The effect of *Casuarina* trees on sea turtle nesting beaches throughout the Indian Ocean and South-East Asia regions: A beach vulnerability assessment

By

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In accordance with Rule G 5.6.3, I hereby declare that the above-mentioned dissertation is my own work and that it has not previously been submitted for assessment to another University or for another qualification.

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SUMMARY

Rapid global change and anthropogenic modification of natural habitats are threatening ecosystems across the globe. Many of these threats and adverse impacts are concentrated on the world's coastlines, with a large portion of the global population choosing to live next to the coast. To accommodate coastal populations and their related activities, the dynamic littoral active zone is often stabilized with hard engineering structures such as sea walls, which disrupt coastal ecological processes. Most natural coastal processes have since become natural disaster risks to the anthropogenically-modified coasts. Coastal stabilization has led to "coastal squeeze" with modified shorelines unable to respond naturally to changes in sea level. Furthermore, global change through global 'warming' exacerbates sea level rise. The combined impacts result in permanent/episodic inundation and coastal erosion, which may damage human settlements and degrade or destroy coastal habitat. As an alternative to hard armouring structures like sea walls, 'soft' options like large-scale plantations of trees as bio-shields are used as a 'green' option to protect developed coasts. Indeed, green shelter belts have rapidly increased since the December 2004 tsunami event in the Indian Ocean and South-East Asian (IOSEA) region. Extensive portions of the coastal habitat, including sensitive sea turtle nesting habitat, have been modified by planting exotic vegetation. Two invasive species, *Casuarina equisetifolia* and *Casuarina glauca*, are regularly used for coastal dune stabilization or as bio-shields because they are adapted to arid conditions, high salinity and low soil fertility typical of beach systems. The functionality of *Casuarina* trees as a 'comprehensive' coastal protection tool, however, has yet to be tested and the effects of *Casuarina* on sandy beach ecosystems remain largely unquantified. There is no empirical evidence to support the claim that *Casuarina* trees adequately function as a storm protection measure, and other studies have suggested that *Casuarina* species have adverse effects on sandy beach ecosystems, including the promotion of erosion in some instances and negative impacts on fauna, including sea turtles.

This study investigated the potential value of non-native *Casuarina* trees as a coastal protection measure on sea turtle nesting beaches taking into consideration the potential impacts of global change. First, the study estimated local scale effects of *Casuarina* trees within the South African sea turtle nesting rookery in the iSimangaliso Wetland Park by measuring impacts on back-beach substrate characteristics and shape. A few metrics were unaffected, such as grain size, sand penetrability and sand moisture, but sand pH and sand temperature were significantly lower underneath *Casuarina* stands. A mean pH of 8.2 and a median temperature of 26 ± SD1.5^{o}C were recorded under *Casuarina* trees and a pH of 9 and a median temperature of 27.2 ± SD1.9^{o}C under native vegetation. The significantly lower, more stable average temperature underneath *Casuarina* trees may have significant implications for sex ratios of sea turtles as the sex of sea turtles is determined by temperature; Temperatures above 32°C will yield all females and temperatures below 28°C will produce only males, with a pivotal temperature at which a 1:1 sex ratio is developed is about 29°C. Furthermore, sand temperature underneath *Casuarina* trees is less likely to reach lethal temperatures (above ~33°C) that could lead to hatchling mortality than in areas with no

vegetation. So, in terms of hatchling success, the thermal environment created by *Casuarina* trees might be favourable in extremely hot climate areas, especially when considering the effects of climate change.

Casuarina trees, however, affect back-beach and dune dynamics by altering sand movement. Semi-quantitative and qualitative analyses of beach profiles suggested that *Casuarina* trees and shrubs result in wind scouring directly in front of the foredunes as evidenced by the concave shape in front of *Casuarina* stands at some sites. Sites with natural vegetation had mainly convex beach shapes, suggesting sand accretion. Either way, vegetation had an important effect on sand dynamics (both positive and negative) where areas with no vegetation (bare sand) only had a neutral/straight shape. There was, however, a significant interaction between vegetation type and site, indicating that vegetation type alone cannot account for all the differences in beach profile dynamics and that site-specific conditions like wave height, sand budget, precipitation and orientation differences among locations may also have an effect.

The second part of the study had a regional perspective, investigating the effect of *Casuarina* trees on 50 sea turtle nesting beaches across the Indian Ocean South East Asia (IOSEA) region. The study first derived an appropriate (novel) beach vulnerability index using features that drive beach erosion. The index was then applied to 50 turtle rookeries in the presence/absence of *Casuarina* trees. The study noted the extensive distribution of exotic *Casuarina* trees throughout the IOSEA region and established that 28% of the 50 selected sea turtle nesting beaches had non-native *Casuarina* present. There was no significant difference in the erosion vulnerability of beaches with and without *Casuarina* based on the existing indicators. However, the study did show that seven important sea turtle rookeries were highly vulnerable to erosion, some with extensive exotic *Casuarina* stands. Olive ridley (*Lepidochelys olivacea*) nesting beaches in India, were dominated by *Casuarina* trees and were highly vulnerable to erosion. The study showed that the presence of *Casuarina* trees alone could not be viewed as an indicator of erosion but could be a contributing factor, as several other drivers like narrow back-beach width, absence of dunes and development on exposed coasts prone to storms, also contribute to the high erosion vulnerability of beaches.

The study questions the use of exotic vegetation, such as *Casuarina* species*,* for coastal protection by demonstrating local scale effects on the back-beach environment and provides a comprehensive overview of the erosion potential of sea turtle nesting beaches throughout the IOSEA region.

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Chapter 1 : Introduction

1.1 Problem statement

Historically, human existence is closely linked to sandy beach ecosystems, as early records indicate the reliance of people on beaches for food collection (Jerardino et al. 2014). Today, beaches have become synonymous with family vacations and economic opportunities, and consequently a large portion of the human population choose to live close to the coast (Vafeidis et al. 2008). The socio-economic benefits of beaches are thus widely recognised, but the realization that beaches are more than strips of sand and waves, but important functional ecosystems is limited (Dugan et al. 2010, Barbier et al. 2011, Watanabe and Ortega 2011, Costas et al. 2015). Many of our activities therefore, have unintended consequences on coastal systems due to ignorance.

Realising that sandy beaches are indeed ecosystems, we note that they support a unique variety of fauna and flora (Barbier et al. 2011). Macrofauna such as ghost crabs (Ocypodidae) and cirolanid isopods, like *Excirolana*, use the beach as a habitat and live underneath the sand (Cardoso and Defeo 2004, Schlacher et al. 2016). Other threatened species, like sea turtles and a range of sea birds such as the US Pacific coast's Western Snowy Plover (*Charadrius nivosus*) depend on sandy beaches for reproductive purposes (Miller et al. 2003, Nielsen et al. 2013). Beaches also offer other invaluable benefits that include processes like the breakdown of organic materials and pollutants, water filtration and purification, nutrient mineralisation and recycling (Defeo et al. 2009), protection against sea level rise and increased storm activity (Pilkey et al. 2011). Sandy beaches are therefore of critical importance to support a range of specialized biotic assemblages and provide irreplaceable ecosystem services (Barbier et al. 2011).

As a result of human encroachment and global change, beaches are fast becoming an endangered habitat (Dugan et al. 2010). The effects of these threats are evident in the 24% of the world's sandy beaches experiencing erosion rates exceeding 0.5 m/yr (Luijendijk et al. 2018). This is because people have altered shorelines through extensive development to accommodate an increasing coastal population, leaving beaches vulnerable to erosion. In fact, more than 20% of the global population live within 30 km of the coast (Klein 2002). Back-beach stabilization and coastal engineering structures prohibit coastline recession; fixed structures (seawalls, roads and bridges, buildings etc.) are being placed in this dynamic environment, which means that beaches are incapable of retreating with the rising sea level as they naturally would (Pilkey et al. 2011). This has led to the phenomenon now referred to as 'coastal squeeze' (Defeo et al. 2009). Ironically, great coastal engineering efforts are being made to protect coastal infrastructure but not coastal ecosystems like sandy beaches and hence we are losing the ecosystems that make the coast attractive.

There are two types of coastal stabilization solutions used to protect the coast: hard stabilization and soft stabilization solutions (Pilkey et al. 2011). Hard stabilization solutions build solid structures such as seawalls, groynes and piers (Pilkey et al. 2011), whereas soft options employ a variety of different approaches. Hard armouring has now become inevitable in some areas to protect expensive infrastructure, but it is not environmentally sustainable because it affects the erosion and accretion dynamics of the beach. Hard structures eventually lead to habitat loss as eroding beaches become narrower because of rising sea levels or loss of sand (Schlacher et al. 2008, Defeo et al. 2009). Soft stabilization solutions offer a more holistic approach, considering ecological functioning as well as socio-economic needs, and often makes use of natural resources (Pilkey et al. 2011). Popular soft coastal protection options include beach nourishment (Colosio et al. 2007) and strip planting of coastal bio-shields (Feagin et al. 2010). While beach nourishment is a common coastal protection choice in developed countries, it is simply too costly for developing countries to implement (Pilkey et al. 2011). The plantation of fast-growing but often non-native, economically feasible bio-shields are therefore more popular among developing countries (Feagin et al. 2010); tree saplings can be planted by inexpensive, low-skilled labourers and does not require engineering skills or the use of costly equipment and 'high-tech' machinery. While soft stabilization options, such as the use of exotic vegetation, may seem preferable to hard coastal armouring in terms of both economic and ecological benefits, it brings its own set of impacts, of which the effects remain largely unquantified.

The implementation of coastal bio-shields has become very popular throughout the Indian Ocean and South-east Asia region, as it is seen as a more natural approach than hard armouring options (Tanaka and Thuy 2010), and is widely utilized in coastal regions where there is an added risk of tsunamis (Chaudari et al. 2009). The development of large scale coastal bio-shields, often with exotic vegetation, particularly certain *Casuarina* species (e.g. *Casuarina equisetifolia*), has increased so rapidly that it was raised as a red flag at the 7th convention of the Signatory States of the Indian Ocean and South-East Asian Marine Turtle Memorandum of Understanding (IOSEA MoU). As part of the memorandum's sea turtle habitat restoration outcome, assessment of the extent of exotic vegetation use to stabilize dunes and its possible impacts on beaches, was recommended (R Nel 2016, personal communication, 19 January).

1.2 *Casuarina* distribution in coastal regions

With the widespread distribution of *Casuarina* and its ubiquitous use for coastal foredune stabilization and introduction to the back-beach for storm protection purposes, substantial portions of the littoral active zone, which therefore includes sensitive sea turtle nesting habitat, have *Casuarina* present. In the Kanchipuram district of Tamil Nadu in India, for example, an estimated 180 000 *Casuarina* saplings have been planted on 450 ha of coastal habitat (Chaudari et al. 2009). These plantations back olive ridley (*Lepidochelys olivacea*) sea turtles' nesting habitat (Chaudari et al. 2009). In fact, almost a third of India's coastline has been covered with plantations, initiated as a response to the December 2004 tsunami event (Chaudari et al. 2009, Mukherjee et al. 2009) (e.g. **Figure 1.1**). In China, *Casuarina* species were introduced to tropical and sub-tropical zones in 1897, and cover approximately 300 000 hectares, mostly in coastal regions (Zhong et al. 2010). In the Batticaloa district of Sri Lanka, *Casuarina* trees were artificially established on approximately 400 ha of the coastline, 50 m inland from the mean high tide line (Mathiventhan and Jayasingum 2014).

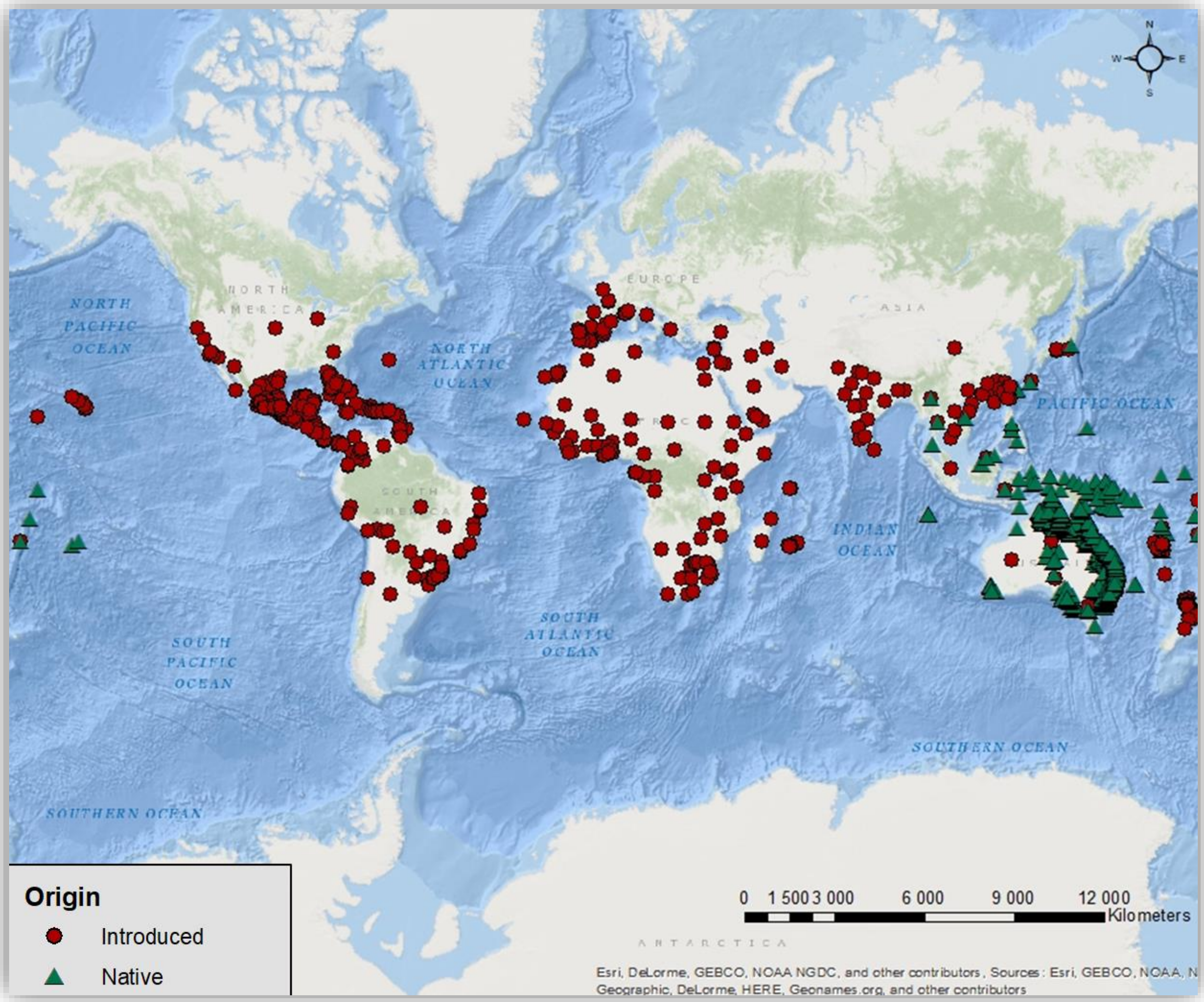
Once established, the removal of *Casuarina* trees is both time consuming and arduous, as evidenced by the systematic removal and restoration of the Dry Tortugas National Park in Florida. The park was covered by extensive *Casuarina* plantations, which included portions of sea turtle nesting habitat (Klukas 1967). From 1963 to 1970, mechanical measures (tree cutting and uprooting) and chemical control were carried out, but was ineffective in dense stands (Doren and Jones 1997). By 1970, *Casuarina* trees covered several thousand hectares of the park and in 1995 the National Park Service developed and implemented a new management plan, systematically treating plants (Doren and Jones 1997). The control program was completed in 1999 (Doren and Jones 1997), but the earliest signs of coastal rehabilitation were seen in 2001, as steep embankments were replaced by gradually sloping beaches (Pernas et al. 2013). The unparalleled ability of certain *Casuarina* species such as *C. equisetifolia*, to alter coastal habitats due to its rapid growth, dense coverage, thick litter accumulation and potential to increase beach erosion in some instances, has led to the regulation and inclusion of these species as Noxious Weeds by the Florida Department of Agriculture and Consumer Services (5B-57.007 F.A.C.) and are listed as Category 1 invasive plants by the Florida Exotic Pest Plant Council (Pernas et al. 2013). In South Africa, loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) nesting beaches within the iSimangaliso Wetland Park, Kwazulu-Natal, have *Casuarina* present on the foredunes. These trees were planted for dune stabilization purposes. Recognising the invasive nature of *Casuarina,* the Conservation of Agricultural Resources Act (1983) was implemented, as certain characteristics of *Casuarina* trees, such as the ability to continuously reseed themselves proved challenging to the successful restoration of the dune system (Potgieter et al. 2014b).

Figure 1.1: Casuarina*-backed beach (Arabian sea). Picture credit: Bishnu Sarangi.*

Casuarina trees are successful beach invaders and are extremely well suited to use for green shelter belts because they are hardy and can grow almost anywhere (Chaudari et al. 2009). These trees are fast growing, flowering, evergreen trees with leaves arranged in whorls at each of the segments along branchlets and small cones ranging 3-35 mm in diameter, depending on species (**Figure 1.2**) (CABI 2018: www.cabi.org/isc). The genus *Casuarina* has both monoecious and dioecious species, as the species of the genus reproduce both sexually (via seed) and vegetatively, through sprouting of new trunks from roots or by rooting along branches in contact with the soil (Hanum and van der Maesen 1997). Some *Casuarina* trees flower all year round, enabling them to produce a great number of seeds annually, which remain viable for up to a year and germinate within 4-8 days in a suitable environment (Hanum and van der Maesen 1997). Reproduction via seeds is aided by wind pollination and may lead to extensive dispersal (Whistler and Elevitch, 2006), contributing to *Casuarina*'s viability for producing dense bio-shield development. Furthermore, some species like *C. equisetifolia* and *C. glauca,* are adapted to arid conditions, low soil fertility and high salinity, and hence ideally adapted for life on sandy beaches and thus are commonly employed as coastal bio-shields (Chaudari et al. 2009, Potgieter et al. 2014a). *Casuarina* continue to disperse, as most parts of the world have been identified as climatically suitable. In fact, Potgieter et al. (2014a) estimated that roughly 8% of the world is bio-climatically similar to the *Casuarina*'s native ranges further promoting its utility as a viable coastal protection measure.

The genus *Casuarina* belongs to the family Casuarinaceae and contains 17 species (Wheeler et al. 2011, CABI 2018: www.cabi.org/isc) of which several species, including *C. cunninghamiana*, *C. equisetifolia* and *C. glauca*, have been officially recorded as either naturalized or invasive (Potgieter et al. 2014b). *C. equisetifolia,* commonly known as casuarinas, beefwood, beach she-oak, Australian Pine or ironwood, has the largest native range of all the *Casuarina* species. *C. equisetifolia* occurs naturally along tropical coastlines in Australia, Malaysia and Thailand, as well the as adjacent coastal regions of the Andaman Sea in southern Myanmar. To the east, its native distribution includes Melanesia and Polynesia (Morton 1980, Gordon 1998, Pernas et al. 2013, Potgieter et al. 2014a; CABI 2018). *C. glauca* (scaly oak or swamp she-oak) and *C. cunninghamiana* (Australian beefwood), only occurs naturally in Australia, the former generally occurring in wetland areas and the latter in riparian habitat (CABI 2018: www.cabi.org/isc). Rejmánek and Richardson (2013) established that these three *Casuarina* species were reported as invasive in several regions; *C. equisetifolia* is known to be an invasive weed tree along the coastlines of North America (Florida), Asia, South Africa, Central America, South America and on the following islands: Ascension, Bermuda, Canary Islands, Cayman Islands, Dominican Republic, Hawaii, Jamaica, Reunion, Ogasawara, Puerto Rico and the Seychelles. *C. cunninghamiana,* was reported as invasive in South Africa, and Reunion and *C. glauca* in North America (Florida) and the Pacific Islands (Hawaii) and potentially Madagascar, both species occurring in coastal habitat (Rejmánek and Richardson 2013). These three species, *C. cunninghamiana*, *C. equisetifolia* and *C. glauca,* were the focus of this study and hereafter are collectively referred to as *Casuarina*. The introduction of these species to the different regions outside their native ranges (**Figure 1.3**) created a global-scale natural experiment, with opportunities to explore the effect the introduction of non-native species at various biological levels (genetic diversity, species, habitats or ecosystem level) and management policies regarding invasive coastal species.

Figure 1.2: A) C. equisetifolia *tree adjacent to a beach. B) Cones of a* C. cunninghamiana *tree. C) Flowers of a* C. glauca *tree.*



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors, Sources: Esri, GEBCO, NOAA, N
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Figure 1.3: Global occurrence and origin (native vs. introduced) of three Casuarina species.: C. cunninghamiana, C. equisetifolia *and* C. glauca*.* C. cunninghamiana *and* C. glauca *are native to Australia, while* C. equisetifolia *is native to Australia and certain regions of South East Asia, including Brunei Darussalam, Cook Islands, Fiji, Indonesia, Japan, Kiribati, Malaysia, Sabah, Sarawak, Myanmar, Nauru, Papua New Guinea, Philippines, Samoa, Solomon Islands, Thailand, Tonga, Vanuatu and Vietnam (CABI International 2000; GBIF 2008).*

1.2.1 Beach structure and function

To understand and manage beaches effectively as ecosystems including the concomitant changes caused by the presence of exotic vegetation such as *Casuarina*, we must first inspect the physical dynamics shaping beach habitats. Following Brown and McLachlan (1990), the term ‘beach’ in this study refers to the littoral active zone, including the surf zone, intertidal shore, back-beach and primary and secondary dunes (**Figure 1.4**). The shape of the beach will be affected both temporally and spatially by various abiotic drivers (**Box 1**). The primary drivers affecting the beach type include wave and wind energy, which defines the morphodynamic state of the intertidal and drives accretion and erosion processes of the beach system (McArdle and McLachlan 1992, Short 1993, Short 1999). Other factors such as vegetation, sediment type, meteorological processes (temporal effect), sea level rise, storms, bathymetry and beach exposure, including the presence of offshore reef environments that alter the dynamics and tidal range are secondary factors affecting the formation of beaches (Benedet et al. 2004, Defeo and McLachlan 2005, McLachlan and Dorvlo 2005, Short 2006).

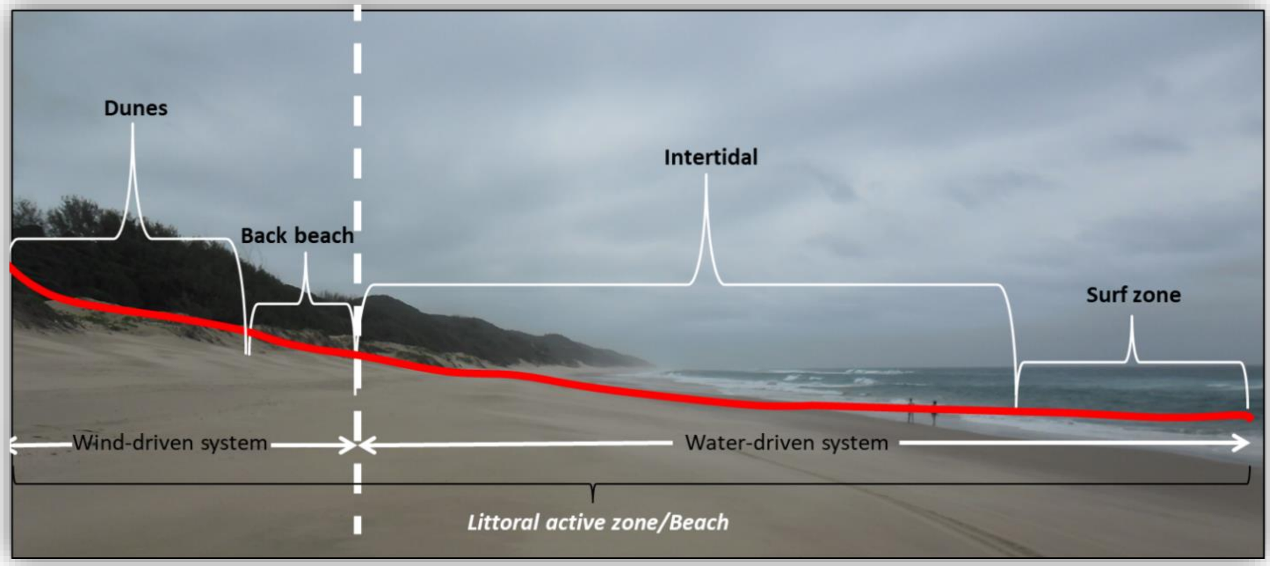


Figure 1.4: The three general sections of the beach as defined by McLachlan (1980).

a) The surf zone and intertidal zone

The surf zone and the intertidal zone is shaped by waves, the tide and sand particle size (McLachlan 1980, Short and Wright 1983). As the intertidal zone is the part of the beach below the high tide line that is exposed at low tide (Pilkey et al. 2011), it may be scoured directly by wind as well as by waves, but it mainly functions as a water-driven system. Alongshore, the surfzone and intertidal are affected by currents that move and deposit sediment along the shore (Seymour 1980). Across shore, beaches absorb energy that shapes the intertidal zone and defines its morphodynamic state (Brown and McLachlan 1990). The intertidal component of beaches with a steep slope, narrow surf zone, low wave energy, small tide range and coarse sand particles constitute a *reflective* morphodynamic state, while beaches with a flat slope, wide surf zone, high wave energy, a large tide range and fine sand particles are known as *dissipative*. There are several *intermediate* states that fall between these extremes, but the intertidal beach face changes from one state to the next, even within a single tidal cycle and lasts for a short period (Brown and McLachlan 1990, McArdle and McLachlan 1992, McLachlan and Dorvlo 2005). A storm event may alter the beach so drastically that it is unrecognisable within hours (Roelvink et al. 2009, Pilkey et al. 2011). However, even though beach shape is dynamic, beaches *per se* are stable landforms with a natural (seasonal) cycle, where sand moves offshore during storms and moves back onshore during calm periods (Inman and Filloux 1960, Brown and McLachlan 1990).

b) The Back-Beach and Dune System

The back-beach is defined as the section between the high tide drift line and the beginning of the primary dune (Pilkey et al. 2011). It is the first section of the dry beach and the wind-driven system, directly in front of the dunes. Most severe beach erosion occurs on the back-beach under conditions of increased wave and tidal height (spring tide or storm events), as waves flow across the beach and penetrates the back-beach section depleting the sand. Waves moving further up the shore erodes the foredune, producing continuous parallel foredune scarping (Short and Wright 1983). Rizzo et al. (2017) highlighted the importance of the back-beach width as an indicator of erosion resilience in beach systems, addressing the critical value of the back beach in maintaining a functioning beach and dune system.

