Langeland and Craddock Burks 1998). Germination typically occurs when water levels are down and the seedlings can grow in saturated soils.

The invasion history of *E. crassipes* first began in 1884, when the Brazilian native was first introduced to the United States as an ornamental aquatic plant at a New Orleans, Louisiana Exposition. Water hyacinth was first recorded in Florida by 1890, and over the next 60 years, dense mats of this highly invasive plant had altered more than 50,000 ha of the state's freshwater habitats (Gopal and Sharma 1981; Schmitz et al. 1993). Water hyacinth mats are capable of creating incredibly high plant density and biomass, with a single hectare containing more than 360 metric tons of plant material. The capacity of water hyacinth to invade and overtake aquatic habitats is remarkable, with growth rates that can double the vegetative population in as little as 1–3 weeks (Mitchell 1976; Wolverton and McDonald 1979; Langeland and Craddock Burks 1998). Because of this, water hyacinth is a considered a Category 1 invasive exotic species in Florida, capable of altering native plant communities by displacing indigenous species and changing community structures or ecological functions permanently (FLEPPC 2017). Some researchers have even gone on to describe *E. crassipes* as one of the worst weeds in the world (Holm et al. 1977).

The negative economic impacts of water hyacinth invasion include the clogging of irrigation channels, the choking off of navigational routes, smothering of native vegetation, loss of fishing areas, and the increase in breeding habitat available to

Fig. 1.13 Example of water hyacinth outcompeting natural flora to bioinvade a freshwater pond ecosystem. The incredibly high plant density and biomass of *E. crassipes* often leads to the infestation and clogging of irrigation canals, navigational channels, and other numerous waterways. (Credit: Cayambe)

disease-transmitting mosquitoes (Room and Fernando 1992) (Fig. 1.13). In the Florida Everglades, large, dense mats of *E. crassipes* can degrade water quality and obstruct essential waterways. Plant respiration and extensive biomass decay can often result in oxygen depletion, leading to hypoxic conditions and fish kills (Langeland and Craddock Burks 1998). Waterways are kept clear of dense infestations only through extraordinary management efforts involving field crews engaged in full-time mechanical removal and biocidal control. Even though the costs associated with the removal and maintenance control of water hyacinth are significant, exhaustive management efforts in the Everglades and other ecosystems over the last few decades have considerably reduced the amount of this invasive plant (Langeland 2008). Even so, complete eradication of *E. crassipes* from South Florida is nearly impossible.

*1.2.5 Hydrilla (***Hydrilla verticillata***)*

Hydrilla (*Hydrilla verticillata*) is well known in South Florida as an invasive aquatic weed that is not easily controlled or managed. A typical submerged, herbaceous perennial that exhibits seasonal winter dieback, hydrilla has long, sinewy branching stems that often reach the surface and form dense mats (Godfrey and Wooten 1979; Carter et al. 1994). Characteristic small, white flowers can be seen growing above the water on stalks, while the stems, which can reach lengths over 7.5 m, are usually covered in pointed, often serrate, leaves arranged in tiny whorls (Cook and Luond 1982; Langeland 1996). Reproductive strategies of hydrilla include several vegetative means, such as regrowth from stem fragments, clonal rhizome reproduction, and utilization of specialized axillary buds, also known as turions (Pieterse 1981; Hurley 1990; Spencer et al. 1994). It is noted that *H. verticillata* can proliferate very rapidly using these methods and remain reproductively viable for extended periods of time (Van and Steward 1990; Sutton et al. 1992).

Hydrilla verticillata has been referred as the most abundant aquatic plant in Florida's public waters, with over 70% of the state's freshwater drainage basins infested with the invasive vegetation (Schardt 1994, 1997). Early introduction into South Florida occurred in the early 1950s, when live samples of hydrilla were shipped from Sri Lanka and India for the aquarium trade and subsequently released into canals near Tampa Bay (Madeira et al. 2004). Soon after, other samples were introduced to the waterways of Miami and the establishment of hydrilla in Florida had been cemented (McCann et al. 1996). Being an aggressive vegetative invader capable of altering ecological community structures and displacing native indigenous plants, hydrilla is currently listed as a Category I invasive exotic plant in Florida and recognized as one of the most invasive weeds throughout the world (Haller and Sutton 1975; Bowes et al. 1977).