Tinley (1985) and Tsoar (2001) classify types of aeolian sand dunes based on dune genesis and wind direction grouping non-vegetated dunes vs. vegetated dunes. Vegetated dunes, shaped primarily by the vegetation itself, include vegetated linear/established foredunes and hummock/incipient foredunes (**Figure 1.5**).

Box 1

Factors that affect the formation of beaches:

a) ***Sediment source:*** The source will affect the sand grain size and grain shape, which ultimately affects the movement of sediment. The sediment source may include adjacent beaches, rivers, glaciers, the seabed, cliff erosion or human activity (Pilkey et al. 2011).

b) ***Fluvial yield:*** Fluvial yield will affect the sediment budgets of the beach. Fluvial yield is affected by the process of sediment transport from rivers mainly during floods (Hsu et al. 2004, Liquete et al. 2009, Huang 2011;) and the opening and closure of inlets and estuaries (Defeo et al. 2009)***.***

c) ***Meteorological processes:*** Temporal beach cycles, like spring-neap and high-low tides are driven by moon phases and planetary alignment (Inman & Filloux 1960, Smith et al. 2010)***.***

d) ***Sea level rise:*** Sea-level rise has a long-term erosion effect on coast lines (Schwartz 1967, Zhang et al. 2004, Corbella and Stretch 2012)

e) ***Storm intensity and storm frequency:*** Storms lead to seasonal erosion of the beach by moving sediment offshore (Morton et al. 1994, van Rijn et al. 2003, Roelvink et al. 2009).

f) ***Beach orientation/exposure:*** The orientation of the beach affects its exposure to waves (McLachlan 1980)

g) ***Bathymetry:*** Alongshore variation in nearshore bathymetry will affect wave impact and tidal surge, as well as longshore sediment transport (Morton and Sallenger 2003)***.***

h) ***Wind climate:*** The backshore section of the beach is defined by the average long-term wind condition (Tsoar 2001). Wind moves sand at speeds of 4 m.s^{-1} – 10 m.s^{-1} when the sand moisture content is less than 2% (Brown and McLachlan 1990).

i) ***Vegetation:*** For the formation of the foredune system, vegetation plays an extremely important role by creating an obstacle that traps sand (Doing 1985, Tsoar 2001). The formation of foredunes is therefore determined by the interaction between wind, vegetation and the penetrability (compactness) of the sand, controlled by sand particle size and soil moisture (Short and Wright 1983, Pilkey et al. 2004).

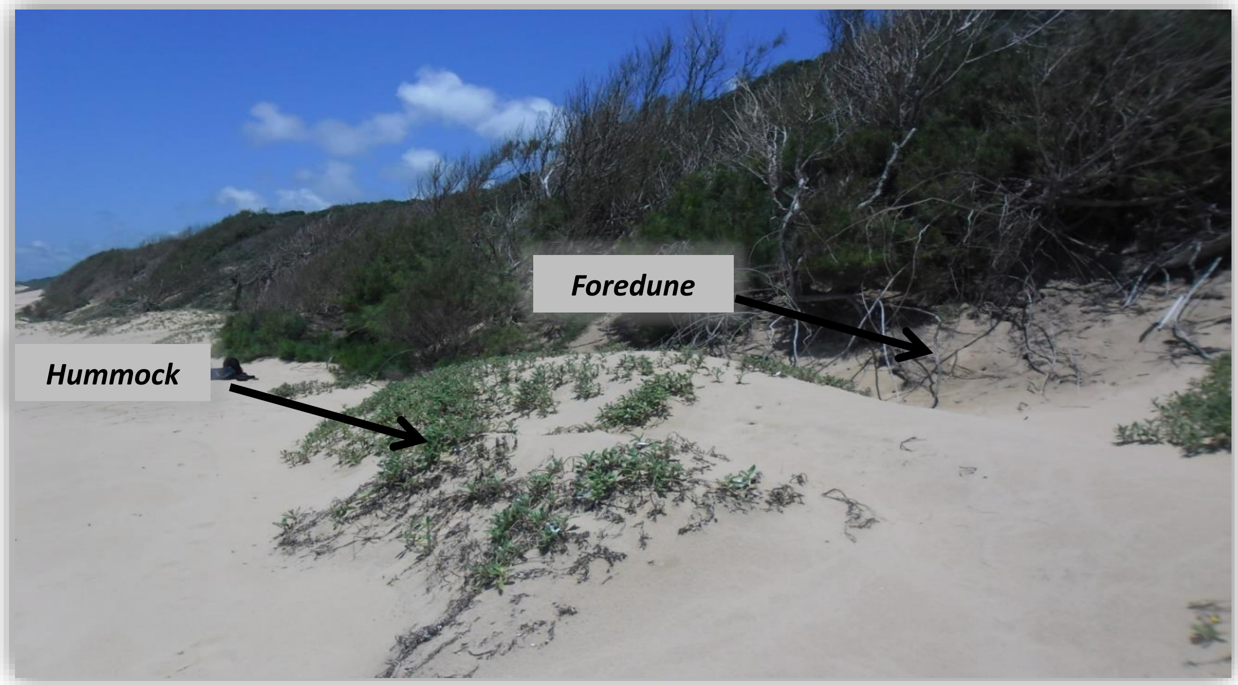


Figure 1.5: Back-beach section/dune system showing an embryo/incipient dune that will eventually coalesce with the established foredune.

Foredunes are vegetated ridges that lie parallel with the strandline vulnerable to onshore winds and extreme wave action (spring tide and storm events) (Tinley 1985, Tsoar 2001). The foredune system comprises of hummock/incipient dunes, the established foredune and the relict foredune (Brown and McLachlan 1990, Hesp 2002, Tsoar 2001) and the formation of this system depends primarily on the presence of vegetation (Doing 1985, Tsoar 2001). Vegetation acts as an obstacle that creates friction and turbulence in front and decreases wind velocity on the leeside of the vegetation, thereby decreasing the entraining of sand particles (Pilkey et al. 2011, Tsoar 2001). Vegetation further decreases the drift potential of sand particles by lowering sand temperature and thereby increasing soil moisture (Brown and McLachlan 1990). The formation of foredunes are therefore essentially a product of the interaction between wind, vegetation and the penetrability (compactness) of the sand, as determined by sand particle size and soil moisture (Short and Wright 1983, Pilkey et al. 2004). The penetrability of sand is a principal factor in preventing erosion (Brown and McLachlan 1990), because the more penetrable the sand is, the easier wind will be able to blow it away. Dunes are extremely important to the functioning of a beach because there is a dynamic interaction between dunes and the intertidal zone, with the dunes continuously source sand to the intertidal (Brown and McLachlan 1990). Dunes act as a long-term sand reserve and supply sand during storm events and accrete sand during fair weather conditions (Brown and McLachlan 1990, Hesp 2002).

The natural succession of vegetation in coastal zones has been studied quite extensively (Doing 1985, van Aarde et al. 1996, García-Mora et al. 1999). Doing (1985) described the coastal foredune zonation in various regions of the world, distinguishing several communities along the beach profile (**Figure 1.6**) and their relevant species. It is typical for the foredune complex of subtropical South-East Africa and the Indian Ocean to have no ephemerous communities present at the normal high tide mark, however *Ipomoea pes-caprae, Arctotheca populifolia, Canavalia maritima* and *Gazania rigens* generally comprise the perennial communities above the high tide mark. *Sporobolus virginicus*, usually establishes on the hummock/incipient dunes or frontal ridge, while the central foredune ridge is established by *Scaevola thunbergii*. In the wind-sheltered zone (behind the primary foredune), *Stipagrosis zeyheri, Aristida junciformis, Tephrosia purpurea* and *Carpobrotus dimidiatus,* occur. Pioneer communities in the sheltered/stabilized zone typically consist of *Passerina rigida, Osteosopermum moniliferum, Helichrysum ericaefolium* and *Casuarina equisetifolia*. Doing (1985) specifies the typical occurrence of woody trees, including *Casuarina equisetifolia,* in the sheltered/stabilized zone of the central foredune ridge. However, the artificial plantation of *Casuarina* takes place from the front (shoreward face) of the foredune ridge all the way through to the to the back of the foredune, covering the entire foredune and changing the natural succession of the dune vegetation (Batish et al. 2001, Hardman et al. 2012). Changing the natural succession of coastal vegetation may have implications for the ecosystem functioning of beaches.

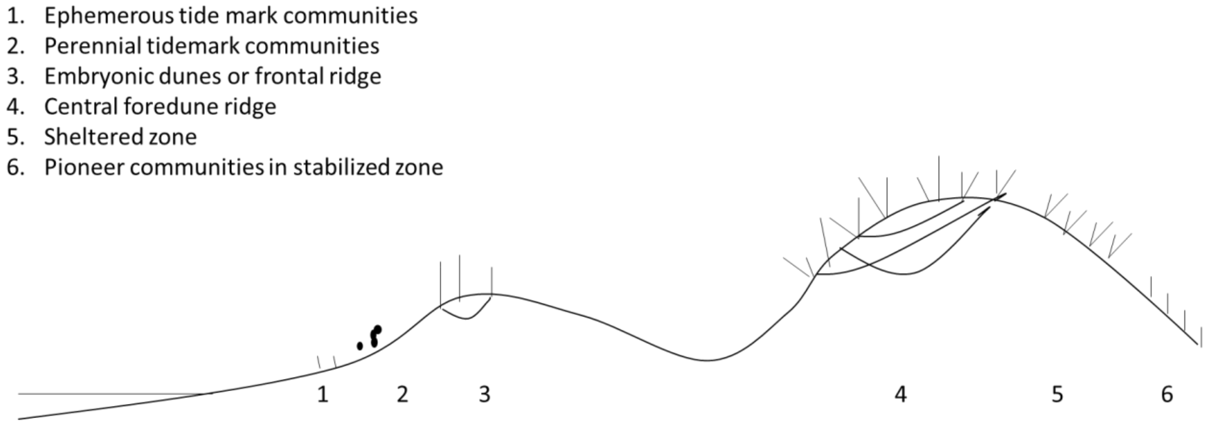


Figure 1.6: Different zones of the foredune complex as distinguished by Doing (1985).

1.3 Use of *Casuarina* as a coastal protection measure

The systematic implementation of bio-shields to mitigate erosion, storms and other extreme episodic events such as tsunamis have been applied for centuries (Feagin et al. 2010). For example, large plantations of *Casuarina* and *Eucalyptus* species have been established to protect coastal settlements against these impacts (Chaudari et al. 2009). The theory underlying the development of bio-shields for coastal protection is that vegetation absorbs/breaks wave energy as it passes through plantations (Forbes and Broadhead 2008). Solid structures, such as sea walls, may be overtopped, smashed or eroded. Bio-shield proponents argue that shelterbelts have the potential to reduce wave impact force, flow depth and velocity (Forbes and Broadhead 2008). This became especially popular after the December 2004 tsunami event that devastated the IOSEA region; some considered using or planting of vegetation as a key coastal protection strategy and the number of studies evaluating the role of vegetation in attenuating extreme storm and other episodic events, grew rapidly (e.g. Danielsen et al. 2005, Tanaka and Thuy 2010, Samarakoon et al. 2013, Mathiventhan and Jayasingum 2014). However, there is no empirical evidence that bio-shields mitigate the impact of long period waves from storm surge or tsunami events (Feagin et al. 2010).

Studies proposing the use of *Casuarina* as coastal breaks are based on anecdotal evidence, substantiated by social surveys (e.g. Riyasahamed 2017). These studies judge the reliability of *Casuarina* forests through personal accounts, post-hoc observational analysis through questionnaire surveys (e.g. De Zoysa 2008) or field surveys of damage (e.g. Mascarenhas and Jayakumar 2008) but not methodical testing. These analyses infer causation; Olwig et al. (2009) analysed imagery pre-and post-tsunami event (2004) to associate damage with vegetation cover. They concluded that mangrove forests and coastal shelterbelts limit damage from tsunami events. However, in this type of analysis it is difficult to distinguish the vegetation effect in isolation (Kerr and Baird 2007), which is frequently confounded by bathymetry and topography (Chaudari et al. 2009). Furthermore, remote sensing is dependent on good quality imagery and high resolution elevation data (Feagin et al. 2010). Modelling studies that estimate friction and drag coefficients for vegetation (e.g. Samarakoon et al. 2013) concluded that vegetation reduces the severity of tsunamis or storm surges by dissipating wave force. These studies are theoretical in approach and cannot replicate the immense scale of tsunami events (Feagin et al. 2010). More importantly, it is noted that vegetation mitigates short-period waves with higher amplitudes (during spring tides or closer to the equinox) differently from those storm surges and tsunamis where water-level is raised for a long period, with greater net wave force over a large spatial scale (Feagin et al. 2010). Therefore, none of these studies can provide conclusive statements on the measure of protection offered by *Casuarina* species against the impacts (inundation and erosion) of extreme episodic events.

Despite the evidence advocating the positive attributes of bio-shields, there are some studies with contradictory evidence; Bhalla (2007) refuted the value of bio-shields with field-based mapping and remote sensing data; A regression between the Normalized Difference Vegetation Index (NDVI) and inundation distance was not significant. Das and Sandhu (2014) reviewed ecosystem services provided by *Casuarina* and found no evidence to validate them as an effective coastal protection tool. Data recorded from a “super cyclone” in October 1999 that caused major destruction in 12 Odisha districts (India), showed that native vegetation provided better storm protection and lowered human casualties, than *Casuarina* trees (Das and Sandhu 2014). Kerr et al. (2006) found no significant relationship between human mortality and the extent of forests in front of coastal hamlets in Tamil Nadu (India), when controlling for difference in elevation and distance from shore. Finally, a number of studies reiterate the lack of science-based decision making in bio-shield policy implementation, and strongly advises against the unmitigated use of exotic vegetation with coastal impacts still largely unquantified, i.e. adopting the precautionary principle (Sridhar 2006, Kerr and Baird 2007).

1.4 Local scale (micro) effects of *Casuarina* on sandy beach systems

Many case studies, particularly in Florida and the Mascarene Islands, examined the effects of *Casuarina* as invasive trees of coastal regions (Morton 1980, Thebaud and Strasberg 1997, Gordon 1998, Baret et al. 2006). They found that *Casuarina* create a sterile soil environment, as the leachate from leaf litter suppresses seed germination of other plant species through negative allelopathic effects (Jadhav and Gaynar 1995). Negative allelopathy refers to the ability of *Casuarina* leaves to produce and excrete bio-chemicals like phenolic compounds, terpenoids and organic cyanides, that are detrimental to the successful growth of other plants (Patil et al. 2002). *Casuarina* stands also have significantly lower sand pH levels, potassium, phosphorus, organic matter concentrations than native vegetation, despite the extensive litterfall underneath these trees (Batish et al. 2001, Buehler and Rodgers 2012). As *Casuarina* are actinorhizal (plants that form a symbiosis with nitrogen fixing actinobacteria, *Frankia*) the trees also affect local nitrogen cycling (Vitousek 1990). These biochemical and soil changes cause a lack of plant diversity underneath *Casuarina* stands, which in turn leads to the reduction of animal diversity including small mammal populations (Mazzotti et al. 1981). By disrupting plant succession and effectively displacing native sand stabilizers from the back beach and dune system, *Casuarina* contribute to increased coastal erosion (Morton 1980, Gordon 1998, Heslenfeld et al. 2008, Wheeler et al. 2011). *Casuarina* have heavy root mats incapable of properly retaining sand (Klukas 1969), whereas native dune vegetation, have adapted stem morphologies for trapping sand. *Casuarina* therefore affects sandy beach sand dynamics by restricting dune formation and disrupting the interaction between the dunes and the intertidal- and surf systems (Chaudari et al. 2009).

Sealey (2006) developed a model describing *Casuarina*-induced beach erosion cycles at Small Hope Bay, Andros in the Bahamas. This six-stage model (**Figure 1.7**) highlights *Casuarina* as an agent of erosion because they facilitate significant sand loss from the top of dunes, and considerable dune and beach retreat after storm events in *Casuarina* locations. Naturally-vegetated dunes seem to stay intact. This storm-related erosion model suggests a perpetual state of beach recession in the presence of non-native *Casuarina* trees. Other studies that highlight the dune stabilization limitations of *Casuarina* include the paper by Swearington (1999). He observed that *Casuarina* trees are easily blown over under severe wind episodes during storms and that high wave conditions undercut the roots of *Casuarina* plants (**Figure 1.8**). As these trees topple over, they increase erosion and cause morphological changes to the beach profile.

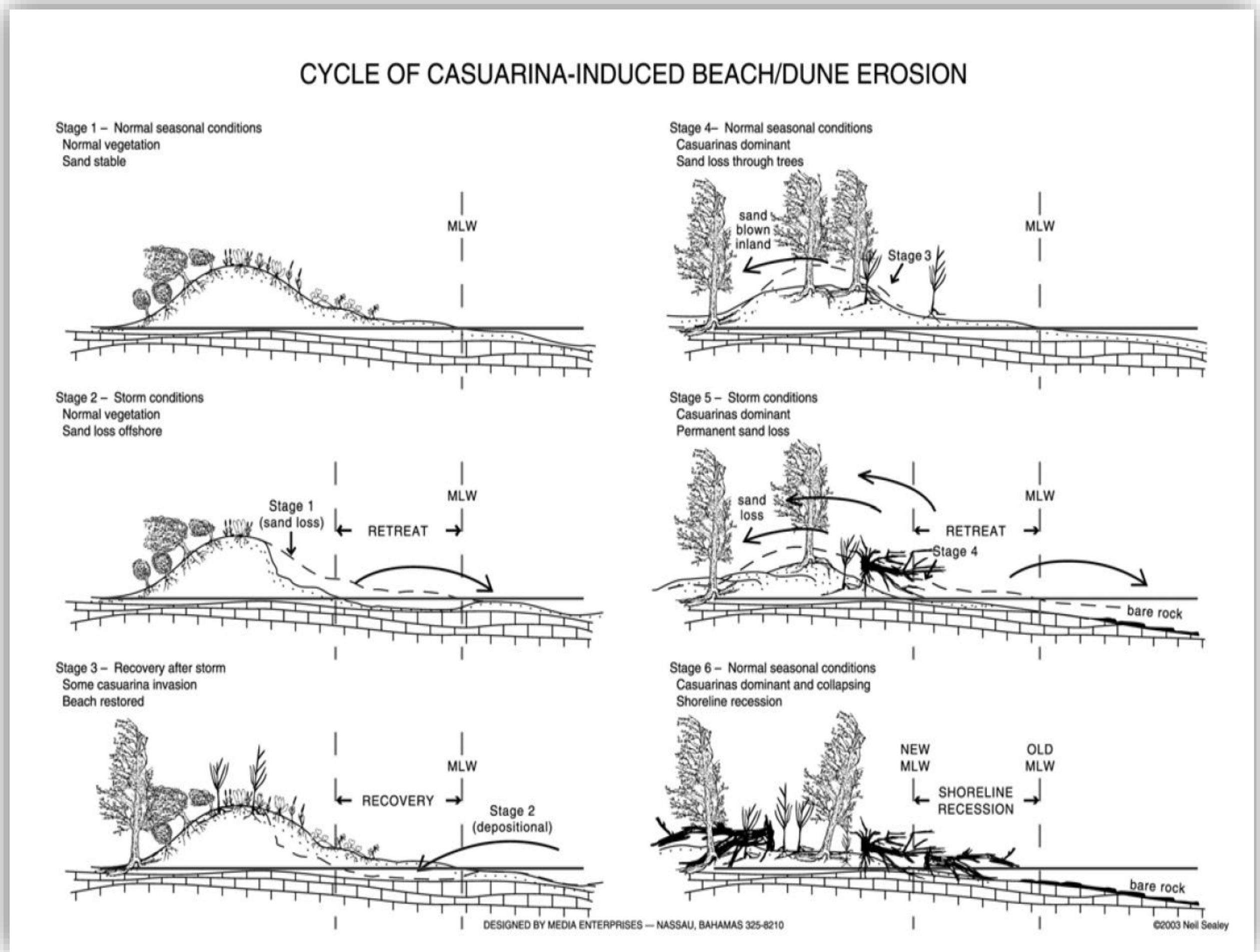


Figure 1.7: The six-stage model of a Casuarina*-induced beach erosion cycle (Sealey 2006). LEFT PANEL:* ***Stage 1*** *illustrates a beach with an intact dune system, without* Casuarina *trees and only native vegetation. The mean low water mark is represented by the dashed line on the low shore.* ***Stage 2*** *represents the same intact beach system undergoing a natural seasonal erosion cycle with sand moving offshore during stormy weather – the mean low water mark shifts higher up the shore as the intertidal erodes and some dune erosion takes place. Sand moves back onshore during calm periods, and the dune repairs with native dune vegetation.* ***Stage 3*** *shows the introduction of* Casuarina *as a protection measure after storm recovery. The effect is a decrease in native vegetation. RIGHT PANEL: In* ***Stage 4****, invasive* Casuarina *dominates with total displacement of natural vegetation. Without native dune stabilizers, the sand overtops the dune to the back of the system and the dune flattens. This process continues even when sand is blown up from the intertidal beach; sand gets carried through the* Casuarina *stand instead of being built up vertically in the dune system.* ***Stage 5*** *represents a post-storm beach state; Extreme wave action drives the mean low water mark to the left as the intertidal is eroded and the dunes retreat. Because the dunes are flatter, the waves may overtop the dunes and displace more sand to the back of the dune system. Extreme wind conditions cause further erosion as sand is blown away. The net result is near total removal of the dune sand reservoir and a familiar exposure of* Casuarina *roots. Because, dune sand is no longer available to the intertidal zone, beach recovery is slowed or eliminated.* ***Stage 6*** *represents final beach destruction; all the sand from the back-beach and dunes is displaced inland and even with fair weather conditions, the beach is too sand starved to rebuild. Beach retreat, if possible, takes place.*

Figure 1.8: The photos depict the type of morphological changes that Casuarina *induce, by destabilizing the dune system when they topple during extreme weather events. Both photos were taken after a seasonal storm of the loggerhead and leatherback nesting beaches in the iSimangaliso Wetland Park, a world-heritage site in South Africa.* Casuarina equisetifolia plants *were not able to withstand the increased wave and wind action. Photo credit: Linda Harris.*

Although numerous studies have showed *Casuarina* negatively impacts certain coastal systems (Morton 1980, Gordon 1998, Batish et al. 2001, Sealey 2006, Chaudari et al. 2009, Wheeler et al. 2011), one should be careful to extrapolate these effects to all systems. For example, areas with native *Casuarina* (e.g. Australia), may not experience the same extent of impact as regions where *Casuarina* are invasive (e.g. India). Natural bio-control species limit *Casuarina* distribution in its native range, controlling abundance and distribution of trees (Keane and Crawley 2002). Rapid increase and distribution in non-native regions may lead to total displacement of native species and various negative effects (Hardman et al. 2012). Even regions where *Casuarina* are considered non-native, extrapolating negative effects to different beach systems (e.g. intact dune system vs. no dune system, high energy vs. low energy beaches etc.), is not necessarily accurate as *Casuarina* may impact different beaches in diverse ways.

1.5 *Casuarina* effects on sea turtle nesting beaches

A few studies examined the impacts of invasive *Casuarina* on sea turtle nesting activities and the nest incubation environment (Schmelz and Mezich 1988; Schmid et al. 2008; Chaudari et al. 2009). Sea turtles nest the back shore and nest close to, in or under vegetation (Hays et al. 1995). Miller et al. (2003) report a general pattern of the nesting process: 1) emergence from the surf, 2) ascending the beach, 3) excavating the body pit, 4) digging the egg chamber, 5) laying the eggs, 6) filling the body pit, and 7) returning to the sea. Because nesting takes place close to or in vegetation, the vegetation type can affect certain aspects of the nesting process specific to the back-beach (excavating/filling the body pit and egg chamber) and change parameters of the nest incubation environment (**Figure 1.9**) (Hays et al. 1995, Chaudari et al. 2009).

Depending on the degree of morphological back-beach shape change (**Figure 1.9**), turtles may be unable to access the back-beach /nesting habitat or may be rendered unable to dig the body pit or egg chamber. The thick leaf litter layer underneath *Casuarina* trees may affect nesting by changing sand characteristics of the immediate back-beach environment, such as sand moisture and penetrability. Sand texture in combination with sand moisture determines sand penetrability (Tinley 1985). To successfully excavate the body pit and egg chamber, penetrability of the sand should be such that the female is able to dig the nest without the walls collapsing (Mortimer 1990). The thick layer of leaf litter that forms underneath *Casuarina* trees (Buehler and Rodgers 2012) may affect sand penetrability by compacting the sand or trapping moisture and fine sand particles, so that a female is unable to dig the body pit and egg chamber.

Nest incubation parameters that determine successful incubation of eggs include temperature, humidity, salinity and levels of respiratory gases (Ackerman 1981), all of which may be affected differently by the presence of *Casuarina* trees versus natural vegetation, because of denser shade and a thick leaf litter mat under *Casuarina* trees.

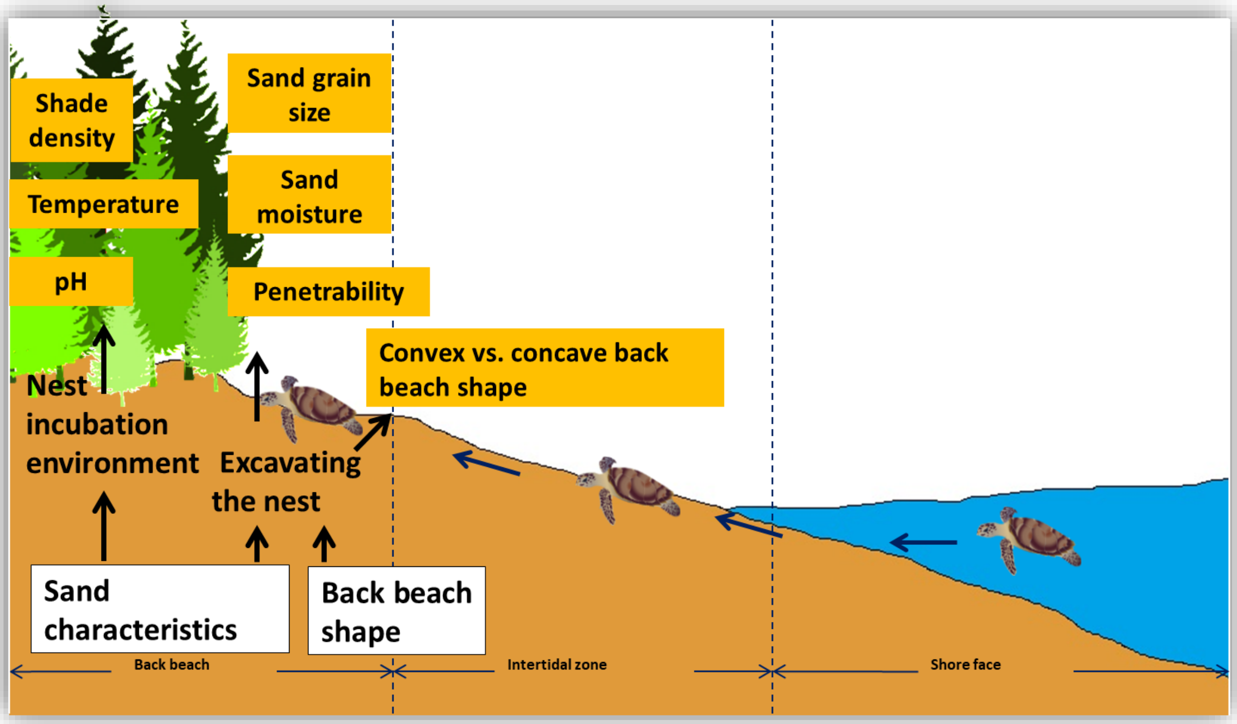


Figure 1.9: The nesting process as described by Miller et al. (2003). Non-native Casuarina *obstruct and change the dynamic exchange of sand between the dune system and the back-beach as a consequence of their thick root mat, which could affect the back-beach shape/slope significantly (Chaudari et al. 2009).*

Changing nest incubation temperature can have significant consequences, as sea turtles have temperature-dependent sex determination (TSD); sand temperature during the middle third of the incubation period determines the sex of sea turtle hatchlings (Mrosovsky and Yntema 1980). The masculinizing and feminizing temperature limits of this transitional range, as demonstrated by Yntema and Mrosovsky (1982), are 32°C and 28°C, respectively. Temperatures above 32°C will yield all females and temperatures below 28°C will produce only males, with a pivotal temperature at which a 1:1 sex ratio is developed is about 29°C (Mrosovsky and Yntema 1980, Yntema and Mrosovsky 1982, Mrosovsky and Pieau 1991). Studies by Schmelz and Mezich (1988), Schmid et al. (2008) and Chaudari et al. (2009) looked at temperature variation underneath *Casuarina* stands versus natural (native) vegetation. While Schmelz and Mezich (1988) and Chaudari et al. (2009) concluded that *Casuarina* trees significantly lowered nest incubation temperature, Schmid et al. (2008) concluded that mean incubation temperatures did not significantly differ among vegetation areas (*Casuarina* present, *Casuarina* removed, or native vegetation). With the opposing results and the significance of nest incubation temperature to turtle sex ratios, further research is critical.

A few studies have observed that fallen *Casuarina* interfere with nesting attempts by forming physical barriers, as they topple over easily during storm events as a result of a shallow root system and thereby prohibit turtles from reaching the back-beach (Morton 1980, Congress 1993, Doren and Jones 1997). Chaudari et al. (2009) recorded significantly lower nest counts and turtle track counts for olive ridley turtles along 40 km of the Tamil Nadu coast (India) on beaches with *Casuarina equisetifolia* plantations vs naturally vegetated or open (no vegetation) beaches, controlling for human disturbance (proximity to settlements), general beach profile and beach composition. Chaudari et al. (2009), however, do not describe a mechanism that may explain the differences observed in these turtle nesting metrics. The study showed that beach slope was significantly steeper on beaches with *Casuarina equisetifolia* plantations compared to the other two beach types (vegetated and open/no vegetatation) but does not specify which part of the beach was affected, i.e. whether slope was measured from the foredune to the surf-zone or only for the intertidal (high to low water mark). Not knowing which part of the beach system is considered steeper in the presence of non-native *Casuarina* trees, makes it difficult to examine *Casuarina* effects on the turtle nesting process. To estimate impacts on the sea turtle nesting process and the nest incubation environment, further research on the morphological change of the back-beach /nesting habitat when non-native *Casuarina* is present vs natural or no vegetation is necessary.

1.7 Regional beach vulnerability to *Casuarina* presence and global change

Considering the introduction of *Casuarina* to coastal regions outside of their native ranges on a global scale, the bio-climatic suitability of beaches to their naturalization or invasion, and research suggesting negative effect on sandy beach ecosystems, the back-beach and sea turtle nesting habitat, targeted research on the effect and distribution of non-native *Casuarina* trees on vulnerable beaches is overdue. Further, beach vulnerability is increasing with rapid global change and anthropogenic modification (Crain et al. 2008, Halpern et al. 2008, Ban et al. 2010), and coasts are being developed at an unprecedented rate threatening the integrity of the dune system (Benassai et al. 2015, Rizzo et al. 2017). Superimposed on these challenges, is rising sea levels due to melting of the polar ice caps and thermal expansion of the ocean (IPCC 2007) and increased frequency and intensity of storms because of climate change, leading to permanent and episodic inundation and erosion of the coastline (Emanuel 2005, Webster et al. 2005, Goswami et al. 2006). *Casuarina* may therefore be a useful tool or a serious management problem by either decreasing or increasing beach erosion vulnerability to global change.

Vulnerability is generally understood to be a function of three components: 1) sensitivity (also referred to as resistance or risk), 2) exposure (also referred to as threat or impact) and 3) adaptive capacity (also referred to as resilience, recovery potential and adaptability) (Kasperson et al. 1995, Brooks 2003, De Lange et al. 2010, Glick et al. 2011). Sensitivity refers to intrinsic factors that indicate a system's tolerance to change (Patwardhan et al. 2007). Conversely exposure refers to extrinsic factors (stressors or threats), specifically the magnitude and rate of change a system might undergo (Goswami et al. 2006). Adaptive capacity indicates a system's ability to accommodate or recover from these changes (Julius et al. 2008).

Various International beach vulnerability assessment methods to climate change have been developed from the IPCC Common Methodology (1991) (Abuodha and Woodroffe 2006). Examples include quantitative modelling methods such as the Synthesis and Upscaling of Sea-level Rise Vulnerability Assessment Studies (SURVAS) (Nicholls et al. 2008), and semi-quantitative coastal vulnerability indices such as the Coastal Vulnerability Index (CVI) (Gornitz et al. 1994) and the Coastal Social Vulnerability Index (CSoVi) (Boruff et al. 2005, Abuodha and Woodroffe 2006). In recent assessments, one of the most commonly used methods, is the CVI originally created by Gornitz et al. (1994) (Di Paola et al. 2011). The CVI method combines the coastal system's vulnerability with its ability to adapt to environmental change (Rangel-Buitrago and Anfuso 2015). The CVI evaluates the coast's vulnerability to the impacts of erosion, permanent inundation and episodic flooding by scoring and combining the cumulative effect of several variables (e.g. shoreline evolution, coastal elevation, tropical storm probability, tide range and wave height). The method is applied in a GIS environment or multivariate analysis (LOICZ 1995) and the main output is generally colour coded maps depicting the relative vulnerability (low, moderate or high) of the shoreline (ex. Thieler and Hammer-Klose 2000, Abuodha and Woodroffe 2006, Kumar et al. 2010, Mclaughlin and Cooper 2010). For a summary of existing vulnerability indices and the variables needed to implement them, see **APPENDIX 1: Summary of existing CVI's**.

The variables that are chosen for cumulative vulnerability assessments are mainly dictated by the target of the assessment; physical factors such as shoreline accretion or recession (Rizzo et al. 2017), socio-economic impacts like damage to infrastructure and human mortalities (Boruff et al. 2005, Li and Li 2011) or ecosystem-level impacts affecting the functioning of coastal ecosystems (Halpern et al. 2008), and the geographic scale of the assessment (Fekete et al. 2010). Vulnerability assessments (VA's) are closely related to scale, as scale often predicts data availability and integrity (Fekete et al. 2010). There is often an inverse relationship between geographic scale and certainty levels when it comes to climate projections and system response, as climate projections tend to be more robust at coarser scales (Glick et al. 2011). But system characteristics, such as sand grain size or remote sensing data, capturing for example shoreline evolution, are generally more accessible at smaller scales (Mclaughlin and Cooper 2010). The intention of the CVI and its variants are to show relative vulnerability (Abuodha and Woodroffe 2006), simplifying complex and interacting variables by allocating relevant scores and quantifying these as a single measure of vulnerability (Mclaughlin and Cooper 2010). The CVI capacity to establish absolute impacts from sea-level rise or increased storm activity is limited (Abuodha and Woodroffe 2006), rather it should be seen as a high level scoping tool to highlight local areas in need of more detailed quantitative analysis that uses analytical and numerical data within specific modelling software (Goodhue et al. 2012, Rizzo et al. 2017).

Vulnerability assessments such as Coastal Vulnerability Index (CVI) by Gornitz et al. (1994) is a tool that can be implemented to assess erosion vulnerability of sea turtle nesting beaches. These assessments can highlight the balance between risks and threats and so expose vulnerable areas susceptible to damage (UNDRO 1982). Coastal managers can use VA's to prioritise regions where existing stressors/risks, such as the presence of exotic vegetation like *Casuarina* trees, might be exacerbated by climate change (Anfuso and Martínez Del Pozo 2009, Mclaughlin and Cooper 2010), and so inform suitable risk-management or planning strategies (Glick et al. 2011).

THESIS OUTLINE

The main aim of this study was to investigate the use and potential use of non-native *Casuarina* trees as a coastal protection measure in sea turtle nesting habitat.

The aim will be addressed by the following broad objectives, structured within two data chapters:

- To investigate the effect of non-native *Casuarina* trees at a local scale (per beach), considering their effect on the back-beach environment (back-beach shape, substrate/sand characteristics and the nest incubation environment) (Chapter 2);
- To establish the distribution of non-native *Casuarina* trees on beaches with a high abundance of sea turtle nesting throughout the IOSEA region (Chapter 3);
- To assess the erosion vulnerability of sea turtle nesting beaches of the IOSEA at a regional scale, as indicated by physical beach features, such as back-beach condition, and threats such as sea level rise and storminess (Chapter 3).

The study therefore aims to answer the following key questions:

1) Do non-native *Casuarina* trees affect the back-beach/sea turtle nesting habitat in a significantly different way from native vegetation, when considering the back-beach shape, substrate/sand characteristics and nest incubation environment?
2) To what extent do non-native *Casuarina* trees occur on beaches with important sea turtle rookeries in the IOSEA region?
3) Based on physical beach features such as back-beach condition, and threats including sea-level rise and storminess, which of these sea turtle nesting beaches can regionally (IOSEA) be considered as more vulnerable to erosion and can *Casuarina* plants be considered an indicator of high erosion vulnerability?

The overall hypothesis is that the back-beach environment and coastline response will be altered in the presence of non-native *Casuarina* trees as opposed to native or no vegetation conditions and that non-native *Casuarina* cannot be considered as an appropriate coastal protection measure.

All content chapters are written as stand-alone chapters to assist with publication and therefore some repetition may be evident in the different chapters.

REFERENCES

ABUODHA, P. A. and WOODROFFE, C. D. 2006. Assessing vulnerability of coasts to climate change: A review of approaches and their application to the Australian coast. *GIS for the Coastal Zone: A selection of Papers from CoastGIS 2006*:458.

ACKERMAN, R. A. 1981. Oxygen consumption by sea turtle (*Chelonia*, *Caretta*) eggs during development. *Physiological Zoology* 54:316–324.

ANFUSO, G. and MARTÍNEZ DEL POZO, J. Á. 2009. Assessment of coastal vulnerability through the use of GIS tools in south sicily (Italy). *Environmental Management* 43:533–545.

AWALE, D. and PHILLOTT, A. D. 2014. A review of the adverse effects of *Casuarina* spp. on coastal ecosystems and sea turtle nesting beaches. *Indian Ocean Turtle Newsleter* 19:15–19.

BAN, N. C., ALIDINA, H. M. and ARDRON, J. A. 2010. Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. *Marine Policy* 34:876–886.

BARBIER, E., HACKER, S., KENNEDY, C., KOCH, E., STIER, A. and SILLIMAN, B. 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81:169–193.

BARET, S., ROUGET, M., RICHARDSON, D. M., LAVERGNE, C., EGOH, B., DUPONT, J. and STRASBERG, D. 2006. Current distribution and potential extent of the most invasive alien plant species on La Rèunion (Indian Ocean, Mascarene islands). *Austral Ecology* 31:747–758.

BATISH, D. R., SINGH, H. P. and KOHLI, R. K. 2001. Vegetation exclusion under *Casuarina equisetifolia* L.: Does allelopathy play a role? *Community Ecology* 2:93–100.

BENASSAI, G., DI PAOLA, G. and AUCELLI, P. P. C. 2015. Coastal risk assessment of a micro-tidal littoral plain in response to sea level rise. *Ocean and Coastal Management* 104:22–35.

BENEDET, L., FINKL, C.W., CAMPBELL, T., and KLEIN, A. 2004. Predicting the effect of beach nourishment and cross-shore sediment variation on beach morphodynamic assessment. *Coastal Engineering*, 51: 839-861.

BHALLA, R. S. 2007. Do bio-shields affect tsunami inundation? *Current Science* 93:831–833.

BORUFF, B. J., EMRICH, C. and CUTTER, S. L. 2005. Erosion hazard vulnerability of US coastal counties. *Journal of Coastal Research* 215:932–942.

BROOKS, N. 2003. Vulnerability, risk and adaptation : A conceptual framework. *Tyndall Centre for Climate Change Research* 38:20.

BROWN, A. C. and MCLACHLAN, A. 1990. Ecology of Sandy Shores. Amsterdam, NE: Elsevier: 5-39 and 243-266.

BUEHLER, C. and RODGERS, J. 2012. Soil property differences between invaded casuarina (*Casuarina equisetifolia* L.) sites and non-casuarina sites in the Bahamas. *Physical Geography* 33:574–588.

CABI. 2018. Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc.

CARDOSO, R. S. and DEFEO, O. 2004. Biogeographic patterns in life history traits of the Pan-American sandy beach isopod *Excirolana braziliensis*. *Estuarine, Coastal and Shelf Science* 61:559–568.

CHAUDARI, S., PRASAD, K. D. and SHANKER, K. 2009. Impact of *Casuarina* plantations on Olive Ridley Turtle nesting along the Northern Tamil Nadu Coast , India. ATREE, Bangalore and MCBT, Mamallapuram, India. pp. 44.

COLOSIO, F., ABBIATI, M. and AIROLDI, L. 2007. Effects of beach nourishment on sediments and benthic assemblages. *Marine Pollution Bulletin* 54:1197–1206.

CONGRESS US. 1993. *Office of Technology Assessment. 1993. Harmful non-indigenous species in the United States*. OTA-F-565. US Government Printing Office, Washington, DC.

CORBELLA, S. and STRETCH, D. D. 2012. Decadal trends in beach morphology on the east coast of South Africa and likely causative factors. *Natural Hazards and Earth System Science* 12:2515–2527.

COSTAS, S., FERREIRA, O. and MARTINEZ, G. 2015. Why do we decide to live with risk at the coast? *Ocean and Coastal Management* 118:1–11.

CRAIN, C. M., KROEKER, K. and HALPERN, B. S. 2008. Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters* 11:1304–1315.

DANIELSEN, F., SØRENSEN, M. K., OLWIG, M. F., SELVAM, V., PARISH, F., BURGESS, N. D., HIRAISHI, T., KARUNAGARAN, V. M., RASMUSSEN, M. S., HANSEN, L. B. AND QUARTO, A. 2005. The Asian tsunami: a protective role for coastal vegetation. *Science*, *310*:643-643.

DAS, S. AND SANDHU, H., 2014. Role of exotic vegetation in coastal protection. *Economic and Political Weekly* 49: 43.

DEFEO, O. and MCLACHLAN, A. 2005. Patterns, processes and regulatory mechanisms in sandy beach macrofauna: a multi-scale analysis. *Marine Ecology Progress Series*: 295:1-20.

DEFEO, O., MCLACHLAN, A., SCHOEMAN, D. S., SCHLACHER, T. A., DUGAN, J., JONES, A., LASTRA, M. and SCAPINI, F. 2009. Threats to sandy beach ecosystems: A review. *Estuarine, Coastal and Shelf Science* 81:1–12.

DE LANGE, H. J., SALA, S., VIGHI, M. and FABER, J. H. 2010. Ecological vulnerability in risk assessment - A review and perspectives. *Science of the Total Environment* 408:3871–3879.

DE ZOYSA, M. 2008. *Casuarina* coastal forest shelterbelts in Hambantota City, Sri Lanka: Assessment of impacts. *Small-scale Forestry* 7:17–27.

DI PAOLA, G., IGLESIAS, J., RODRIGUEZ, G., BENASSAI, G., AUCELLI, P. and PAPPONE, G. 2011. Estimating coastal vulnerability in a meso- tidal beach by means of quantitative and semi-quantitative methodologies. *Journal of Coastal Research* 61:1–7.

DOING, H. 1985. Coastal fore-dune zonation and succession in various parts of the world. *Vegetatio* 61:65–75.

DOREN, R. F. and JONES, D. T. 1997. Plant management in Everglades National Park. *Strangers in Paradise. D. Simberloff, DC Schmitz and TC Brown, eds. Island Press, Washington, DC*, pp.275-286

DUGAN, J. E., DEFEO, O., JARAMILLO, E., JONES, A. R., LASTRA, M., NEL, R., PETERSON, C. H., SCAPINI, F., SCHLACHER, T. and SCHOEMAN, D. S. 2010. Give beach ecosystems their day in the sun. *Science* 329:1146.

EMANUEL, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436:686–688.

FEAGIN, R. A., MUKHERJEE, N., SHANKER, K., BAIRD, A. H., CINNER, J., KERR, A. M., KOEDAM, N., SRIDHAR, A.,

ARTHUR, R., JAYATISSA, L. P., LO SEEN, D., MENON, M., RODRIGUEZ, S., SHAMSUDDOHA, M. and DAHDOUH-GUEBAS, F. 2010. Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters. *Conservation Letters* 3:1–11.

FEKETE, A., DAMM, M. and BIRKMANN, J. 2010. Scales as a challenge for vulnerability assessment. *Natural Hazards* 55:729–747.

FORBES, K. and BROADHEAD, K. 2008. The role of coastal forest in the mitigation of tsunami impacts. *RAP publication, FAO*.

GARCÍA-MORA, M. R., GALLEGO-FERNÁNDEZ, J. B. and GARCÍA-NOVO, F. 1999. Plant functional types in coastal foredunes in relation to environmental stress and disturbance. *Journal of Vegetation Science* 10:27–34.

GBIF. 2008. Global Biodiversity Information Facility (GBIF) Work programme 2009–2010. Available: http://www.gbif.org/WP2009-10.pdf. Accessed 21 Feb 2017, UK.

GLICK, P., STEIN, B. A. AND EDELSON, N. A. 2011. Scanning the conservation horizon: a guide to climate change vulnerability assessment. *Washington, DC: National Wildlife Federation. 176 p.*

GOODHUE, N., ROUSE, H., RAMSAY, D., BELL, R., HUME, T. AND HICKS, M., 2012. Coastal adaptation to climate change: Mapping a New Zealand coastal sensitivity index. *A report prepared as part of the Coastal Adaptation to Climate Change Project under contract (CO1XO802) to MBIE, NIWA, Hamilton, New Zealand. 43p*.

GORDON, D. R. 1998. Effects of invasive, non-indigenous plant species on ecosystem processes : Lessons from Florida. *Ecological Applications* 8:975–989.

GORNITZ, V. M., DANIELS, R. C., WHITE, T. W. and BIRDWELL, K. R. 1994. The development of a coastal risk assessment database: Vulnerability to sea-level rise in the U.S. south-east. *Journal of Coastal Research*:327–338.

GOSWAMI, B. N., VENUGOPAL, V., SENGUPTA, D., MADHUSOODANAN, M. S. and XAVIER, P. K. 2006. Increasing trend of extreme rain events over India in a warming environment. *Science* 314:1442–1444.

HALPERN, B. S., WALBRIDGE, S., SELKOE, K. A., KAPPEL, C. V., MICHELI, F., D'AGROSA, C., BRUNO, J. F., CASEY, K. S., EBERT, C., FOX, H. E., FUJITA, R., HEINEMANN, D., LENIHAN, H. S., MADIN, E. M. P., PERRY, M. T., SELIG, E. R., SPALDING, M., STENECK, R. and WATSON, R. 2008. A global map of human impact on marine ecosystems. *Science* 319:948–952.

HANUM, F. and VAN DER MAESEN, L.J.G. 1997. Plant Resources of South-East Asia 11. Auxiliary Plants. PROSEA Foundation, Bogor, Indonesia.

HARDMAN, C. J., WILLIAMS, S., MANCO, B. N. and HAMILTON, M. A. 2012. Predicting the potential threat of *Casuarina equisetifolia* to three endemic plant species on the Turks and Caicos Islands. *Oryx* 46:204–212.

HAYS, G. C., MACKAY, A., ADAMS, C. R., MORTIMER, J. A., SPEAKMAN, J. R. and BOEREMA, M. 1995. Nest site selection by sea turtles. *Journal of Marine Biological Association of the United Kingdom* 75:667–674.

HESLENFELD, P., JUNGERIUS, P. and KLIJN, J. 2008. European Coastal Dunes: Ecological Values, Threats, Opportunities and Policy Development. In: Martinez, M. L., Psuty, N. P. (eds) Coastal Dunes. Ecological Studies, vol 171 pp. 342–391.

HESP, P. 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. *Geomorphology* 48:245–268.

HSU, S. C., LIN, F. J., JENG, W. L., CHUNG, Y. C., SHAW, L. M. and HUNG, K. W. 2004. Observed sediment fluxes in the southwesternmost Okinawa Trough enhanced by episodic events: Flood runoff from Taiwan rivers and large earthquakes. *Deep-Sea Research Part I: Oceanographic Research Papers* 51:979–997.

HUANG, G. 2011. Time lag between reduction of sediment supply and coastal erosion. *International Journal of Sediment Research* 26:27–35.

INMAN, D. L. and FILLOUX, J. 1960. Beach cycles related to the tide and local wind regime. *Journal of Geology* 68:225–231.

IPCC. 2007. Climate change 2007: The physical science basis. *Intergovernmental Panel on Climate Change* 446:727–728.

JADHAV, B. B. and GAYNAR, D. G. 1995. Effect of *Casuarina equisetiolia* J.R. leaf litter leachates on germination and seedling growth of rice and cowpea. *Allelopathy Journal* 2:105-108.

JERARDINO, A., NAVARRO, R. A. and GALIMBERTI, M. 2014. Changing collecting strategies of the clam *Donax serra* Röding (Bivalvia: Donacidae) during the Pleistocene at Pinnacle Point, South Africa. *Journal of Human Evolution* 68:58–67.