The control and management of hydrilla has proved to be both difficult and expensive. With the vast loss of recreational lake area due to *H. verticillata* infestation, the state of Florida has spent many millions of U.S. dollars in an attempt to curb their numbers (Langeland and Stocker 2001). Dense beds of hydrilla not only make recreational lakes unusable to the public, but oxygen depletion is a serious consequence from the decomposition of the plant's large biomass (Canfield et al. 1983). This can then lead to a negative ecological cascade where the water chemistry is altered, zooplankton populations drastically decline, fish populations are permanently lowered, and higher trophic animals, such as amphibians, reptiles, and mammals, are critically affected (Colle and Shireman 1980; Schmitz and Osborne 1984; Schmitz et al. 1991) (Fig. 1.14).

1.3 Invasive Fauna

*1.3.1 Red Lionfish (*Pterois volitans*)*

The red lionfish, *Pterois volitans*, is a highly invasive marine fish that has swarmed the east coast of the United States, including coastal Florida, since the turn of the twenty-first century. *P. volitans* has a very distinct appearance with red and white striped bands, elaborate fan-like pectoral fins, and long separated dorsal spines (Fig. 1.15). Fleshy tabs surrounding the mouth and above the eyes are another characteristic feature of this invasive species (Myers 1991; Whitfield et al. 2002). Lionfish have 18 spines that are used defensively against predators and to assist in

Fig. 1.14 A lagoon frog (*Lithobates grylio*), also referred to as a southern bullfrog or pig frog, forages within a hydrilla-infested canal in the Florida Everglades. The large amount of decomposition from the hydrilla biomass often leads to a permanent change in the water's chemistry, which then negatively affects higher trophic groups in search of essential food resources. (Credit: USGS)

Fig. 1.15 The red lionfish, *Pterois volitans*, is a voracious reef predator that has distinctive red and white banded stripes over its body for camouflage. Fleshy tabs can be seen around the mouth and above the eyes, and the long pectoral fins and dorsal spines contain a toxic venomous poison. (Credit: Chris Makowski)

prey capture. The long dorsal and pectoral spines of *P. volitans* are known to be venomous, as the poison is produced by glands located in grooves along the spine-covered integument (Halstead et al. 1955; Ruiz-Carus et al. 2006).

Typically growing to a size of 15–30 cm, larger lionfish specimens have been measured over 40 cm in length (Baker et al. 2004). Sexual reproduction (i.e., the external fertilization of eggs) usually occurs early in the year and involves a series of complex courtship and mating behaviors between the male and female (Ruiz-Carus et al. 2006). Overall, this invasive species is generally solitary outside of the reproductive season, but during courtship, males will aggregate with multiple females to form schools of up to ten fish. Competing males will even use their spines and fins to visually display aggression towards other suitors (Fishelson 1975). In the end, females release a pair of mucus-encapsulated clusters, each containing between 2000–15,000 eggs, to the pelagic environment where they are fertilized by the males (Ruiz-Carus et al. 2006). The fact that so many eggs are fertilized at once makes population control of this invasive species very difficult.

Lionfish are widely considered to be the first marine (non-estuarine) invasive fish in South Florida (Meister et al. 2005). As one of the most popular marine ornamental species in residential aquariums, their recent introduction to nearshore reefs was most likely the result of intentional release from unwanting owners (Whitfield et al. 2002). The first recorded lionfish in Florida was reported off Dania Beach in 1985; however, the first documented release of *P. volitans* in South Florida was in fact an accidental release of six individual specimens. This occurred in the wake of destruction from Hurricane Andrew (1992), when a large private aquarium was washed away into Biscayne Bay (Courtenay 1995). Those fish were then observed alive in the adjacent marine habitat several days later.

Pterois volitans is well established and reproducing in South Florida waters, with local populations of lionfish rapidly expanding (Whitfield et al. 2002; Ruiz-Carus et al. 2006) (Fig. 1.16). This invasive fish has high fidelity to a particular location, which means once breeding adults find a suitable habitat, they tend to remain and can reach densities of more than 500 adults per hectare. These numbers are staggering, especially since the alien species in question is known to have such a voracious appetite. Lionfish are stalking predators that often corral, or herd, prey into a corner by spreading their pectoral fins (Allen and Eschmeyer 1973). In fact, they are the only fish species known to blow water at potential prey items in an effort to get the prey to turn toward the lionfish before being eaten (Sano et al. 1984). In a single rapid motion, they can consume prey that are more than half of their own length and are known to devour more than 70 marine fish and invertebrate species, including yellowtail snapper, Nassau grouper, parrotfish, banded coral shrimp, and other cleaner species. Lionfish also compete for food with native predatory fish, such as grouper and snapper, and usually negatively impact the overall coral reef ecosystem by eliminating organisms that serve important ecological roles (e.g., herbivorous fish that limit algae growth upon the reef substrates) (Whitfield et al. 2002; Ruiz-Carus et al. 2006).