JULIUS, S. H., WEST, J. M., JOYCE, L. A., KAREIVA, P., KELLER, B. D., PALMER, M. AND PETERSON, C. 2008. Preliminary review of adaptation options for climate-sensitive ecosystems and resources. *National Parks*, *1*: 1-6

KASPERSON, J. X., KASPERSON, R. E. AND TURNER, B. L. 1995. *Regions at risk*. United Nations University Press.

KEANE, R. M. and CRAWLEY, M. J. 2002. Exotic plant invasions and the enemy release hypothesis. *Trends in Ecology and Evolution.* 17:164–170.

KERR, A. M. and BAIRD, A. H. 2007. Natural barriers to natural disasters. *BioScience* 57:102–103.

KERR, A. M., BAIRD, A. H. and CAMPBELL, S. J. 2006. Comments on ‘Coastal mangrove forests mitigated tsunami’ by K. Kathiresan and N. Rajendran [Estuar. Coast. Shelf Sci. 65 (2005) 601-606]. *Estuarine, Coastal and Shelf Science* 67:539–541.

KLEIN, R. J. T. 2002. Coastal Vulnerability, Resilience and Adaptation to Climate Change: An Interdisciplinary Perspective. PhD Thesis submitted to Mathematisch-Naturwissenschaftliche Fakultät of the Christian-Albrechts-Universität zu Kiel. 40 pp.

KLUKAS, R. W. 1969. Exotic terrestrial plants in South Florida with emphasis on Australian pine (*Casuarina equisetifolia*). *Homestead, Florida: Everglades National Park. Report*, (33030).

KUMAR, T., MAHENDRA, R., NAYAK, S., RADHAKRISHNAN, K. and SAHU, K. 2010. Coastal vulnerability assessment for Orissa State, east coast of India. *Journal of Coastal Research* 26:523–534.

LI, K. and LI, G. S. 2011. Vulnerability assessment of storm surges in the coastal area of Guangdong Province. *Natural Hazards and Earth System Science* 11:2003–2010.

LIQUETE, C., CANALS, M., LUDWIG, W. and ARNAU, P. 2009. Sediment discharge of the rivers of Catalonia, NE Spain, and the influence of human impacts. *Journal of Hydrology* 366:76–88.

LOICZ. 1995. Coastal zone resources assessment guidelines. LOICZ, Manila

LUIJENDIJK, A., HAGENAARS, G., RANASINGHE, R., BAART, F., DONCHYTS, G. AND AARNINKHOF, S. 2018. The state of the world’s beaches. *Scientific Reports* 8:1-11

MASCARENHAS, A. and JAYAKUMAR, S. 2008. An environmental perspective of post-tsunami scenario along the coast of Tamil Nadu, India: role of sand dunes and forests. *Journal of Environmental Management* 89:24–34.

MATHIVENTHAN, T. and JAYASINGAM, T. 2014. Coastal green belt in Batticaloa district, Sri Lanka: Is *Casuarina* a success? *International Journal of Marine Science* 4: doi: 10.5376/ijms.2014.04.0055.

MAZZOTTI, F. J., OSTRENKO, W. and SMITH, A. T., 1981. Effects of the exotic plants *Melaleuca quinquenervia* and *Casuarina equisetifolia* on small mammal populations in the eastern Florida Everglades. *Florida Scientist* 44:65-71.

MCARDLE, S. B. and MCLACHLAN, A. 1992. Sandy beach ecology: Swash features relevant to the macrofauna. *Journal of Coastal Research* 8:398–407.

MCLACHLAN, A. 1980. The definition of sandy beaches in relation to exposure: A simple rating system. *South African Journal of Science* 76:751–752.

MCLACHLAN, A. and DORVLO, A. 2005. Global patterns in sandy beach macrobenthic communities. *Journal of Coastal Research* 21:674–687.

MCLAUGHLIN, S. and COOPER, J. A. G. 2010. A multi-scale coastal vulnerability index: A tool for coastal managers? *Environmental Hazards* 9:233–248.

MILLER, J. D., LIMPUS, C. J. and GODFREY, M. H. 2003. Nest site selection, oviposition, eggs, development, hatching, and emergence of loggerhead turtles. In: Bolten, A., Witherington, B. (eds), The Biology of the Loggerhead Turtle, Smithsonian Institution Press, Washington, DC, pp. 125–143.

MORTIMER, J. A. 1990. The influence of beach sand characteristics on the nesting behavior and clutch survival of Green Turtles (*Chelonia mydas*). *Copeia* 1990:802–817.

MORTON, J. F. 1980. The Australian pine or beefwood (*Casuarina equisetifolia* L.), an invasive 'weed' tree in Florida. *Proceedings of the Florida State Horticultural Society* 93:87–95.

MORTON, R. A, PAINE, J. G. and GIBEAUT, J. C. 1994. Stages and durations of post-storm beach recovery, southeastern Texas Coast , U.S.A . *Journal of Coastal Research* 10:884–908.

MORTON, R. A and SALLENGER JR., A. H. 2003. Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research* 19:560–573.

MROSOVSKY, N. and PIEAU, C. 1991. Transitional range of temperature, pivotal temperatures and thermosensitive stages for sex determination in reptiles. *Amphibia-Reptilia* 12:169–179.

MROSOVSKY, N. and YNTEMA, C. L. 1980. Temperature dependence of sexual differentiation in sea turtles: implications for conservation practices. *Biological Conservation* 18:271-280.

MUKHERJEE, N., BALAKRISHNAN, M. and SHANKER, K. 2009. Bioshields and ecological restoration in tsunami-affected areas in India. In: Dahl, E., Moksness, E. and Støttrup, J. (eds) *Integrated Coastal Zone Management,* Wiley-Blackwell,Chichester, UK. pp 131–144.

NICHOLLS, R. J., WONG, P. P., BURKETT, V., WOODROFFE, C. D. and HAY, J. 2008. Climate change and coastal vulnerability assessment: Scenarios for integrated assessment. *Sustainability Science* 3:89–102.

NIELSEN, K. J., MORGAN, S. G. and DUGAN, J. E. 2013. *Baseline Characterization of Sandy Beach Ecosystems in California's North-Central Coast Region*. 118 pp.

OLWIG, M. F., SØRENSEN, M. K., RASMUSSEN, M. S., DANIELSEN, F., SELVAM, V., HANSEN, L. B., NYBORG, L., VESTERGAARD, K. B., PARISH, F. and KARUNAGARAN, V. M. 2009. Using remote sensing to assess the protective role of coastal woody vegetation against tsunami waves. *International Journal of Remote Sensing* 30:3817–3820.

PATIL, R. H., HUNSHAL, C. S. and ITNAL, C. J. 2002. Effect of casuarina litter leachates on crops. *Allelopathy Journal* 10:141–146.

PATWARDHAN, A., SEMENOV, S., SCHNIEDER, S., BURTON, I., MAGADZA, C., OPPENHEIMER, M., PITTOCK, B., RAHMAN, A., SMITH, J., SUAREZ, A. AND SUKUMAR, R. 2007. Assessing key vulnerabilities and the risk from climate change. *Climate change*, pp.779-810.

PERNAS, T., WHEELER, G., LANGELAND, K., GOLDEN, E., PURCELL, M., TAYLOR, J., BROWN, K., TAYLOR, S. D. and ALLEN, E. 2013. Australian Pine Management Plan for Florida. *Florida Exotic Pest Plant Council, www.fleppc.org*.

PILKEY, O. H., NEAL, W. J. and BUSH, D. M. 2004. Coastal Erosion. In: Isla, F. I. and Iribarne, O. (eds). Coastal Zones and Estuaries - *Encyclopedia of Life Support Systems* EOLSS Publishers. pp 32-42.

PILKEY, O. H., NEAL, W. J., KELLEY, J. T. and COOPER, J. A. G. 2011. The World's Beaches. University of California Press, Berkeley, CA, pp. 251.

POTGIETER, L. J., RICHARDSON, D. M. and WILSON, J. R. U. 2014a. *Casuarina*: Biogeography and ecology of an important tree genus in a changing world. *Biological Invasions* 16:609–633.

POTGIETER, L. J., RICHARDSON, D. M. and WILSON, J. R. U.. 2014b. *Casuarina cunninghamiana* in the Western Cape, South Africa: Determinants of naturalisation and invasion, and options for management. *South African Journal of Botany* 92:134-146.

RANGEL-BUITRAGO, N. and ANFUSO, G. 2015. Risk assessment of storms in coastal zones: Case studies from Cartagena (Colombia) and Cadiz (Spain). *SpringerBriefs in Earth Sciences* Book Series, Springer, Berlin. pp7–14.

REJMÁNEK, M. and RICHARDSON, D. M. 2013. Trees and shrubs as invasive alien species - 2013 update of the global database. *Diversity and Distributions* 19:1093–1094.

RIYASAHAMED, A. M. 2017. Coastal bio-shields in Ampara District, Sri Lanka : Evaluation of greenbelt plantation. *Trends in Biosciences* 10:3369–3374.

RIZZO, A., AUCELLI, C. P. C., GRACIA, F. J. and ANFUSO, G. 2017. A novelty coastal susceptibility assessment method: application to Valdelagrana area (SW Spain). *Journal of Coastal Conservation* doi.org/10.1007/s11852-017-0552-2

ROELVINK, D., RENIERS, A., VAN DONGEREN, A., VAN THIEL DE VRIES, J., MCCALL, R. and LESCINSKI, J. 2009. Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering* 56:1133–1152.

SAMARAKOON, M. B., TANAKA, N. and IIMURA, K. 2013. Improvement of effectiveness of existing *Casuarina equisetifolia* forests in mitigating tsunami damage. *Journal of Environmental Management* 114:105–114.

SCHLACHER, T. A., SCHOEMAN, D. S., DUGAN, J., LASTRA, M., JONES, A., SCAPINI, F. and MCLACHLAN, A. 2008. Sandy beach ecosystems: Key features, sampling issues, management challenges and climate change impacts. *Marine Ecology* 29:70–90.

SCHLACHER, T. A., LUCREZI, S., CONNOLLY, R. M., PETERSON, C. H., GILBY, B. L., MASLO, B., OLDS, A. D., WALKER, S. J., LEON, J. X., HUIJBERS, C. M., WESTON, M. A., TURRA, A., HYNDES, G. A., HOLT, R. A. and SCHOEMAN, D. S. 2016. Human threats to sandy beaches: A meta-analysis of ghost crabs illustrates global anthropogenic impacts. *Estuarine,* *Coastal and Shelf Science* 169:56–73.

SCHMELZ, G. W. and MEZICH, R. R. 1988. A preliminary investigation of the potential impact of Australian pines on the nesting activities of the loggerhead turtle. In: Schroeder, B. A. (compiler). *Proceedings of the eighth annual conference on sea turtle biology and conservation. NOAA Technical Memorandum NMFSSEFC-214. On file at South Florida Ecosystem Office, US Fish and Wildlife Service, Vero Beach, Florida*: 63-66.

SCHMID, J., ADDISON, D., DONNELLY, M., SHIRLEY, M. and WIBBELS, T. 2008. The Effect of Australian pine (*Casuarina equisetifolia*) removal on Loggerhead Sea Turtle (*Caretta caretta*) incubation temperatures on Keewaydin Island, Florida. *Journal of Coastal Research* 55:214–220.

SCHWARTZ, M. L. 1967. The Bruun Theory of sea-level rise as a cause of shore erosion. *The Journal of Geology* 75:76–92.

SEALEY, N. 2006. The cycle of *Casuarina*-induced beach erosion - A case study from Andros, Bahamas. pp. 197–205, *The 12th Symposium on the Geology of the Bahamas and other Carbonate Regions (2004)*.

SEYMOUR, R. J., 1980. Longshore sediment transport by tidal currents. *Journal of Geophysical Research: Oceans*, 85:1899-1904.

SHORT, A. D. (ed.) 1993. Beach and surf zone morphodynamics*. Journal of Coastal Research, Special Issue no. 15.* Coastal Education and Research Foundation, Lawrence, USA: pp 231.

SHORT, A. D. 1999. Short, wave-dominated beaches. In: Short, A. D. (ed.). Handbook of Beach and Shoreface Morphodynamics, pp 173-203. Wiley, Chichester, UK.

SHORT, A. D. 2006. Australian beach systems - nature and distribution. *Journal of Coastal Research*, 22:11-27.

SHORT, A. D. and WRIGHT, L. D. 1983. Physical variability of sandy beaches. In: McLachlan, A., Erasmus, T. (eds). *Sandy Beaches as Ecosystems*. Developments in Hydrobiology Vol 19:133–144. Springer, Dordrecht.

SMITH, A. M., MATHER, A. A., BUNDY, S. C., COOPER, J. A. G., GUASTELLA, L. A., RAMSAY, P. J. and THERON, A. 2010. Contrasting styles of swell-driven coastal erosion: examples from KwaZulu-Natal, South Africa. *Geological Magazine* 147:940–953.

SRIDHAR, A. 2007. Pre-and post-tsunami coastal planning and land-use policies and issues in India. In: Broadhead, J. S. and Leslie, R. N. (eds). *Proceedings of the workshop on coastal area planning and management in Asian tsunami-affected countries*. 27–29 September 2006, Bangkok, Thailand. Food and Agriculture Organisation of the United Nations Regional Office for Asia and the Pacific, Bangkok. RAP Publication 2007/06. pp 81-110.

SWEARINGTON, J. M. 1999. Australian pine; *Casuarina equisetifolia* L. Alien Plant Work Group, US National Park Service.

TANAKA, N. and THUY, N. B. 2010. Tsunami force mitigation by tropical coastal trees, *Pandanus odoratissimus* and *Casuarina equisetifolia*, considering the effect of tree breaking. *International Conference on Sustainable Built Environment (ICSBE-2010, Kandy, Sri Lanka* 13–14 December 2010, pp 7-14.

THÉBAUD, C. and STRASBERG, D. 1997. Plant dispersal in fragmented landscapes: A field study of woody colonization in rainforest remnants of the Mascarene Archipelago. In: Laurance, W. F. and Bierregaard Jr., R. O., (eds). *Tropical forest remnants: Ecology, management, and conservation of fragmented communities*. University of Chicago Press, Chicago. pp 321-332.

THIELER, E. R. AND HAMMER-KLOSE, E. S. 2000. *National Assessment of Coastal Vulnerability to Sea-Level Rise: Preliminary Results for the US Pacific Coast*. Woods Hole, MA: United States Geological Survey (USGS), Open File Report 00-178, 1p.

TINLEY, K. 1985. Coastal dunes of South Africa. South African National Scientific Programmes Report No 109, CSIR. p 300.

TSOAR, H. 2001. Types of aeolian sand dunes and their formation. In: Balmforth, N. J. and Provenzale, A. (eds). *Geomorphological Fluid Mechanics. Lecture Notes in Physics* vol 582:403–429. Springer, Berlin.

UNDRO. 1982: *Natural disasters and vulnerability analysis.* Geneva: Office of the United Nations disaster relief co-ordinator.

VAFEIDIS, A. T., NICHOLLS, R. J., MCFADDEN, L., TOL, R. S. J., HINKEL, J., SPENCER, T., GRASHOFF, P. S., BOOT, G., KLEIN, R. J. T., VAFEIDIS, A. T., NICHOLLS, R. J., MCFADDEN, L., TOLN, R. S. J., HINKELW, J., SPENCER, T., GRASHOFF, P. S., BOOT, G. and KLEIN, R. J. T. 2008. A new global coastal database for impact and vulnerability analysis to sea-level rise. *Journal of Coastal Research* 24:917–924.

VAN AARDE, R. J., COE, M. and NIERING, W. A. 1996. On the rehabilitation of the coastal dunes of KwaZulu-Natal. *South African Journal of Science* 92:122–124.

VAN RIJN, L. C., WASLTRA, D. J. R., GRASMEIJER, B., SUTHERLAND, J., PAN, S. and SIERRA, J. P. 2003. The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based profile models. *Coastal Engineering* 47:295–327.

VITOUSEK, P. M. 1990. Biological invasions and ecosystem processes: Towards an integration of population biology and ecosystem studies. *Oikos* 57:7–13.

WATANABE, M. D. B. and ORTEGA, E. 2011. Ecosystem services and biogeochemical cycles on a global scale : valuation of water, carbon and nitrogen processes. *Environmental Science and Policy* 14:594–604.

WEBSTER, P. J., HOLLAND, G. J., CURRY, J. A. and CHANG, H. R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309:1844–1846.

WHEELER, G. S., TAYLOR, G. S., GASKIN, J. F. and PURCELL, M. F. 2011. Ecology and management of Sheoak (*Casuarina* spp.), an Invader of Coastal Florida, U.S.A. *Journal of Coastal Research* 27:485–492.

WHISTLER, A.W. and ELEVITCH, C.R. 2006. *Casuarina equisetifolia* (beach she-oak) *C. cunninghamiana* (river she-oak). Species profiles for Pacific Island Agroforestry. 2(I). Retrieved from http://www.agroforestry.net/tti/Casuarina-she-oak.pdf on April 16, 2016

YNTEMA C. L., and MROSOVSKY N. 1982. Critical periods and pivotal temperatures for sexual differentiation in loggerhead sea turtles. *Canadian Journal of Zoology 60*:1012-1016.

ZHANG, K., DOUGLAS, B. C. and LEATHERMAN, S. P. 2004. Global warming and coastal erosion. *Climate Change* 64:41–58.

ZHONG, C., ZHANG, Y., CHEN, Y., JIANG, Q., CHEN, Z., LIANG, J., PINYOPUSARERK, K., FRANCHE, C. and BOGUSZ, D. 2010. *Casuarina* research and applications in China. *Symbiosis* 50:107–114.

Chapter 2 : *Quantifying the local scale effects of* Casuarina *trees on sea turtle nesting habitat*

ABSTRACT

Extensive portions of coastal habitat are being anthropogenically modified with large scale plantations of *Casuarina,* but the effects of *Casuarina* trees on beach ecosystems remain largely unquantified. The main aim of this study was thus to investigate the effects of *Casuarina* on sandy beaches by comparing parameters such as back-beach profile, back-beach sand penetrability and moisture, shade density, sand temperature and pH among sites with, and without *Casuarina* trees. The study was conducted at three locations (Bhanga Nek, Manzengwenya and Sodwana) within the iSimangaliso Wetland Park of South Africa backed by *Casuarina* trees and with nesting sea turtles (*Caretta caretta* and *Dermochelys coriacea*). A total of eight experimental sites were chosen, three experimental sites at location one and two and two sites at location three, based on accessibility. At each site vegetation cover along the foredune line were selected for; *Casuarina*, native vegetation or no vegetation cover. A qualitative analysis of beach profiles across the experimental sites showed a difference in modal back-beach shape amongst vegetation-cover types: *Casuarina*-backed beaches had predominantly concave back-beach shapes, whereas beaches with native vegetation had a convex back-beach shape and sites with no vegetation had a straight back-beach profile. *Casuarina* trees further affected beach substrate characteristics and incubation environment differently from native vegetation by significantly lowering sand pH (ANOVA test: F (2, 15) = 13.8, $p < 0.001$) from ~9.5 to ~8.3 and temperature (Kruskal-Wallis: X^2 (2) = 1549.1, $p < 0.0001$) with about 2°C. The introduction of non-native *Casuarina* and the consequential disruption of coastal vegetation succession may affect the distribution of fauna, as vegetation structure and associated micro climates are important factors influencing faunal distribution, especially within dune habitats. Furthermore, the significantly lower, more stable average temperature underneath *Casuarina* trees may have significant implications for sex ratios of sea turtle hatchlings. The results of this study suggest that *Casuarina* trees have potentially negative impacts on sandy beaches and fauna such as sea turtles and that native species are preferable to *Casuarina* as a dune stabilizer.

2.1 INTRODUCTION

Beaches are important habitats and complex ecosystems that accommodate ecologically diverse fauna and flora, often endemic to the beach environment (Dahl 1952, Dugan et al. 2010, Defeo and McLachlan 2013, Harris et al. 2014). Focal species, like shorebirds, pinnipeds and sea turtles preferentially use the back-beach as breeding or pupping areas. Migratory sea turtles, for example, come from distant feeding grounds to nest on the backshore above the drift line of specific beaches (Bouchard and Bjorndal 2000). Nesting females arrive at the nesting beaches where they were born from (through natal philopatry) and remain there for a few months to lay several clutches of eggs on the back-beach (Miller 1997). Throughout incubation the interaction between the back-beach /dune conditions (physical environment) determines nest and hatchling success (embryo development and hatchling emergence); beach conditions, such as sediment characteristics, presence/absence of vegetation, and climate (rainfall, air temperature and wind) influence embryo survivorship, hatchling quality and sex ratio (Ackerman 1981, Wood et al. 2000) which ultimately affects sea turtles population dynamics. Therefore, beach conditions should allow for sufficient water-, gas- and heat exchange within the nest to allow successful hatchling development and ultimately hatchling emergence (Foley et al. 2000); The mechanism highlighting the complexity and multi-level interaction within a beach ecosystem.

Beaches function as ecosystems, but the importance of sandy beaches as coastal ecosystems is poorly recognized (Dugan et al. 2010) because they are viewed as desert landscapes with an absence of obvious biota (Nel et al. 2014). This has led to the mismanagement of beaches, with coastal policy decisions often disregarding scientific and ecological principles (Feagin et al. 2010). An example of coastal policy implementation without scientific backing is the anthropogenic modification of substantial portions of coastal habitat by planting invasive tree species such as *Casuarina* species, for purposes such as dune stabilization and storm protection (Feagin et al. 2010). For example, an estimated 450 ha of the Tamil Nadu coastline in India, which includes important nesting habitat for olive ridley (*Lepidochelys olivacea)* marine turtles, have been converted to *Casuarina* forests (Chaudari et al. 2009) to provide 'protection' for coastal systems and local communities.

Casuarina trees (Australian pines, beefwoods or colloquially known as *Casuarina*) are fast-growing evergreen trees native to Australia, specific regions of Southeast Asia and the Pacific archipelagos (Wheeler et al. 2011). Because of some economic (e.g. timber production and coastal protection), social (e.g. aesthetic component) and environmental benefits, like food for bird species like Glossy Black-Cockatoo (*Calyptorhynchus lathami*), *Casuarina* trees are valued both within and outside of their native ranges and have been exported and traded on a global scale. The introduction of *Casuarina* outside of their native ranges have thus led to the naturalization and invasion by three *Casuarina* species in particular; these are *C. cunninghamiana*, *C. equisetifolia* and *C. glauca* (Potgieter et al. 2014). Two of these species, *C. equisetifolia* and *C. glauca,* with *C. equisetifolia* being the preferred species, are regularly used for coastal dune stabilization because they are highly adapted to arid conditions, with high salinity and low soil fertility like on beaches (Chaudari et al. 2009, Potgieter et al. 2014).

Invasive plants, such as *C. cunninghamiana*, *C. equisetifolia* and *C. glauca*, that successfully establish in new locations, can however be detrimental to the structure and functioning of natural systems (van Wilgen et al. 2008). These species are known to displace native vegetation (Hardman et al. 2012), reduce the local abundance of small mammals (Mazzotti et al. 1981), increase erosion (Sealey 2006) and shoreline steepness (Chaudari et al. 2009), lower potassium, phosphorus, organic matter concentrations (Buehler and Rodgers 2012) and pH levels (Batish et al. 2001, Buehler and Rodgers 2012). Chaudari et al. (2009), found that fewer sea turtles nested on northern Tamil Nadu beaches with *Casuarina* present on the back-beach, whereas Klukas (1969) observed that *Casuarina* interfere with sea turtles nesting by toppling over during storm events because of their shallow root system obstructing access to the nesting area (back-beach). Other studies analysed the effect of *Casuarina* on sand temperature and found that *Casuarina* significantly affected sand temperature under tree stands (Schmelz and Mezich 1988, Chaudari et al. 2009).

Given the documented effect of *Casuarina* on beaches, it is surprising that the large-scale application of these species as bio-shields are advocated for. Specific research on the effects of *Casuarina* on coastal morphology, sand characteristics and the incubation environment are needed before it can be applied as a broad scale coastal protection tool. The aim of the project is therefore to quantify the effect of *Casuarina* trees on sandy beaches by comparing back-beach (including the primary dune) conditions for three different vegetation-cover types (or treatments); *Casuarina*, natural vegetation and no vegetation/sand. The objectives are i) to determine if there is a difference among back-beach shape in front of these three treatments; ii) to determine if there is a difference among the substrate characteristics (sand penetrability, sand moisture, pH) of the different treatments; and iii) to compare sea turtle nest incubation environment (i.e. shade density above the sand surface and sand temperature at turtle nest depth) underneath the different vegetation-cover types.

I hypothesise that i) *Casuarina* trees exacerbate erosion above the drift line, as the root system of *Casuarina* will obstruct sand exchange between the dune system and back-beach, and so predict that the back-beach profile will be characterised by the presence of scarps in front of *Casuarina*, moderate for natural vegetation and neutral for bare sand. ii) I also hypothesise that the thick *Casuarina* leaf litter directly under the trees/shrubs compact the sand and trap sand moisture, and therefore predict cooler, moister conditions below *Casuarina* than under native vegetation, or bare sand and iii) that leaching from *Casuarina* leaf litter will significantly lower sand pH levels.

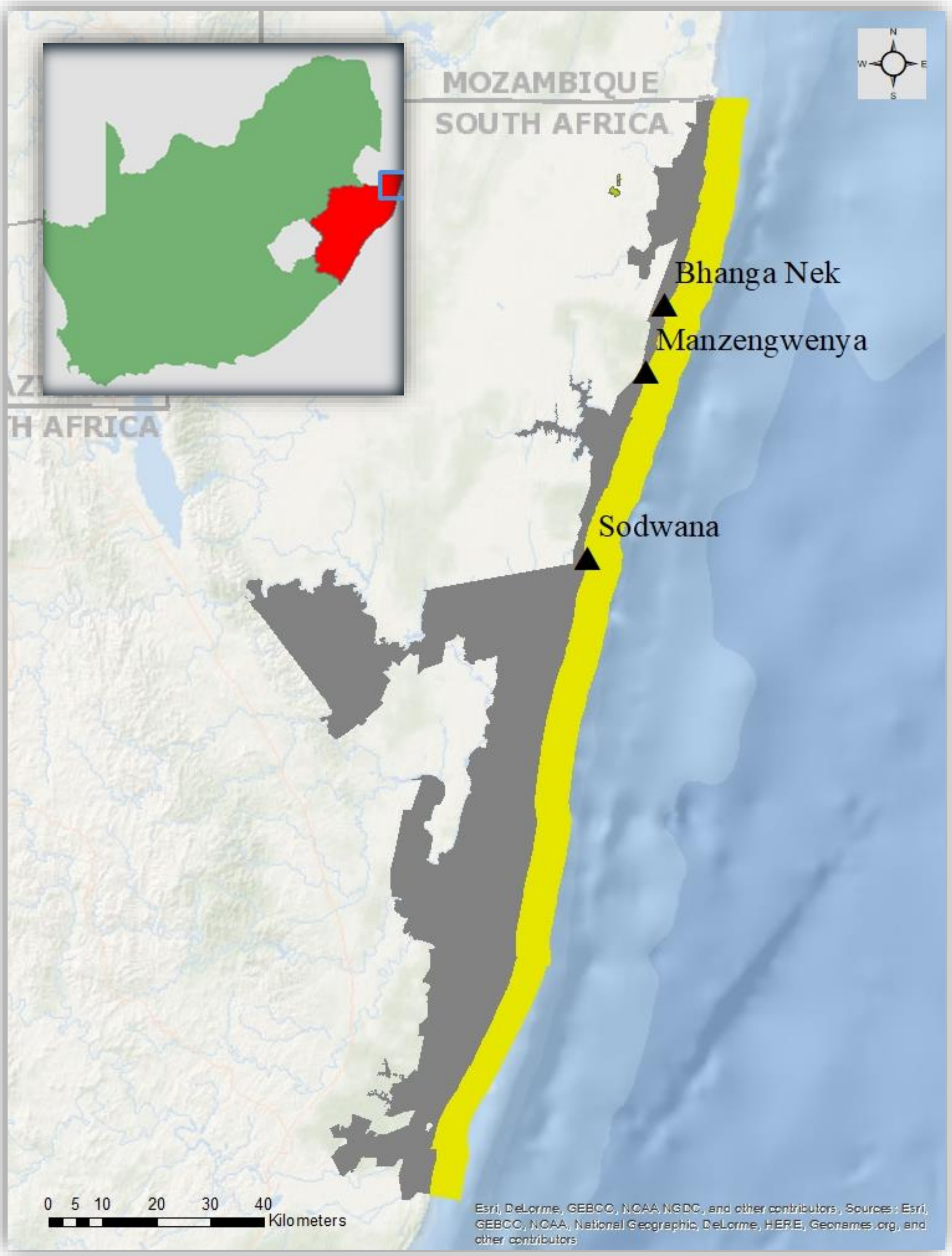
2.2 METHODS

2.2.1 Study site

The iSimangaliso Wetland Park is located on the northeast coast of South Africa and extends from Ponto do Ouro in the north to Mapelane in southern KwaZulu-Natal province. The park stretches along 200 km of the coastline of which 56 km of the northern portion are being monitored as part of a sea turtle monitoring program, as it is important nesting habitat for leatherback (*Dermochelys coriacea)* and loggerhead (*Caretta caretta)* turtles. The northeast coast of South Africa has sandy beaches backed by high forested dunes and can be described as a high to moderate energy, mesotidal (2 – 4 m) environment with a northward longshore drift. For the formation of the vegetated foredune system along the coastline, waves and wind energy play a more important role than tidal range (Mitchell et al. 2005). The vegetation along the coast consists of subtropical seashore vegetation and northern coastal forest (Mucina et al. 2006), but a few beaches have invasive *Casuarina* tree stands present on the foredune system. These trees were planted for dune stabilization purposes, before the Conservation of Agricultural Resources Act (1983) recognised their invasive nature and restricted the use of *Casuarina*.

2.2.2 Sampling design

The study locations (with access points at Bhanga Nek, Manzengwenya and Sodwana, **Figure 2.1**) within the iSimangaliso Wetland Park were selected to enhance variation in the environmental conditions for the experiments (**Figure 2.2**). Experimental sites were selected at each location, based on accessibility, and shoreline orientation to control for wave exposure. The first and second location, had three experimental (replication) sites respectively, and two sites were selected for the third location due to access restrictions. A total of eight experimental sites were therefore accessed from three locations.



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors, Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure 2.1: The three study locations (Bhanga Nek, Manzengwenya and Sodwana Bay) within the iSimangaliso Wetland Park. The grey area represents the terrestrial protected area of the iSimangaliso Park, while the yellow indicates the marine protected area. The Park falls within the KwaZulu-Natal province (red shading) of South Africa (green shading).

Figure 2.2: An example of the sample design at location one (Bhanga Nek). Three experimental sites were chosen and vegetation along the foredune line was categorised as Casuarina *present, natural vegetation present and no vegetation present. The red marker represents a* Casuarina equisetifolia *stand, while the green marker is natural vegetation and the yellow marker is sand (no vegetation). The different vegetation conditions had to be closer than 150 m from each other to be considered of the same site. Sites 1, 2, 3 are along a near-straight beach, with Site 3 going into a slight embayment (on the right of the image).*

The distances among the experimental sites (per location) varied as the sites were locally selected on the presence of different vegetation-cover types as treatments; vegetation-cover types along the foredune line were selected for a) *Casuarina* present, b) natural vegetation present (see **Table 2.1** for natural vegetation species) and c) no vegetation, only sand present (**Figure 2.3**). The order of the placement of the treatments varied locally but had to be closer than 150 m from each other to be considered of the same site, experiencing the same environmental forces, and the vegetation type had to occur on the primary dune to define the vegetation type of the site. A representative range of environmental co-variates, such as exposure, precipitation, wind etc., experienced along the coast are assumed to have been captured within this range of sites. A variety of experiments were conducted across these sites and depending on the environmental variable to be measured, the appropriate number and experimental sites were chosen from the eight approved experimental sites of the locations to conduct targeted experiments.

Table 2.1: Three vegetation-cover types were selected per site, including the control indicated by bare sand with no vegetation, the Casuarina *vegetation type represented by* Casuarina equisetifolia *stands and native/natural vegetation conditions which included the species listed below across the sites.*

SITES	NATIVE SPECIES ACROSS SITES
Location 1 (Bhanga Nek)	
Experimental site 1	*Gazania rigens*
Experimental site 2	*Gazania rigens*
Experimental site 3	*Gazania rigens*
Location 2 (Manzengwenya)	
Experimental site 1	*Canavalia rosea*
Experimental site 2	*Canavalia rosea*
Experimental site 3	*Canavalia rosea*
Location 3 (Sodwana)	
Experimental site 1	*Scaevola plumieri*
Experimental site 2	*Gazania rigens*

*Figure 2.3: Different vegetation-cover types: A and B) Photos of natural vegetation (*Canavalia rosea *and* Scaevola plumieri*) type; C) Photo of sand with no vegetation and D) Photo of* Casuarina equisetifolia *plants on a fordune.*

2.2.3 Beach profiles

Two different sets of beach profiles were obtained at different time scales; Semi-lunar monitoring to test the effect of wave and swash processes over a spring-neap cycle to determine erosion attributed to temporal changes (tidal cycle) and 'vegetation-cover profiles' to monitor the effect of waves and wind on the high-shore and dune processs in front of three different vegetation-cover types (*Casuarina*, natural vegetation and no vegetation/bare sand). All beach profiles were measured from the top of the primary dune and ended at the swash line on the low shore, over a semi-lunar and semi-seasonal cycle.

A) Semi-lunar tidal profiles

To infer the effect of wave and swash processes on beach profile by vegetation type, it was necessary to factor in natural, temporal effect of the spring-neap tidal cycle on beach profile. Beach shape was thus recorded over a spring-neap tide cycle (14 days). However, due to the distances among sites and the frequency with which these profiles needed to be conducted, these transects were only conducted at one location. Four different transects were recorded at Bhanga Nek (Location One) over a full spring to neap to spring cycle. The sites for the transects were chosen arbitrarily but it was useful to start at existing beacons demarcating turtle nesting area as a permanent benchmark for the beginning of the profile. Four transect sites were selected (**Figure 2.4**).

Figure 2.4: The tidal cycle profile transects at the first location (Bhanga Nek). On the far left is transect 1 moving right there is transect 2, transect 3 and furthest right is transect 4.

Transect profiles were measured every day, from the 10th of Jan 2016 to the 22nd of Jan 2016, starting on a spring tide. Beach profiles were measured using a dumpy level (Wild NA20 Automatic model), within one hour after low tide to see the entire extent of the beach and was measured from the top of the primary dune (at the turtle beacon) to the swash line on the low shore. Bad weather conditions did not allow for all transects to be obtained and a total of 47 beach profiles were measured over the spring-neap cycle (14 days) for the four transects. Therefore, 13 profiles were measured at transect 1 (site 1: 3S), 12 profiles at transect 2 (site 2: 1N), 13 profiles at transect 3 (site3: 2N) and seven profiles at transect 4 (site 4: 4N). Only seven profiles were conducted for transect four, due to transport complications (vehicle broke down). However, sufficient replications were conducted to continue with a neap to spring cycle analyses. Beach-shape change over a neap spring cycle was analysed qualitatively; Beach profiles were drawn (in MS Office 365's Excel) and described to standardize sampling to assess the effect of vegetation type on beach profile (next section).

B) Vegetation effect on beach profiles

The effect of wind and vegetation type on high shore beach profile, 'vegetation condition transects' were measured using the Emery method (Emery 1961). These profiles also started at the top of the primary dune and ended at the swash line on the low shore and were measured at spring low tide. These profiles were replicated at seven experimental sites (three locations), with three vegetation treatments per site and replicated at five different times (**Table 2.2**). A total of 105 profiles were measured.

Qualitative analysis of vertical (height) differences among vegetation type profiles

A visual inspection of the profiles suggested that most variation in beach profile presented in the first 30 metres from the dune to the high tide mark (see **APPENDIX 2.1: Vegetation effect profiles**). To standardise the transect length, only the data from the first 30 m were used for the shape analyses. To test for significant difference of beach shape among vegetation-cover types the *vertical height range* (m) (maximum profile height minus the minimum profile height) per site per vegetation type per sampling event were calculated ($n = 35$ range values per vegetation type). A Shapiro-Wilks normality test showed that the data were normally distributed for *Casuarina* ($W= 0.9$; $p > 0.05$) and natural vegetation ($W=0.9$, $p > 0.1$) range data and non-normal distribution for the sand profile range data ($W=0.9$, $p < 0.01$).

Table 2.2: Coordinates of transect locations and sampling dates of beach profiles

				Profile Start		**Profile End**		**Sampling events**
Location	**Experimental Site**	**Vegetation condition**	**Transect**	**Y**	**X**	**Y**	**X**	
1	1	*Casuarina* spp.	1	-26.99203	32.86738	-26.9921	32.86774	2015/12/16 2016/01/10 2016/01/23 2016/04/25 2016/05/08
		Natural vegetation	2	-26.99191	32.86748	-26.992	32.86776	
		No vegetation/sand	3	-26.99172	32.86754	-26.9919	32.86784	
	2	*Casuarina* spp.	4	-26.98583	32.87024	-26.986	32.87062	
		Natural vegetation	5	-26.98695	32.86978	-26.9871	32.87013	
		No vegetation/sand	6	-26.98724	32.86966	-26.9874	32.87004	
	3	*Casuarina* spp.	7	-26.98214	32.87151	-26.9823	32.87189	
		Natural vegetation	8	-26.98185	32.87164	-26.982	32.872	
		No vegetation/sand	9	-26.98271	32.87138	-26.9828	32.87172	
2	1	*Casuarina* spp.	10	-27.26126	32.77513	-27.2615	32.77565	2015/12/15 2016/01/16 2016/01/22 2016/04/24 2016/05/06
		Natural vegetation	11	-27.26236	32.77472	-27.2626	32.7752	
		No vegetation/sand	12	-27.2661	32.77321	-27.2663	32.77372	
	2	*Casuarina* spp.	13	-27.26073	32.77533	-27.261	32.77589	
		Natural vegetation	14	-27.26199	32.77498	-27.2622	32.77532	
		No vegetation/sand	15	-27.26486	32.77369	-27.265	32.77406	
3	1	*Casuarina* spp.	16	-27.5377	32.67519	-27.5374	32.67578	2015/12/12 2016/01/13 2016/01/28 2016/04/22 2016/05/10
		Natural vegetation	17	-27.53723	32.67499	-27.537	32.67562	
		No vegetation/sand	18	-27.53683	32.67477	-27.5367	32.67534	
	2	*Casuarina* spp.	19	-27.53601	32.6745	-27.5358	32.67503	
		Natural vegetation	20	-27.53508	32.67407	-27.535	32.67468	
		No vegetation/sand	21	-27.53464	32.6739	-27.5345	32.67462	
Total number of transects (considering five sampling events): 105								

Although assumptions of normality are violated by the skewed sand range data and homoscedasticity among vegetation groups (Fligner test: χ^2_2= 6.3; p = 0.04), a parametric test (two factor ANOVA) was chosen to test for significant differences in vertical height range among vegetation groups and experimental sites, based on the normal data distribution of the *Casuarina* and natural vegetation data and the robustness of ANOVA tests concerning the violation of normality (Schmider et al. 2010). The purpose of the two factor ANOVA test was to establish different effects of two independent variables, site and vegetation type, to ensure that differences ascribed to vegetation type effect are not driven by site differences.

Qualitative description of beach shape among *vegetation-cover* ***types***

Vertical height range (m) gives a semi-quantitative estimate of the vertical differences of sand supply in front of different vegetation-cover types but is not a good indication of variation in beach shape.

Therefore, a qualitative analysis describing back-beach shape for the different vegetation type profiles was conducted. Beach profiles were drawn in Microsoft Excel 2010 and the first 9 m of the beach profiles (back-beach section) were analysed for beach shape variation among vegetation-cover types, as literature has indicated an erosional effect by *Casuarina* on the back-beach (e.g. Sealey 2006). Back-beach is defined here, as the section between the high tide drift line and the middle of the windward side of the primary dune. Beach profiles for each of the five sampling events (2nd spring tide of December 2015, 1st and second spring tide of January and April 2016) across seven experimental sites (three locations) (n=105; 35 profiles per vegetation type) were described according to beach shape (convex, concave or straight). A frequency histogram was used to depict the modal shape of the back-beach in front of the different vegetation-cover types per site. Please view **APPENDIX 2.1** for all the vegetation effect profiles (n=105 profiles).

2.2.4 Substrate characteristics and incubation environment

Substrate and incubation environment variables were measured across six experimental sites of location one and two, with the three vegetation-cover types on the foredune. Location three was excluded on account of accessibility issues. See **Table 2.3** for the coordinates of the experimental sites. At each of these sites, sand penetrability, moisture and pH were obtained for the substrate, as well as shade density and temperature at 50 cm, which approximated loggerhead nest depth. All analyses were conducted in R, version 3.1 (Core Team 2018), except for grain size which was conducted in Gradistat ver. 8.0 (Blott and Pye 2001).

Table 2.3: Coordinates of experimental sites of the substrate characteristics and incubation environment variables.

Coordinates of experimental sites of substrate characteristics and incubation environment variables				
Location	**Experimental Site**	**Vegetation condition**	**Y**	**X**
1	1	*Casuarina*	-26.99203	32.86738
		Natural vegetation	-26.99191	32.86748
		No vegetation/sand	-26.99172	32.86754
	2	*Casuarina*	-26.98583	32.87024
		Natural vegetation	-26.98695	32.86978
		No vegetation/sand	-26.98724	32.86966
	3	*Casuarina*	-26.98214	32.87151
		Natural vegetation	-26.98185	32.87164
		No vegetation/sand	-26.98271	32.87138
2	1	*Casuarina*	-27.26158	32.77498
		Natural vegetation	-27.26171	32.77493
		No vegetation/sand	-27.26094	32.77525
	2	*Casuarina*	-27.25893	32.7762
		Natural vegetation	-27.25916	32.77611
		No vegetation/sand	-27.25958	32.77587
	3	*Casuarina*	-27.27304	32.77205
		Natural vegetation	-27.27315	32.77208
		No vegetation/sand	-27.27296	32.77197

A) Penetrability

Sand penetrability was measured with a 1-m steel rod (weighing 270 g) with a sharpened tip, called the penetrability instrument. The rod was dropped from a fixed height of 50 cm, and the penetration depth (in cm) was recorded. A measurement was taken at the *top*, the *middle* and the *bottom* of the foredune and the mean calculated for three replicate sites (1 – 3), for each location (1 and 2) and vegetation type (*Casuarina*, natural and sand). Therefore, a total of 54 measurements were recorded, equalling 18 mean measurements (six mean measurements per vegetation type).

Data analyses were conducted for the 18 mean measurements (six mean measurements per vegetation type), comparing penetrability among vegetation type groups across the six experimental sites of location one and two. To determine significant differences of sand penetrability underneath *Casuarina* stands vs. other vegetation-cover types an ANOVA test was conducted, as the data met assumptions of normality (Shapiro-Wilk normality test: *Casuarina*, W=0.9, p > 0.1; natural vegetation, W=0.9, p >0.5; sand, W=0.9, p >0.1) and equal variance (Fligner test: $\chi^2_2 = 0.4$; p > 0.5). A post-hoc Tukey test was conducted to establish among which vegetation-cover types a significant difference occurred.

B) Sand moisture

To measure volumetric soil moisture, the surface layer (5 cm) of the sand was removed and a probe pushed into the sand. Sand moisture was recorded with a FieldScout TDR 300 Soil Moisture Meter, measuring volumetric sand moisture as a volumetric percentage (%). Triplicate measurements were also taken; but three at the *top*, three in the *middle* and three at the *bottom* of the foredune. The mean was then calculated for the top, middle and bottom of the dune, and repeated for each vegetation type (*Casuarina* present; natural vegetation present and no vegetation) across the three experimental sites of location one. The probe failed and thus no replication for the second location.

The sample size was therefore three positions (top, middle, bottom/mean of the triplicate measurements taken at each position) x 3 experimental sites (1, 2, and 3) x 3 vegetation treatments (*Casuarina*, natural and sand), so 27 measurements were taken. Data analyses were conducted for the 27 measurements (9 measurements per vegetation type), comparing sand moisture among vegetation-cover types across the three experimental sites at location one. To determine significant difference between sand moisture underneath *Casuarina* vs. other vegetation-cover types, a one way ANOVA test was conducted to test for significant difference in soil moisture among the vegetation-cover types as two data sets (natural vegetation and sand) met assumptions of normality (Shapiro-Wilk normality test: natural vegetation, W=0.9, p >0.1; sand, W=0.9, p > 0.05). *Casuarina* data were non-normal (Shapiro-Wilk normality test: *Casuarina*, W=0.7, p < 0.0001), but the datasets had equal variance (Fligner test: $\chi^2_2 = 4.2$; p > 0.1), therefore an ANOVA was considered robust enough (Schmider et al. 2010) to establish different sand moisture content (%) among vegetation groups. A post-hoc

Tukey test was conducted to establish among which vegetation-cover types a significant difference occurred.

C) Sand grain size

Sand samples were collected from the surface of the substrate (top 10 cm) in 350 ml sample jars. A sample was collected at the *bottom* of the foredune, for three replicate sites (1 – 3) for location 1 and vegetation type (*Casuarina*, natural and sand), so a total of nine samples were collected. Once back in the laboratory, 50 g of the sand samples were oven dried for 48 hours (at 60^{o}C) after which the sand was sieved using a mini-sifter machine (Spellbound 1420 model) with a sieve column in phi intervals running 10 min per sample and weighed (fractions of g) per sieve. Mean grain size, sorting and skewness was calculated using Gradistat ver. 8.0 (Blott and Pye 2001).

The program Gradistat ver. 8.0 (Blott and Pye 2001) was used to further analyse the average grain size, uniformity of sorting, measure of skewness and measure of kurtosis. No analyses were conducted to determine significant differences among the sand particle size for the different vegetation-cover types, however a range of sand particle size were established for the different vegetation-cover types. The nine samples (three samples per vegetation type) from location one was processed to establish sand grain size range per vegetation type.

D) pH

Sand samples were also collected for pH metrics, using 350 ml sample jars. A sample was taken at the *top*, the *middle* and the *bottom* of the foredune, for three replicate sites (1 – 3) for each location (1 and 2) and vegetation type (*Casuarina*, natural and sand). Therefore, a total of **54 samples** were collected. Approximately 100 g of sand was mixed with water at a 1:1 ratio. The samples were left for 3 hours and pH readings of the water were obtained by using a portable pH, mV and temperature instrument, Ph100 ecoSense YSI model. The pH meter was calibrated using 2-point calibration. The first point was a 7.00 buffer and the second point was a 9.18 buffer. A total of 54 measurements were taken and the mean calculated per site for each vegetation type, equalling a total of 18 mean measurements (six mean measurements per vegetation type) across the six experimental sites.

Data analyses were conducted for the 18 mean measurements, comparing pH among vegetation type groups across the six experimental sites of location one and two. To determine significant difference between sand pH underneath *Casuarina* stands vs. other vegetation-cover types an ANOVA test was conducted, as the data met assumptions of normality (Shapiro-Wilk normality test: *Casuarina*, $W=1$, $p > 0.5$; natural vegetation, $W=1$, $p > 0.5$; sand, $W=0.9$, $p >0.1$) and equal variance (Fligner test: $\chi^2_2= 2.8$;

$p > 0.1$). A post-hoc Tukey test was conducted to establish among which vegetation-cover types a significant difference occurred.

E) Shade density

A light meter (LI-COR: LI – 250 A model) was used to record light intensity (in µmol.m^{-2}.s^{-1}) underneath different vegetation-cover types. Triplicate recordings were taken at the top, the middle and the bottom of the foredune slope (total of nine measurements) and the mean calculated, for each vegetation type (*Casuarina*, natural and sand), per site (1- 3), per location (1 and 2). The sample size was 3 replicates x 3 positions (top, middle, bottom) x 6 experimental sites (1, 2, 3, 4, 5 and 6) x 3 vegetation treatments (*Casuarina*, natural and sand), which totals to 162 replicates, equalling 18 mean measurements, six measurements per vegetation type.

Data analyses were conducted for the 18 mean measurements (six measurements per vegetation type), comparing light intensity (in µmol.m^{-2}.s^{-1}) among vegetation-cover types across the six experimental sites at location one and two. The natural vegetation data were normal (Shapiro-Wilk normality test: $W = 0.9$, $p > 0.1$) and data showed equal variance (Fligner test: $\chi^2_2 = 0.03$; $p > 0.5$), however a Kruskal-Wallis test was conducted to determine significant difference in light intensity underneath the different vegetation-cover types, as two vegetation groups' data did not meet assumptions of normality (Shapiro-Wilk normality test: *Casuarina*, $W = 0.7$, $p < 0.01$; sand, $W = 0.7$, $p < 0.05$). A post-hoc Nemenyi test was conducted to establish among which vegetation-cover types a significant difference occurred.

F) Temperature

Temperature was recorded (in °C) for two sampling events (December 2015 and April 2016). *In situ* temperature recordings were obtained by deploying iButtons (from Fairbridge Technologies, DS1922L-F5#, ±0.5°C accuracy) along the dune margin under different vegetation-cover types. All iButtons were pre-calibrated in the laboratory before deployment, against a mercury thermometer in a water bath at 30°C (Gallenkamp, Cat. No. 1H350). Filed recordings from each iButton were later normalised by adding or subtracting the difference of the iButton temperature reading to that of the mercury thermometer.

The deployment in the field was around a central marker placed at each of the vegetation-cover types; for *Casuarina* treatment the central marker was placed at the tree's trunk, for natural vegetation the marker was placed in the densest part of the vegetation and for the control, the marker was placed to ensure no vegetation shade should cover the sample area at any time of the day. Four iButtons, each sealed in a 120 ml-sample jar, were deployed at loggerhead nest depth (~50 cm), to the north, east, west and south of the central marker (**Figure 2.5**). This was done to control for different sun exposures during the day. The iButtons were deployed for 48 hours, recording temperature every 15 min. The mean temperature of the four iButtons were calculated for each recording (per every 15 min) for each 48-hour cycle. Temperature was recorded in both mid and late summer (December 2015 and April 2016).

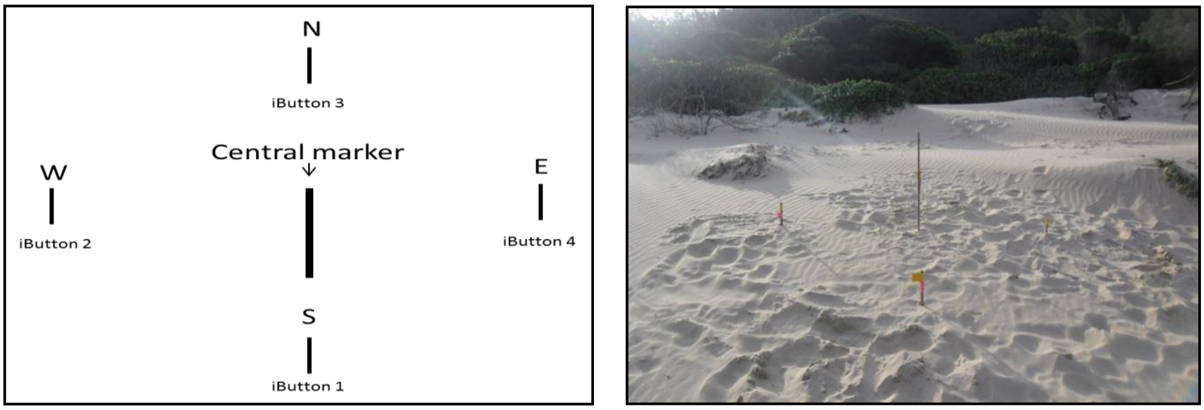


Figure 2.5: Sampling design as (left) a schematic diagram and (right) a photograph, illustrating the placement of iButtons around a central marker. One iButton was placed at each of the four Cartesian points around a central marker at a 50 cm depth. The mean of the four iButtons were calculated for each recording (every 15 minutes) to total 1158 temperature mean measurements per vegetation condition at location one and two, respectively. Therefore n = 2304 mean measurements per vegetation condition across two locations.

Data analyses were conducted for 2162 mean measurements (mean of four iButtons recording temperature every 15 min per site per vegetation condition) per vegetation condition across the six experimental sites of location one and two (36 iButtons per location). To determine significant differences between temperature of *Casuarina* trees vs. other vegetation-cover types, a Kruskal-Wallis test was conducted as data did not meet assumptions of normality (Shapiro-Wilk normality test: *Casuarina*, $W = 0.9$, $p < 0.0001$; natural vegetation, $W = 0.9$, $p < 0.0001$ and sand, $W = 0.9$, $p < 0.0001$) and equal variance (Fligner test: $\chi^2_2 = 189.37$; $p < 0.001$). A post-hoc Nemenyi test was conducted to establish among which vegetation-cover types a significant difference occurred.

2.3 RESULTS

2.3.1 Beach shape

A) Semi-Lunar Tidal Profiles

Beach profiles among the four sites were quite variable, but the most eroded profiles were consistently two or three days before spring tide (**Figure 2.6)**. Spring tide was therefore chosen to standardize vegetation effect beach profile sampling.

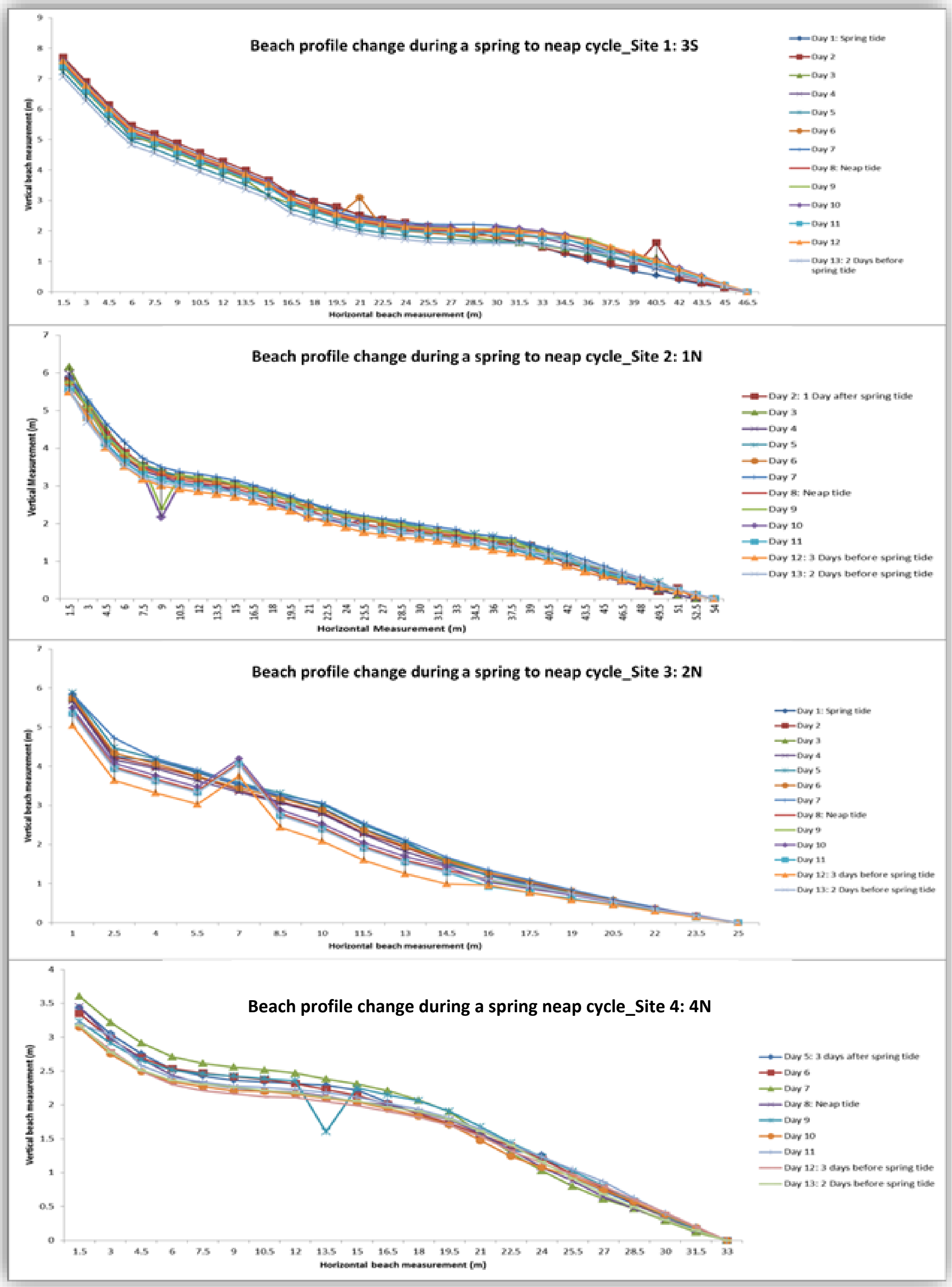


Figure 2.6: Beach profiles representing beach shape change over a tidal cycle at location one (Bhanga Nek) in January 2016 (n = 47 profiles). The first graph represents Site 1 (3S), the second graph is Site 2 (1N), the third graph is Site 3 (2N) and the last graph represents Site 4 (4N). The x-axis represents the horizontal measurements (m) across the beach, while the y-axis is the vertical height (m) of the beach profile.

B) Profiles to describe the effect of vegetation on beach shape

Qualitative analysis of vertical (height) differences among vegetation type profiles

To describe differences in the *vertical height (max. height – min. height, in metres)* of profiles for each vegetation type height range was compared across seven experimental sites (three locations) for all five sampling events (n = 35 profiles/range values per vegetation type).

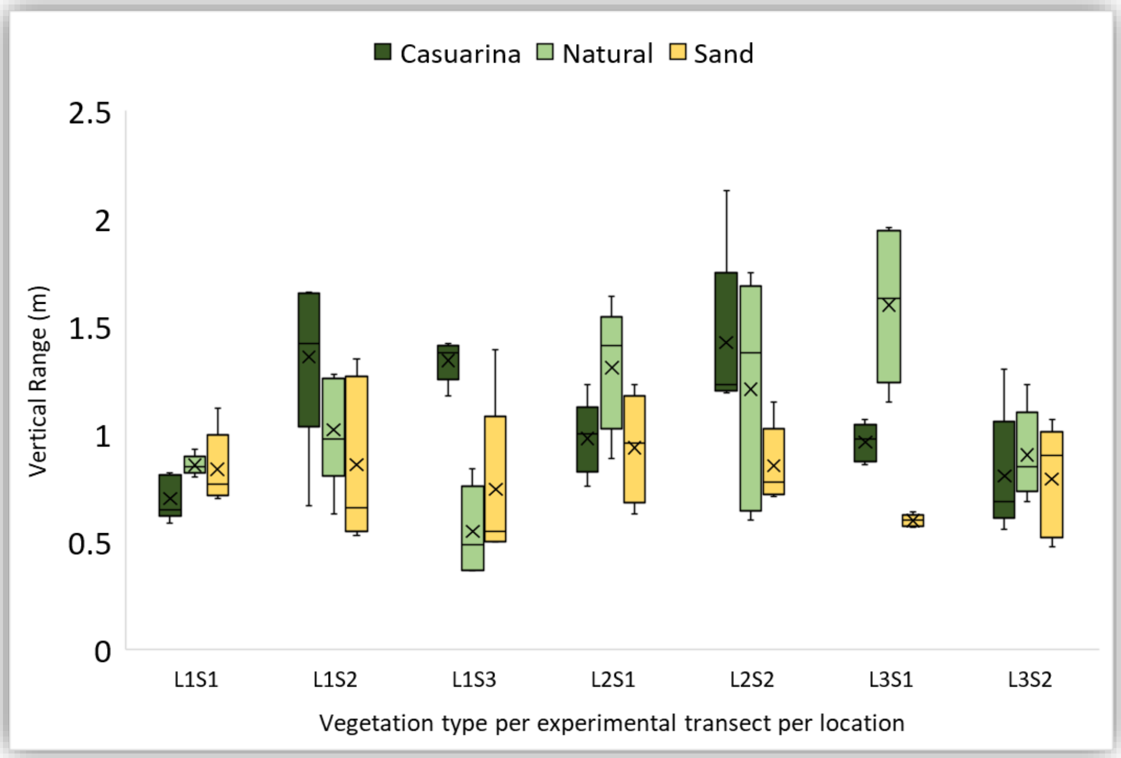


Figure 2.7: Boxplot depicting vertical height range per vegetation type per site per location over time (five different sampling events) (n = 15 height values per site).

The greatest variability in vertical height occurred for *Casuarina* and natural vegetation profiles (*Casuarina* range = 1.57 m and natural vegetation range = 1.59 m), indicating bigger beach shape change for these two vegetation groups across sampling events and sites, while sand profiles remain more neutral (range = 0.91 m). *Casuarina* profiles (**Figure 2.7**) had the biggest median height range (1.02 m) compared to natural vegetation (0.97 m) and sand (0.73 m), possibly indicating bigger **scarps** (dips) or **berms** (mounds) for *Casuarina* profiles. **Figure 2.7,** also indicates differences among sites, for example site five (L2S2), natural vegetation, showed extreme variability in vertical height range from 0.71 m to 1.15 m. Test for significant differences in *vertical height range (m) showed significant* *differences* among sites (ANOVA: F (6,84) = 4, $p < 0.001$) and vegetation type (ANOVA: F (2,84) = 11, $p < 0.0001$), with a significant interaction between site and vegetation type (ANOVA: F (12,84) = 4, $p < 0.0001$) (**Figure 2.7**). Both site and vegetation type can therefore be considered as factors, however the highly significant results for vegetation type allows for it to be considered as a main effect, acknowledging variability among sites as a second factor driving variability in vertical height range for profiles**.** A post-hoc Tukey test (excluding sites as a factor), revealed a significant difference between *vertical height range* (m) of *Casuarina* and sand profiles ($p < 0.01$) and natural vegetation and sand profiles ($p < 0.01$). Comparing the overall effect of vegetation type, there was no significant difference between vertical height range of *Casuarina* and natural vegetation profiles ($p > 0.1$) (**Figure 2.8**).

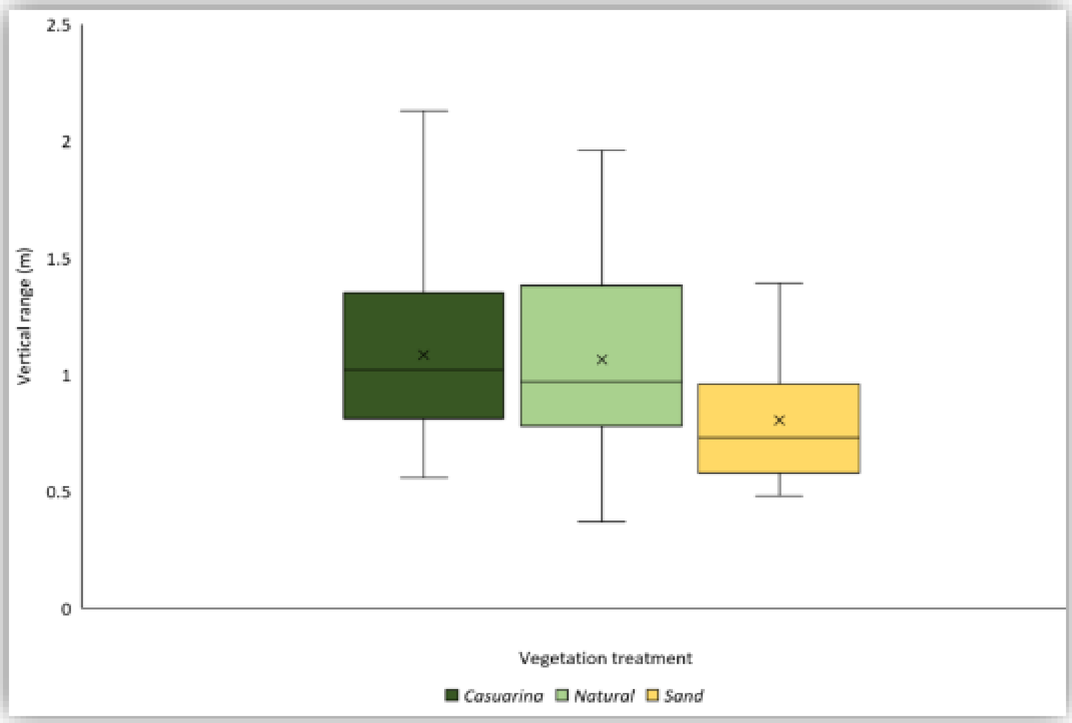


Figure 2.8: Boxplot depicting the results of the vertical height range (m) among vegetation type profiles (n=105 profiles, 35 profile per vegetation type) if vegetation type data are pooled across all seven sites (excluding site as a factor).

Qualitative description of beach shape among *vegetation-cover* ***types***

Qualitative analysis of the back-beach (0 – 9 m of beach profile) for all five sampling events across the seven sites (three locations) (n= 105 profiles) showed differences in back-beach shape among the vegetation-cover types and across the experimental sites. Overall, the modal beach shape in front of *Casuarina* stands are concave, as 18 out of 35 profiles had a concave shape (e.g.

Figure 2.10). Modal beach shape in front of natural vegetation is mostly convex (22 out of 35 profiles had a convex shape) and modal beach shape for sand (with no vegetation) is straight/neutral (18 out of 35 profiles had no particular shape) (see **Appendix 2.1**: Vegetation effect profiles and **Figure 2.9**). Across the five sampling events, *Casuarina* profiles showed the least variability (back-beach shape was consistent), while the back-beach shape for natural vegetation and sand was quite variable. However, differences in sites also account for shape change, reiterating the interaction between vegetation type and experimental site location (**Figure 2.9**).

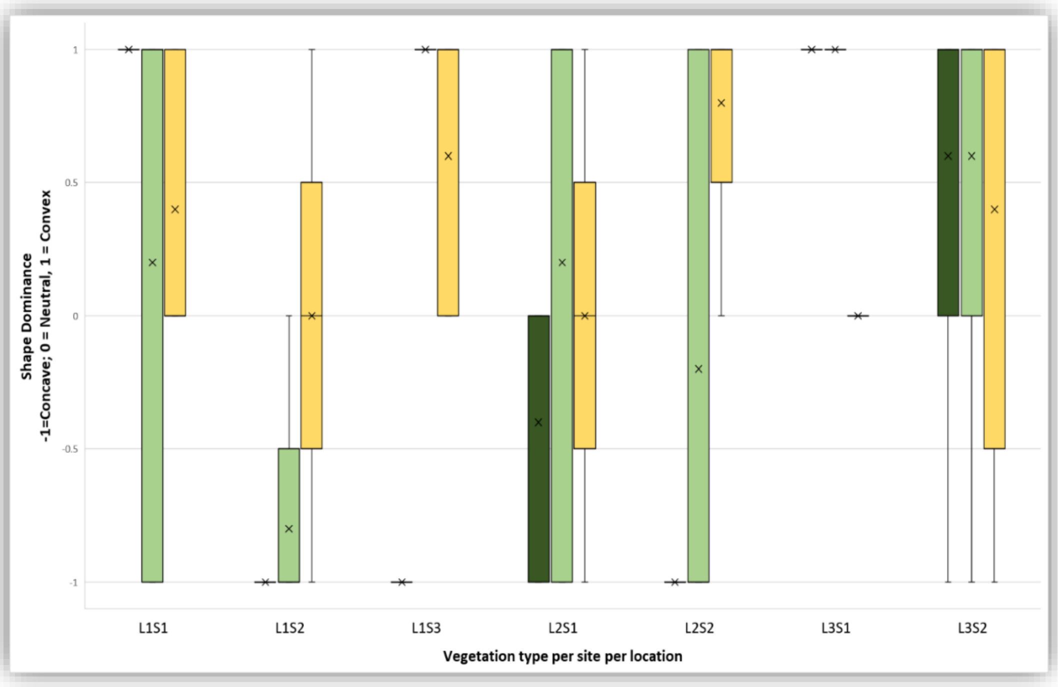


Figure 2.9: Boxplot depicting the dominant shape (concave = -1, neutral = 0 and convex = 1) per site per vegetation type (n = 105 profiles, 15 profiles per site). There is high variability in shape change for natural vegetation and sand, while Casuarina *profile shape remained more constant. Some location specific patterns also emerge, for example, the profiles at location three are mainly convex.*

Combining the results of vertical range and shape indicate that that the greatest variability in vertical height exist for *Casuarina* and natural vegetation profiles, but indicates of the three vegetation-cover types, the back-beach shape in front of *Casuarina* stands are generally more consistent from one sampling event to the next (shape does not change). Shape and range of dunes with no vegetation is fairly neutral and varies least in vertical height. Back-beach shape is thus mainly dictated by site, however, overall (across sampling events and sites) *Casuarina* had a concave back-beach shape more often than the other two vegetation-cover types.

Figure 2.10: A Casuarina *stand at site five, exhibiting extreme scouring in front of the foredune after a storm.*

2.3.2 Substrate characteristics and incubation environment

A) Penetrability

A visual inspection of the penetrability data showed little difference among experimental sites, in that the penetrability of sand underneath *Casuarina* stands were consistently higher across all sites, except for one site (L2S2) (**Figure 2.11**). This allowed for penetrability data to be pooled and analysed across the six experimental sites for location one and two (18 mean measurements, six mean measurements per vegetation condition) to allow for multiple comparison among vegetation-cover types (*Casuarina*, natural vegetation, no vegetation), excluding site as a factor. Mean penetrability equalled 15 cm (SD = 4.3 cm). The minimum penetrability (lowest recorded penetrability measurement) was recorded for sand (with the metal rod penetrating 5 cm into substrate) and maximum penetrability for natural vegetation (penetrated 27 cm into the substrate), but sand underneath *Casuarina* had the highest penetrability on average (18 cm) compared to the other two vegetation-cover types (natural vegetation = 16 cm and sand = 11 cm) (Error! Reference source not found.).

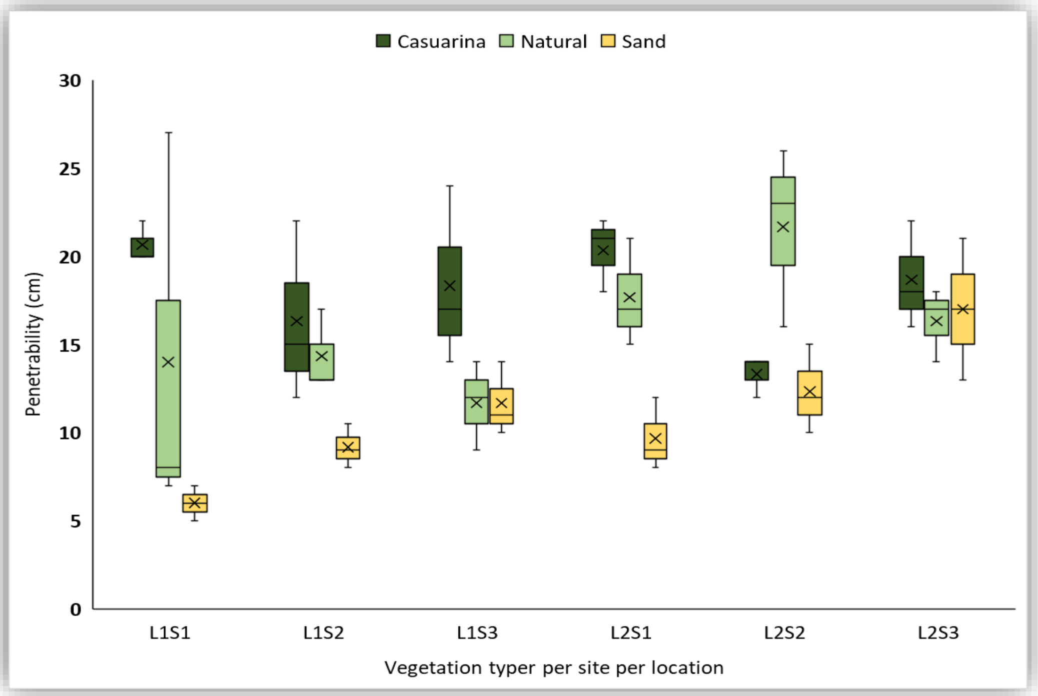


Figure 2.11: Boxplot depicting sand penetrability per site (site 1 – 6) per vegetation type (n = 18 mean measurements, 3 mean measurements per site). Across all sites (except site five), Casuarina sand is most penetrable. There is an outlier at location one, site one, where the substrate underneath natural vegetation had a penetrability of 27 cm, possibly biasing results and contributing to differences among vegetation-cover types.

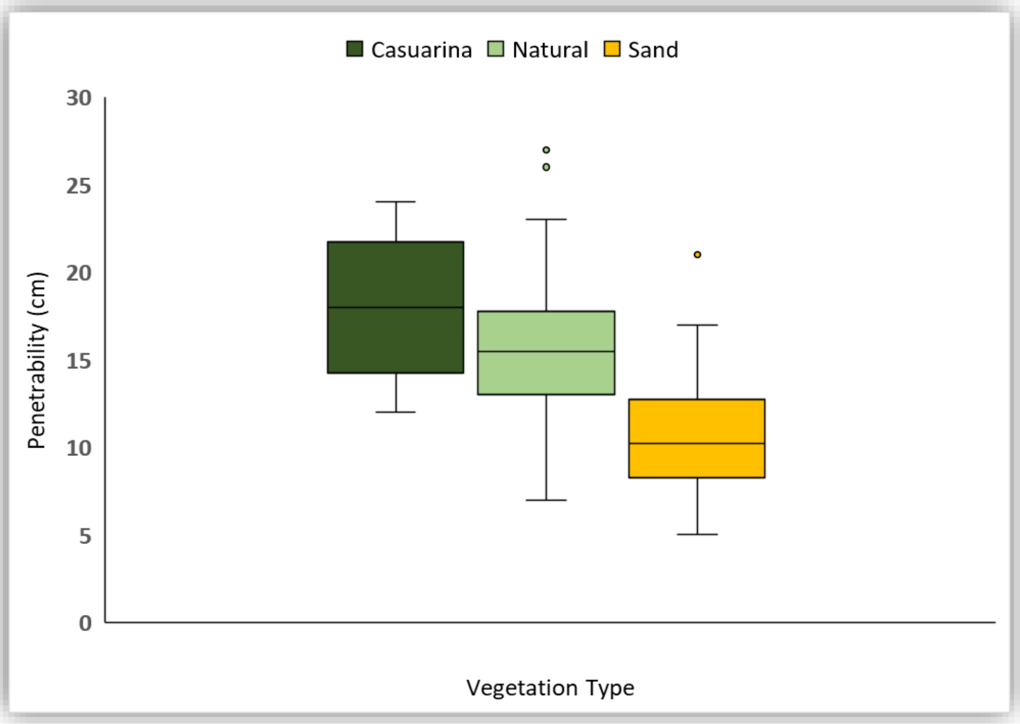


Figure 2.12: Boxplot depicting results for substrate penetrability (cm) measurements among the three different vegetation-cover types for location one and two across all six experimental sites (all data pooled, n = 18 mean measurements, 6 mean measurements per vegetation condition).

Analysis across the six experimental sites showed a significant difference in penetrability of the substrate underneath the vegetation-cover types (ANOVA test: $F(2,15) = 7$, $p < 0.01$) and a post-hoc Tukey test revealed a significant difference between penetrability underneath *Casuarina* and sand with no vegetation ($p < 0.01$). There was no significant difference between *Casuarina* and natural vegetation ($p > 0.5$) and natural vegetation and sand ($p > 0.05$) (**Figure 2.12**). However, the extreme variability for natural vegetation at site one, could possibly bias the significance of the results.

B) Sand moisture

As mentioned in the methods section, data were only collected and analysed for the three experimental sites at location one, as the soil moisture instrument malfunctioned. A visual inspection of the sand moisture data suggested that there was little differences among experimental sites, in that sand moisture measurements underneath *Casuarina* stands were consistently higher (except for site one) than the other vegetation-cover types (**Figure 2.13**). Therefore, sand moisture data were pooled and analysed across three experimental sites at location one (27 measurements, 3 replicates per vegetation condition) to allow for multiple comparison among vegetation conditions (*Casuarina*, natural vegetation, no vegetation), excluding site as a factor. Mean sand moisture equalled 4.6% (SD = 4.5%). The minimum sand moisture content (1.3%) was recoded for sand and the maximum (23.3%) was recorded underneath a *Casuarina* stand. *Casuarina* also had the highest sand moisture content on average (6.6%) compared to the other two vegetation-cover types (natural vegetation = 4.9% and sand = 2.4%) (**Figure 2.14)**.

Analysis across the three experimental sites, showed no significant difference in sand moisture underneath the vegetation-cover types (ANOVA test: $F(2,24) = 2$, $p > 0.1$), therefore no post-hoc test was conducted (**Figure 2.14**). However, sample size for sand moisture among different vegetation-cover types were not sufficient and these results should be considered as preliminary a more replications are needed.

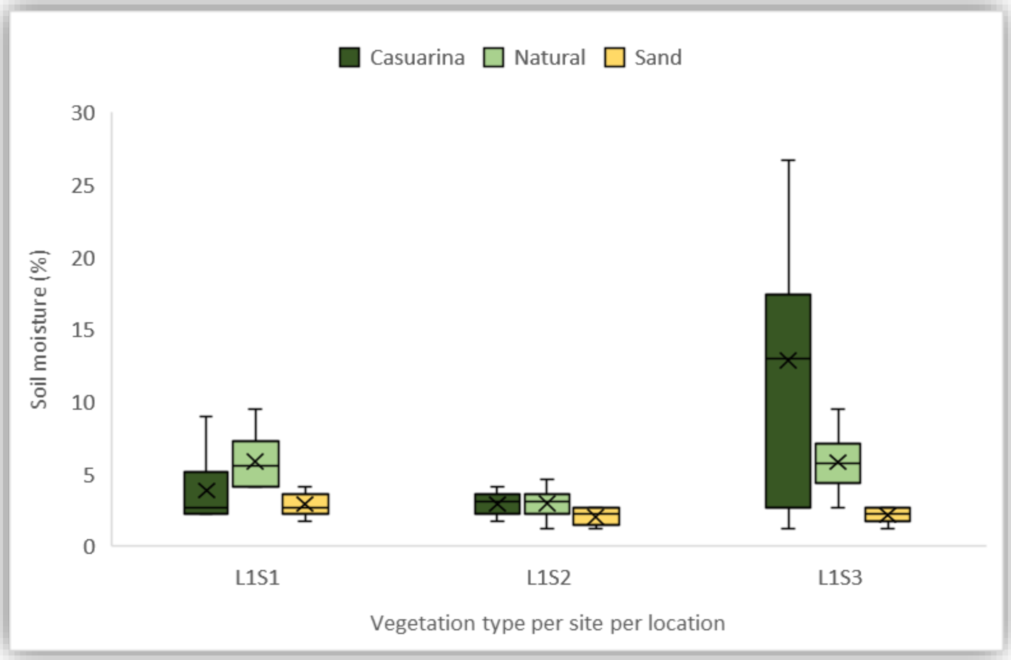


Figure 2.13: Boxplot depicting sand moisture per vegetation type per site (1-3) at location one (n = 27 measurements, 9 measurements per site). Sand moisture was higher for Casuarina *substrate at site one and three. Sand moisture was extremely variable at site three underneath the* Casuarina *stand with an outlier value (26.7%), possibly biasing the results and contributing to differences among vegetation-cover types.*

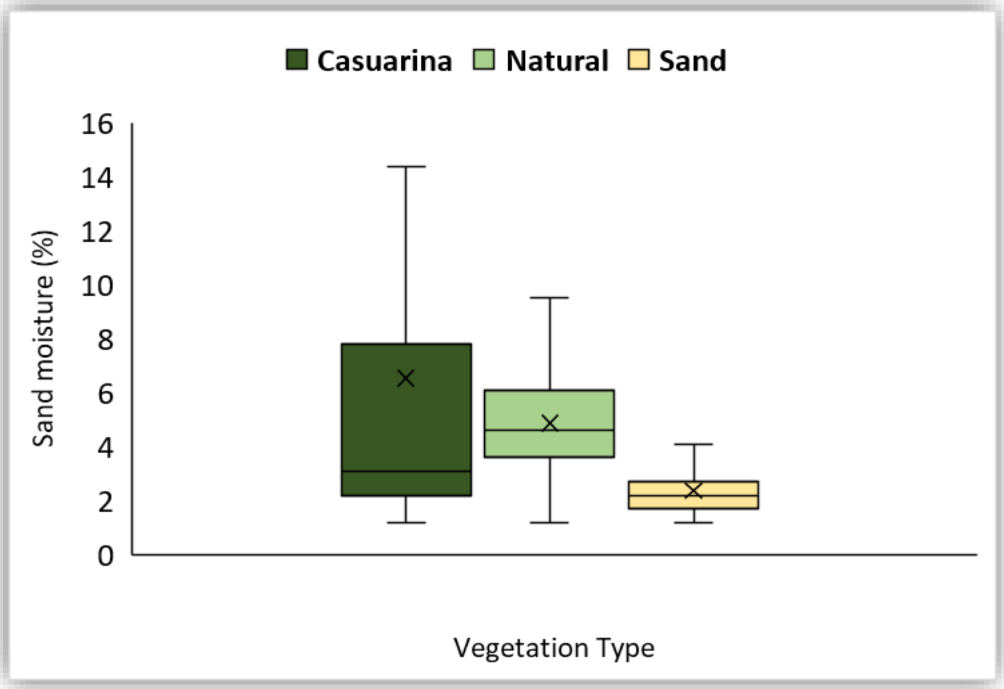


Figure 2.14: Boxplot depicting results for sand moisture content (%) among the three different vegetation-cover types (at Bhanga NeK) across three experimental sites (all data pooled, n = 27 measurements, 9 measurements per vegetation type).

C) Sand grain size

The sediments at Bhanga Nek (location one) at all experimental sites and three vegetation-cover types can be described as well-sorted, medium sand, representative of the location's uniform wind blow sand at the dune/high shore interface of the region, including the Manzengwenya and Sodwana locations (Harris 2012).

Table 4: Sand grain size mean (µm), sorting, skewness and kurtosis, across the three experimental sites (S1, S2 and S3) per vegetation type (n = 3 sand samples per vegetation type).

	***Casuarina* (Location 1)**	**Natural (Location 1)**	**Sand (Location 1)**
SEDIMENT NAME:	S1. Well Sorted Medium Sand	Well Sorted Medium Sand	Well Sorted Medium Sand
MEAN (µm):	**279.77**	**252.69**	**305.52**
SORTING:	72.47	74.77	100.84
SKEWNESS:	0.91	-0.21	1.72
KURTOSIS:	14.50	3.31	8.45
SEDIMENT NAME:	S2. Well Sorted Medium Sand	Very Well Sorted Medium Sand	Very Well Sorted Medium Sand
MEAN (µm):	**315.95**	**287.70**	**331.73**
SORTING:	97.35	66.66	100.52
SKEWNESS:	1.83	0.78	2.11
KURTOSIS:	7.29	11.45	6.94
SEDIMENT NAME:	S3. Well Sorted Medium Sand	Well Sorted Medium Sand	Well Sorted Medium Sand
MEAN (µm):	**372.77**	**321.03**	**310.39**
SORTING:	135.92	98.60	92.35
SKEWNESS:	1.00	1.90	1.86
KURTOSIS:	2.40	7.02	8.18

D) pH

A visual inspection of the pH data showed little difference among sites, in that sand pH underneath *Casuarina* stands were consistently higher (across all sites) than the other vegetation-cover types (**Figure 2.15**). This allowed for pH data to be pooled and analysed across the six experimental sites for location one and two (18 mean measurements, six mean measurements per vegetation condition) to allow for multiple comparison among vegetation-cover types (*Casuarina*, natural vegetation, no vegetation), excluding site as a factor. Mean pH equalled 9 (SD = 0.2). The lowest pH level (7.5) was recorded underneath a *Casuarina* stand and the highest (9.8) was recorded for no vegetation/sand.

Casuarina also had the lowest pH value on average (8.2) compared to the other vegetation-cover types (natural vegetation = 9 and sand = 9.4) (**Figure 2.16).**

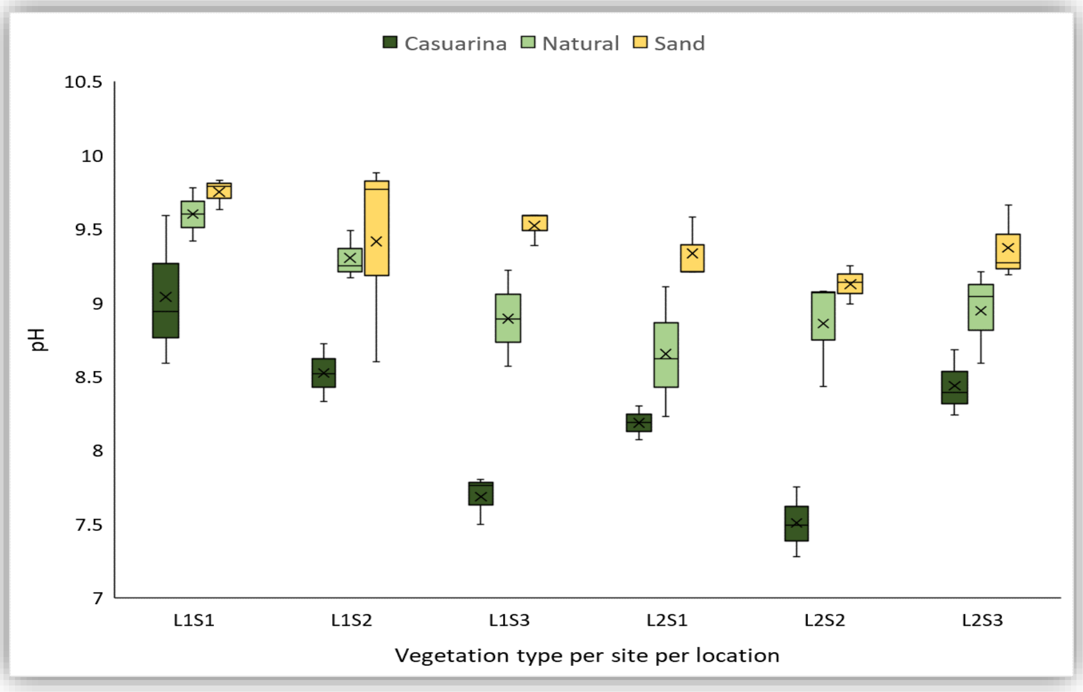


Figure 2.15: Boxplot depicting sand pH per location per site per vegetation type (n = 18 mean measurements, 3 mean measurements per site). The sand pH underneath Casuarina trees are the lowest across all sites.

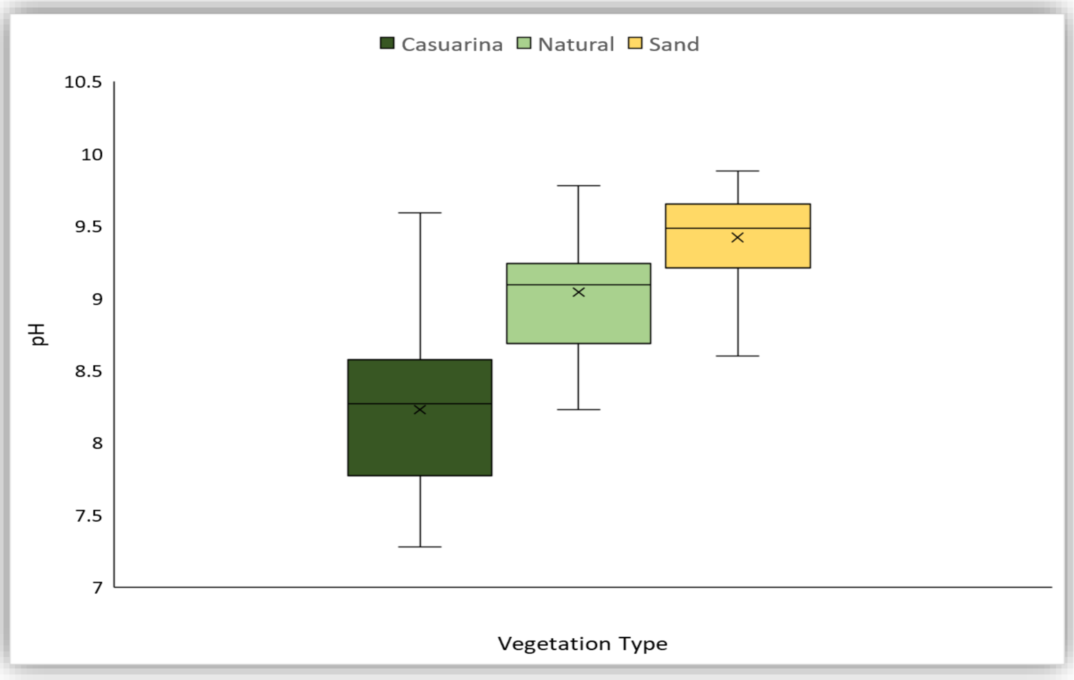


Figure 2.16: Boxplot depicting results for pH levels among the three different vegetation-cover types for location one and two across all six experimental sites (all data pooled, n=18 mean measurements, 6 mean measurements per vegetation condition).

Analysis across the six experimental sites of location one and two, showed a significant difference in pH of the substrate underneath the vegetation-cover types (ANOVA test: F (2,15) = 13.8, $p < 0.001$) and a post-hoc Tukey test revealed a significant difference between pH underneath *Casuarina* and natural vegetation ($p < 0.01$) and *Casuarina* and sand/no vegetation ($p < 0.001$) (**Figure 2.16**). There was no significant difference between natural vegetation and sand ($p > 0.1$)

E) Shade density

A visual inspection of the light intensity data showed that there was a difference between the results of the two locations (**Figure 2.17**); At location one, natural vegetation had the lowest light intensity/denser shade and at location two *Casuarina* trees had the lowest light intensity/denser shade. The difference between the data from the two locations, may be explained by the different growth characteristics of *Casuarina* across the two locations. *Casuarina* at location one is shrubs with less foliage, while *Casuarina* at location two are trees with thick foliage. Shade density data were pooled and analysed across the six experimental sites for location one and two (18 mean measurements, six measurements per vegetation type) to allow for multiple comparison among vegetation-cover types (*Casuarina*, natural vegetation, no vegetation), excluding site as a factor. Median shade density equalled 368 µmol.m^{-2}.s^{-1} (SD = 686.6 µmol.m^{-2}.s^{-1}). The lowest light intensity (47 µmol.m^{-2}.s^{-1}) was recoded underneath natural vegetation and the highest (1810 µmol.m^{-2}.s^{-1}) was recorded for sand. *Casuarina* had the lowest shade density on average (272.6 µmol.m^{-2}.s^{-1}) compared to the other two vegetation-cover types (natural vegetation = 349.2 µmol.m^{-2}.s^{-1}and sand = 1382.6 µmol.m^{-2}.s^{-1}).

Analysis across the six experimental sites of location one and two, showed a significant difference in light intensity of the substrate underneath the vegetation-cover types (Kruskal-Wallis: X^2 (2) = 9.3, $p < 0.01$) and a post-hoc Nemenyi test revealed a significant difference between light intensity underneath *Casuarina* and sand/no vegetation ($p < 0.05$) (**Figure 2.18**). There was no significant difference between *Casuarina* and natural vegetation ($p > 0.5$), and natural vegetation and sand ($p > 0.05$).

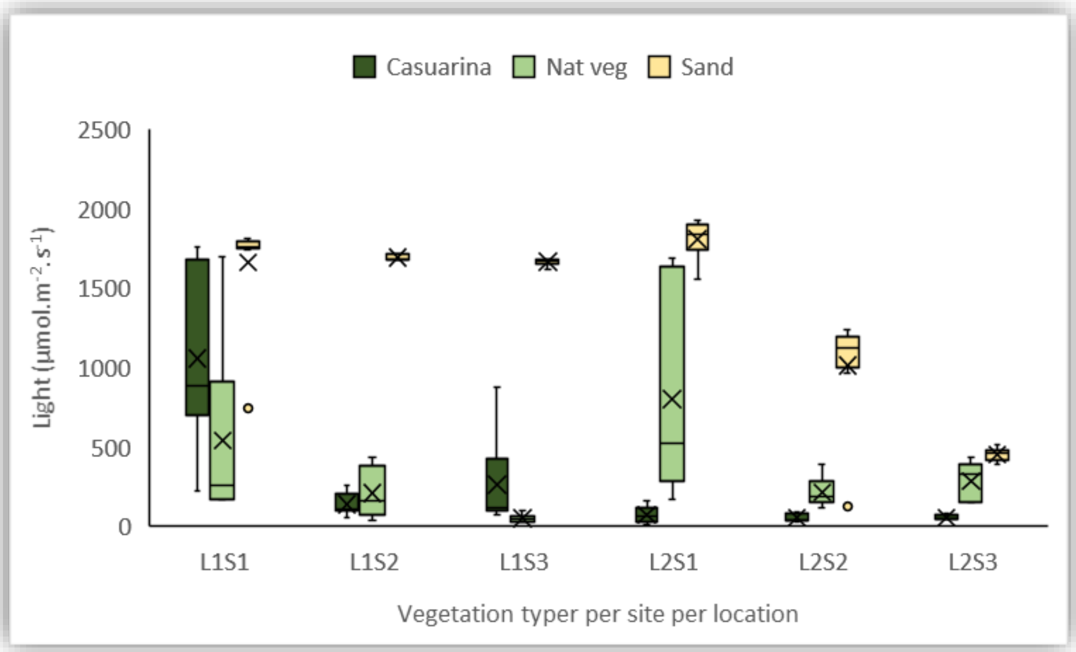


Figure 2.17: Boxplot depicting light intensity (µmol.m^{-2}.s^{-1}) per location per site for each vegetation type (18 mean measurements, 3 mean measurements per site).

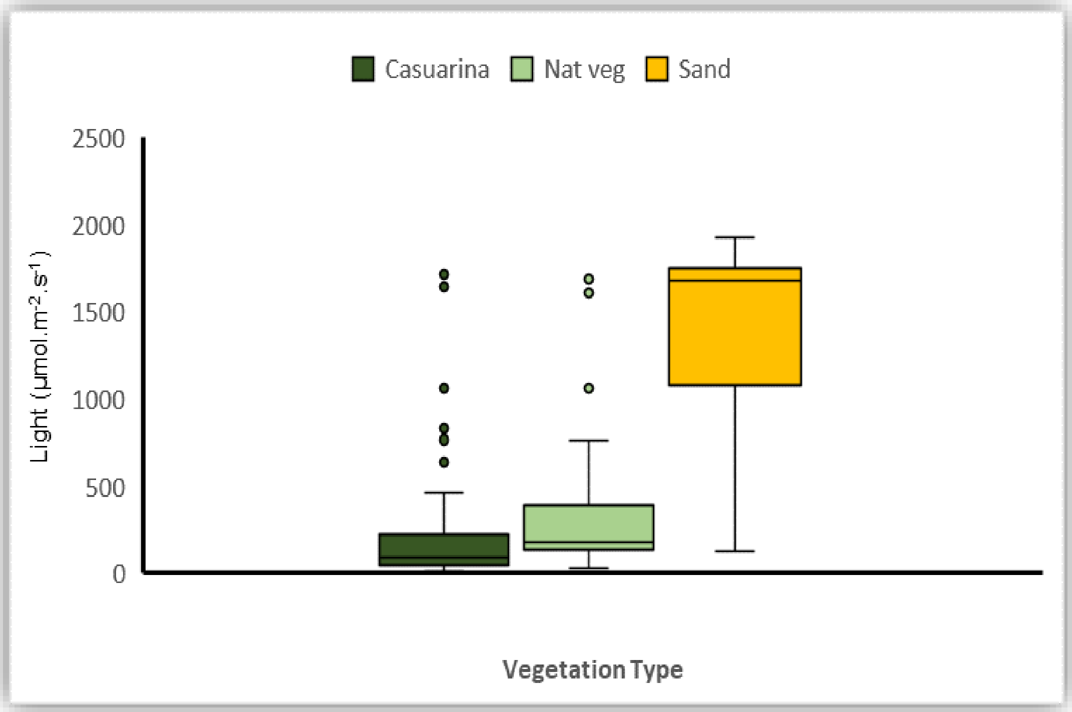


Figure 2.18: Boxplot depicting results for shade density (µmol.m^{-2}.s^{-1}) among the three different vegetation-cover types for location one and two across all six experimental sites (all data pooled, n = 18 mean measurements, 6 mean measurements per site).

F) Sand temperature

Four iButtons were deployed underneath each vegetation type, therefore a total of 12 iButtons were deployed per site for the six experimental sites at location one and two. These sets of iButtons were deployed over a 48 hour cycle, recording temperature every 15 minutes. Two sets of the iButtons were stolen during field sampling; one from under a *Casuarina* tree (four iButtons = 192 mean readings) at site one (location one) and one from sand (no vegetation) type iButtons (four iButtons = 192 mean readings) of site two (location two). Since the experiment was repeated for two sampling events (December 2015 and April 2016), the remaining vegetation type measurements were sufficient for analyses (total *Casuarina* mean measurements = 2112, natural vegetation mean measurements = 2304 and no vegetation/sand mean measurements = 2112).

Daily temperature profiles showing the fluctuation of temperature over 48 hours for each location per site per vegetation type per sampling event (warmer and colder month), showed *Casuarina* temperature to be consistently lower than the other two vegetation-cover types (except for site two at location two where natural vegetation was lower for the colder month) (see temperature profiles for location one, **Figure 2.19**). Boxplot graphs per location per site per vegetation type (outliers removed) further reiterates that sand temperature underneath *Casuarina* stands were consistently lower (except for location two, site two, sampling event two) than the other vegetation-cover types, indicating little difference among sites (**Figure 2.20** and **Figure 2.21**). This allowed for temperature data to be pooled and analysed across the six experimental sites for location one and two for both sampling events to allow for multiple comparison among vegetation-cover types (*Casuarina*, natural vegetation, no vegetation) (outliers removed).

Median temperature across all experimental sites (excluding ambient temperature) was 27.6°C (SD = 1.9°C). The minimum temperature (23.4°C) was recorded underneath natural vegetation and the maximum (32°C) was also recorded for natural vegetation, however *Casuarina* had the lowest median temperature (26°C) compared to the other two vegetation-cover types (natural vegetation = 27.1°C and sand = 29.4°C) (**Figure 2.22).** Substrate temperature indicated daily temperature cycles/fluctuations as the substrate temperature experiences a delayed heating and cooling time relative to ambient temperatures, due to the thermal insulation of the sand (**Figure 2.22)**. At site three, there was an extreme spike in temperature for all three vegetation-cover types consistent with the rise in ambient temperature, however the phenomena does not repeat itself at any of the other sites for any of the sampling events (**Figure 2.22)**.

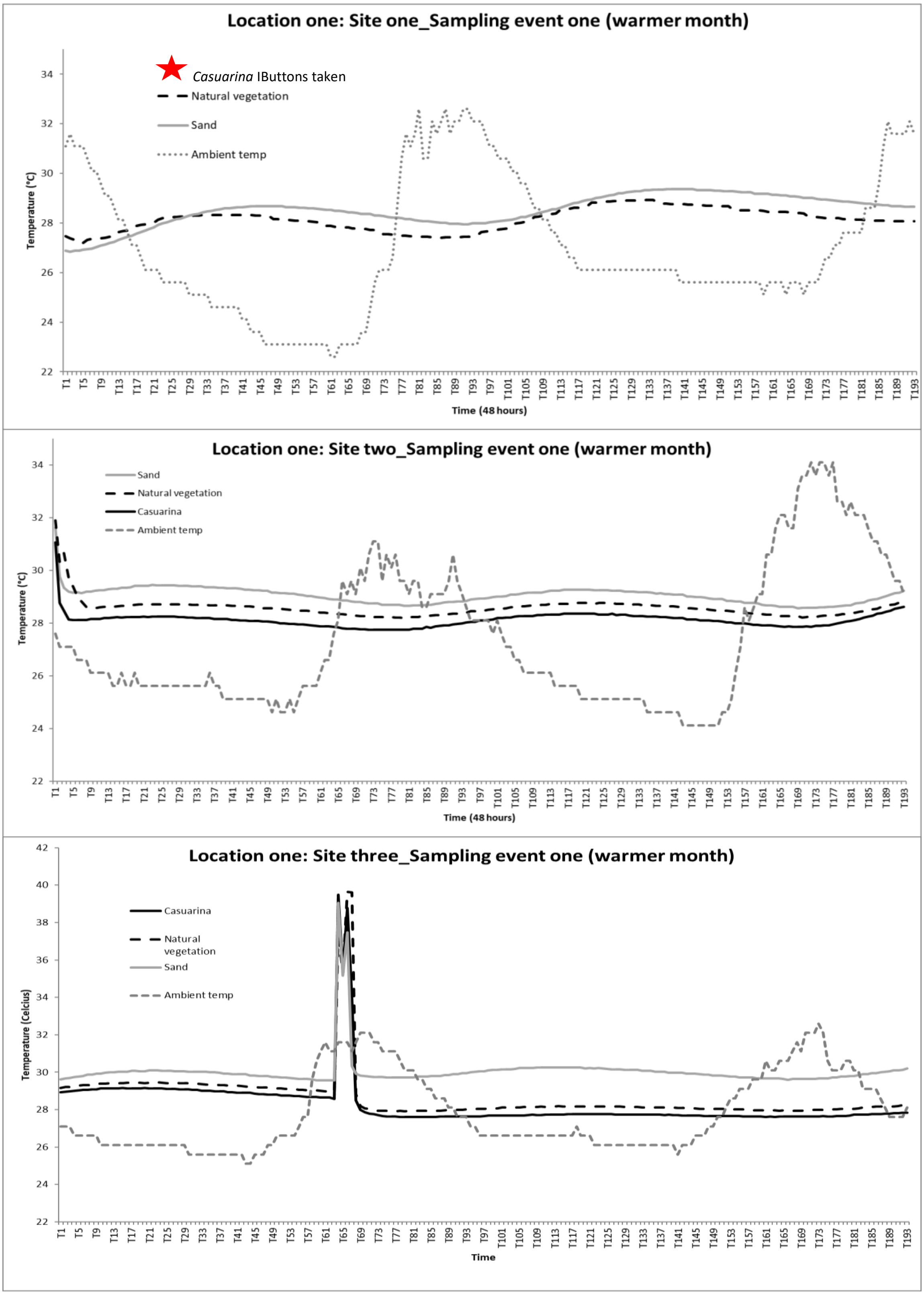


*Figure 2.19: Sand temperature profiles for vegetation-cover types at location one, across all three sites for one sampling event (warmer month, December 2015). The y-axis represents temperature (°C) and the x-axis represents readings every 15 minutes over a 48-hour cycle (T1 = reading one) with a total of 192 readings (T192), thus n = 192 temperature readings per vegetation type per site. To view the rest of the temperature profiles (location one, sites one to three for the second sampling event; location two, sites one to three for the first and second sampling event) see **APPENDIX 2.2**: **Temperature profiles for vegetation-cover types**.*

There was a difference in temperature variability between sampling events, where temperatures for the warmer month were more variable than for the colder month. During the warmer months sand temperature underneath *Casuarina* showed some fluctuation (10% centile = 27°C and 90% centile = 28.7°C), but the temperature was very stable during the colder month (10% centile = 25°C and 90% centile = 25.5°C). Areas with no vegetation reached the highest temperature fluxes in the warmer (10% centile = 28.6°C and 90% centile = 30.3°C) and colder (10% centile = 25.6°C and 90%centile = 27°C) months, respectively (see **Figure 2.20** and **Figure 2.21**).

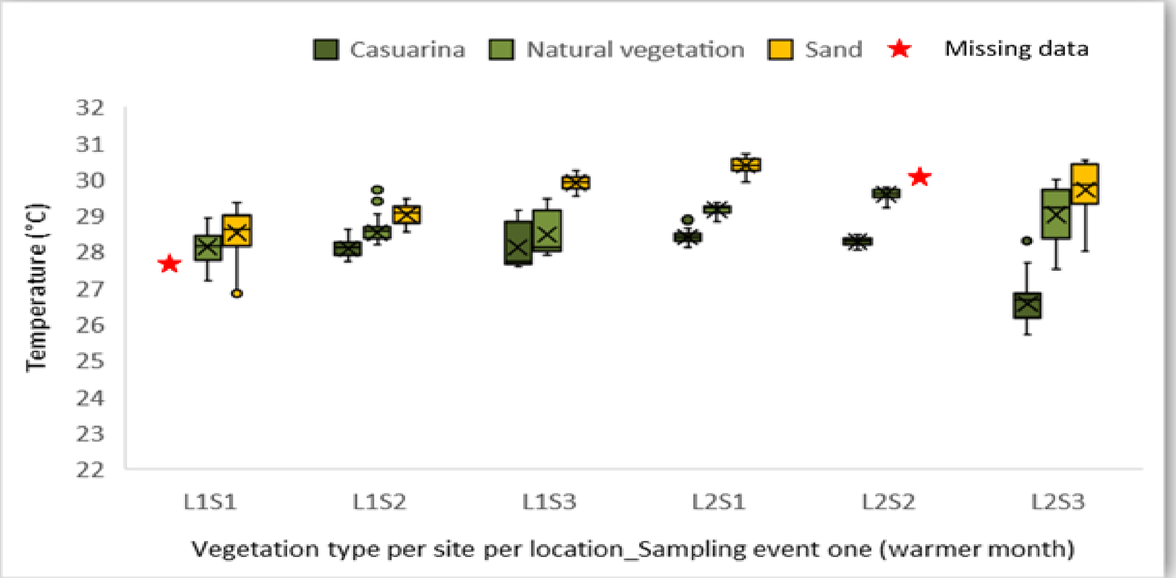


Figure 2.20: Boxplot graph (extreme outliers removed) depicting the sand temperature of different vegetation-cover types for sites one to three at location one and two for sampling event one (warmer months: December for location one and January for location two). There is missing data for the Casuarina vegetation type at location one, site one and sand at location two, site two, as the beach clean-up crew mistook the iButtons for refuse. Location two, site three showed relative variability for all three vegetation-cover types and will therefore not bias results towards any vegetation group. Sand underneath Casuarina had the lowest temperature across all sites.

Pooled data across the six experimental sites of locations one and two for both sampling events showed a significant difference in temperature among the vegetation-cover types (Kruskal-Wallis: X^2 (2) = 1549.1, $p < 0.0001$). A post-hoc Nemenyi test revealed a significant difference between temperature underneath *Casuarina* and natural vegetation ($p < 0.0001$), a significant difference between natural vegetation and sand ($p < 0.0001$) and a significant difference between *Casuarina* and no vegetation/sand ($p < 0.0001$) (see **Figure 2.22)**.

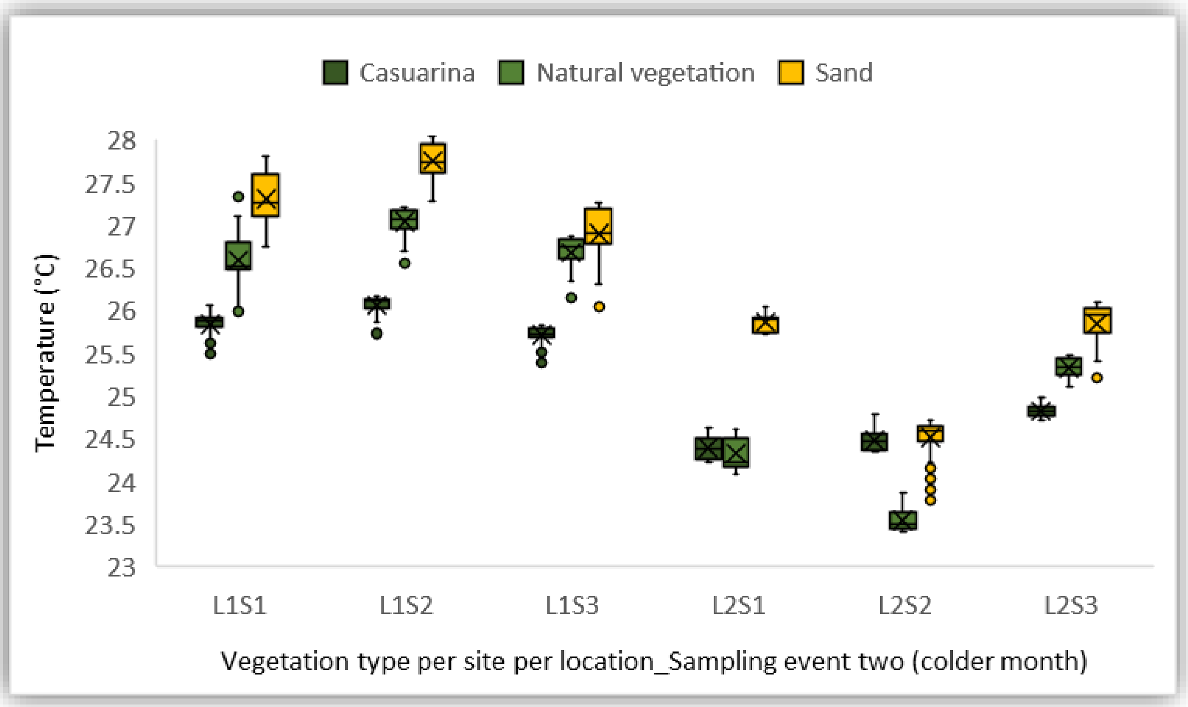


Figure 2.21: Boxplot graph (extreme outliers removed) depicting the sand temperature of different vegetation-cover types for sites one to three at location one and two for sampling event two (colder month: April for location one and two). The temperature is for the colder month show little variability across all vegetation-cover types, however no vegetation/sand temperature is somewhat variable.

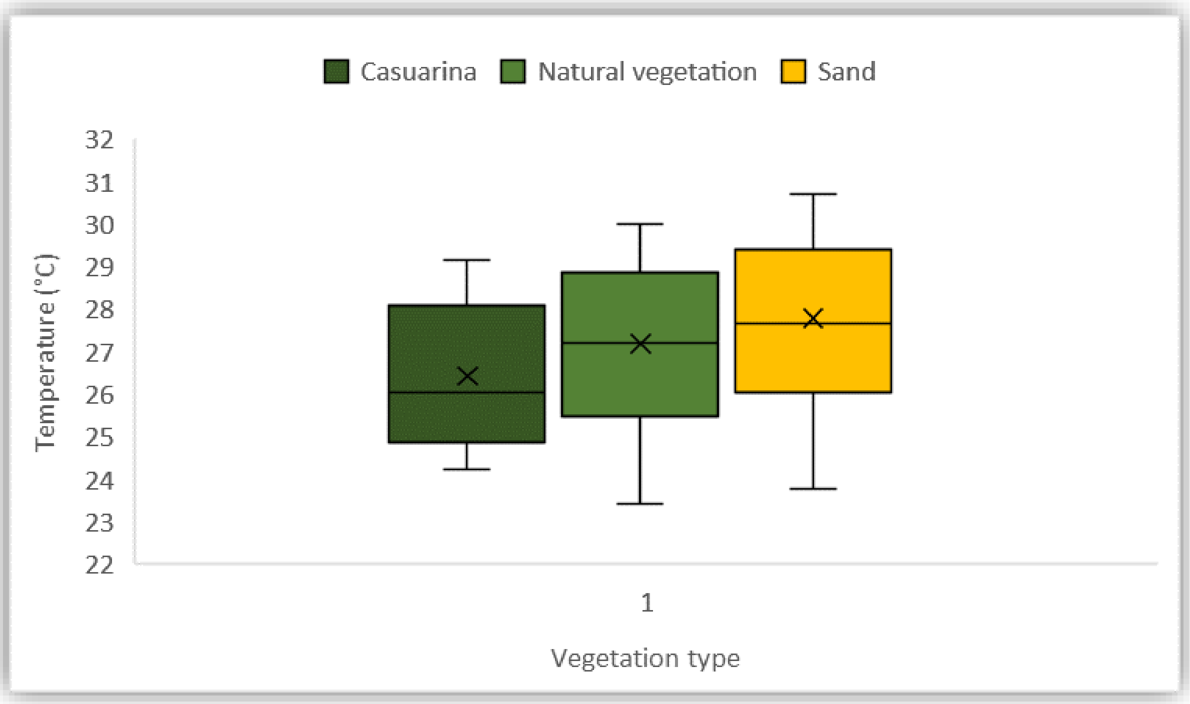


Figure 2.22: Boxplot depicting the results for sand temperature (°C) among the three different vegetation-cover types across the six experimental sites of locations one and two for sampling event one and two (all temperature data pooled and outliers removed) (Casuarina = 2112 mean measurements, natural vegetation = 2304 mean measurements and no vegetation/sand = 2112 mean measurements).

2.4 DISCUSSION

The aim of the study was to investigate the effect of non-native *Casuarina* trees on the back-beach at a local scale to thereby estimate its potential use as a coastal protection measure for beaches; this means that *Casuarina* should stabilize coastal dunes without affecting back-beach morphology, substrate characteristic and the nest incubation environment. However, the results suggest that even though some characteristics like sand moisture and shade density remain unaffected, *Casuarina* affect the back-beach and the primary foredune negatively by (i) changing the back-beach shape; (ii) lowering substrate pH levels; and (iv) lowering *in situ* sand temperature at sea turtle nest depth (around 50 cm). The use of *Casuarina* trees as a coastal protection measure is therefore questionable, especially on turtle nesting beaches and on beaches where these species are considered exotic.

2.4.1 Casuarina *effect on sandy beaches*

This study demonstrates that despite the differences in vegetation cove*r* and structure between *Casuarina* and natural vegetation, light intensity underneath natural vegetation and *Casuarina* were similar, with a mean light intensity of 272.6 $\mu mol.m^{-2}.s^{-1}$ underneath *Casuarina* trees and 349.2 $\mu mol.m^{-2}.s^{-1}$ underneath natural vegetation. Furthermore, the study showed no significant difference in penetrability, with the mean penetrability underneath *Casuarina* equalling 18 cm and the penetrability underneath natural vegetation equalling 16 cm. Therefore, *Casuarina* will not affect the microclimate of the back-beach and dune system through the alteration of penetrability, sand moisture or light intensity.

Casuarina will however negatively affect the back-beach and foredune microenvironment by reducing pH levels. The first 10 cm of soil underneath *Casuarina* had a significantly lower pH at 8.2, than from substrate underneath natural vegetation ($p < 0.01$), where the mean pH underneath natural vegetation was above 9. Patil et al. (2002) suggest that the presence of phenolics in the leaf litter and sand may be responsible for the lower pH in the sand underneath *Casuarina* trees. Very little research has been done on the effect of lowered pH levels on sandy beach and dune ecosystems, but several studies report that interstitial meiofauna are directly affected by the toxic effect of lower pH (McGwynne et al. 1988, Jones et al. 2010). However thresholds still need to be established. Research with respect to climate change and the addition of CO_2 to the atmosphere has predicted the reduction of pH of the ocean waters and the concurrent calcification of corals (IPCC 2001), but it may also affect other species (e.g., molluscs and crustacea) that extract calcium carbonate from sea water for their shells (Jones et al. 2010). The effect of rainwater, which generally has an aproximate pH of 5.7 (Carroll 1962), combined with lowered substrate pH underneath *Casuarina*, might be relatively greater than other vegetation-cover types on interstitial harpacticoids inhabiting the backshore; If their calcium metabolism is compromised, sandy-beach species that rely on robust shell to protect them from abrasion or predation, might be affected (Jones et al. 2010).

Casuarina impacts the back-beach and dune habitat by altering sand movement. Semi-quantitative and qualitative analysis of beach profiles suggested that *Casuarina* trees and shrubs result in wind scouring directly in front of the foredunes as evidenced by the concave shape in front of *Casuarina* stands at some sites. Sites with natural vegetation had mainly convex beach shapes, suggesting sand accretion. Either way, vegetation had an important effect on sand dynamics (both positive and negative) where areas sand only had a neutral shape. There was however a significant interaction between vegetation type and site, indicating that vegetation type alone cannot account for differences in beach profile dynamics and that site-specific conditions like wave height, sand budget, precipitation and orientation differences among locations may also have an effect (McArdle and McLachlan 1992, Short 1999, Benedet et al. 2004, Defeo and McLachlan 2005, McLachlan and Dorvlo 2005, Short 2006).

Casuarina affect sand dynamics by displacing native vegetation (beach crawlers) (Batish et al. 2001, Chaudari et al. 2009) and site-specific interactions with wind and waves. When *Casuarina* dominate over natural vegetation the substrate is exposed, resulting in the displacement of sand to the back of the dune system by wind erosion (Sealey 2006). When storms occur, the low water mark moves higher up shore and waves over-top the lowered dunes, further displacing sand to the back of the dune system and taking sand out of the beach system (Sealey 2006). Extreme wind conditions cause further erosion as sand is blown away. The net result is near total removal of the dune sand reservoir and a familiar exposure of *Casuarina* roots (Sealey 2006). The results concur with the findings of other studies stating that non-native *Casuarina* trees are not effective dune stabilizers (Morton 1980, Chaudari et al. 2009, Feagin et al. 2010) and furthermore that fallen *Casuarina* trees (as a result of storm events) might negatively affect fauna such as sea turtles by physically impeding the nesting females from accessing the nesting grounds/ back-beach as they are unable to climb over or pass the fallen trees or disorientating hatchlings as they emerge from the nest (Klukas 1969, Morton 1980, Congress 1993, Doren and Jones 1997).

2.4.2 Casuarina *effect on sea turtle nesting habitat*

Sea turtles use the back-beach to nest close to, in or under vegetation (Hays et al. 1995) and thus vegetation has a direct effect on the incubation environment and ultimately hatchling sex ratios and hatchling success (Wood et al. 2000). *Casuarina* trees had a significant effect on substrate pH (p <

0.01), where substrate pH underneath *Casuarina* ranged from 9.04 to 7.5, while pH underneath natural vegetation ranged from 9.6 to 8.6. No reasearch has been done on the effect of lowererd pH on sea turtle eggs and hatchling success, but some studies investigated the effect of acidification on amphibian embryo development (Pough 1976, Pough and Wilson 1977, Pierce 1985, Dunson et al. 1992, Blaustein et al. 1998). Mortality of spotted salamander (*Ambystoma maculatum*) embryos increased in even slighlty acidic pond water (Pough and Wilson 1977). However a study by Pierce (1985) specifies that studies only showed increased mortality below a pH of 4. Therefore, changes in pH underneath *Casuarina* may not have a direct effect on turtle hatchlings, but may possibly affect sandy beach ecology and indirectly affect incubation environment.

The significantly lower, more stable average temperature underneath *Casuarina* trees may have significant implications for sex ratios of sea turtle hatchlings. Research by Yntema and Mrosovsky (1982) demonstrated that there is a pivotal temperature (~ 30°C) above which only female hatchlings are produced and below which only male hatchlings are produced. Further research by Tucek (2014) established that sex ratios are affected by diel fluctuations and that hatchling sex ratios depend on the daily proportion of embryonic development that occurs above the pivotal temperature for sex determination rather that the proportion of time spent above the threshold (~ 30°C). Georges (1989) derived a model where female-biased populations are produced if more than half of daily embryonic development occurs at temperatures above the pivotal temperature and that male bias nests are produced if more than half of daily embryonic development occurs below the pivotal temperature.

The boundary between male producing and female producing conditions will therefore depend both on mean nest temperature and the magnitude of daily fluctuations in temperature (Georges et al. 1994) above and below the pivotal temperature. Sand temperature underneath *Casuarina* showed little temperature fluctuation (IQR = 3.2°C) at a significantly ($p < 0.0001$) lower mean temperature (mean temperature = 26.4°C) compared to natural vegetation and considering the average pivotal temperature for sea turtles (approximately 30°C), predictions for male bias clutches underneath *Casuarina* should be accurate. Other than the impact on sex-ratios, elevated temperature fluctuation may also have an impact on hatchling success. If sand temperature surpasses 33°C for an extended period of time, hatchling success may decrease (Matsuzawa et al. 2002). Sand temperature underneath *Casuarina* is less likely to reach these lethal limits than areas with no vegetation. So, in terms of hatchling success rate the thermal environment created by *Casuarina* might almost seem favourable in extremely hot climate areas, especially when considering the effects of climate change.

When considering effect of vegetation on sea turtle nesting habitat, it is important to consider the differences in species' nesting behaviours. Loggerheads nest near or just into foredune vegetation (Hays and Speakman 1993), leatherbacks prefer to nest in open sandy beach zones (Whitmore and Dutton 1985, Kamel and Mrosovsky 2004). Both green turtles and hawksbill turtles nest within vegetation (Whitmore and Dutton 1985, Kamel and Mrosovsky 2004) and olive ridley turtles has been known to nest close to or sometimes within vegetation (Eckrich and Owens 1995, Chaudari et al. 2009). The results suggest that the South African loggerhead and leatherback hatchlings could be male biased, as a substantial portion of the high intensity nesting area are backed by dense *Casuarina* stands. However, a study by Tuçek (2014) indicates a female bias. Loggerhead sex ratio (2009 – 2011) was estimated at 86.9 ± SE 0.35% female-biased and leatherback (2010) was estimated to be 97.1% female-biased (Tucek 2014). Tucek (2014), also demonstrated high hatchling emergence success for both South African loggerhead (73.6 ± SD 27.68%) and leatherback (73.8 ± SD 22.70%) turtles, indicating that the combined effect of *Casuarina* on the back-beach (shape, substrate characteristics and incubation environment) has not had a negative impact on the hatchlings. For species such as hawksbills and olive ridleys which nests within vegetation, the effects might be more pronounced.

Casuarina were introduced in the 1980's to the high nesting density area of the iSimangaliso Wetland Park, long-term data (1960 – 2010) indicate a significant increase in the number of loggerhead nesting females, and leatherback female numbers seem to have stabilized with a possible marginal increase (Nel 2008), indicating that nesting females were not deterred by the presence of *Casuarina* stands on the back-beach. *Casuarina* effects seem therefore not to have had population level impacts. However, both loggerhead and leatherback turtles do not nest within the vegetation, and *Casuarina* impact on the back-beach and foredune environment may therefore be mitigated. Furthermore, the South African nesting beaches are high energy environments with high wind and wave action, while studies conducted on beaches with different energy environments have demonstrated *Casuarina* impact. For example, Chaudari et al. (2009), demonstrated that fewer olive ridley females nested on beaches with *Casuarina* than beaches with natural vegetation or no vegetation along the Tamil Nadu coast, India. Chaudari et al. (2009), monitored the different vegetation type beaches for 43 nights (17 *Casuarina*, 14 open/sand and 12 vegetated) and did not consider long-term trends for nesting on the different beaches. Since the *Casuarina* forests of the '*Casuarina* beach' of the Chaudari et al. (2009) study were only recently established (December 2006), it could be beneficial to consider long-term olive ridley nesting data to elucidate if there is a difference in nesting before and after the establishment of the *Casuarina* forest.

2.4.3 Exotic vegetation and coastal ecosystems

Sandy beach habitats are vulnerable ecosystems, not only because of their position at the land-sea margin and the definite threat of global change, but because of the omission of scientific research in coastal management policies (Dugan et al. 2010, Feagin et al. 2010). Research on the detrimental effects of exotic/invasive organisms, are gaining ground and the invasion of ecosystems by alien species has been identified as a significant and continuing threat to ecosystems and their services (D'Antonio and Meyerson 2002). Moving forward, it is important to acknowledge sandy beaches as functioning ecosystems (Dugan et al. 2010) with important ecosystem services such as a supportive function to a range of fauna and flora (Schlacher et al. 2007, 2008, Defeo et al. 2009) and to incorporate science in our management of this fragile habitat. Research to date on the sustainability of using exotic *Casuarina* trees in coastal regions has demonstrated physical impacts on sandy beaches (Morton 1980, Jadhav and Gaynar 1995, Gordon 1998, Batish et al. 2001, Patil et al. 2002, Sealey 2006, Chaudari et al. 2009, Wheeler et al. 2011, Hardman et al. 2012) which could ulimately affect sandy beach ecosystem functioning. Therefore bio-shield policy should carefully consider these effects before finalising and implementing management plans (Bhalla 2007, Feagin et al. 2010, Das and Sandhu 2014).

2.4.4 Way forward

Further research needs to be conducted on the effect of altered environmental conditions, such as lower pH and temperature levels on the functioning of sandy beach ecosystems, specifically the impact on beach fauna and flora. Specific to the project, a larger sample size concerning the volumetric soil moisture content underneath *Casuarina* is suggested, as sample size was not adequate to demonstrate effect. It is also suggested that studies quantifying sand budget in front of extensive *Casuarina* stands, by making use of a differential GPS needs with repetitive surveys during storm and calm conditions needs to be conducted as a descriptive approach of beach shape is not adequate to conclude on the possible erosive effect of *Casuarina*. Furthermore, a quantitative study looking at beach recovery time (after storm events) in front of different vegetation-cover types would contribute greatly to the argument of the sustainability of *Casuarina* trees as bio-shields. The results of the study suggest changing the experimental approach, as the mixture of the different vegetation-cover types (*Casuarina*, native/natural vegetation and sand) in close proximity to each other (between 10 and 150 m) on the experimental sites, made it difficult to distinguish larger scale impacts on sand dynamics (erosion or accretion) in the presence or absence of *Casuarina*. An approach similar to Chaudari et al. (2009), where beaches with only *Casuarina* or native vegetation were compared, while controlling for beach orientation and wave and wind climate. An experimental system, either through laboratory simulation or field-based, i.e. planting *Casuarina* or native vegetation sections in a beach environment for experiments, is not feasible.

2.4.5 Conclusion

The demonstrated effects caused by introduced *Casuarina* trees calls to question the suitability of exotic trees, such as *Casuarina equisetifolia*, as a sustainable coastal protection measure. Unmitigated development of large *Casuarina* bio-shields outside of their native ranges, could be detrimental to the functioning of sandy beach ecosystems and may contribute to dune de-stabilization as the trees have been observed to fall over easily during extreme weather events. The descriptive approach on beach shape does not allow for definitive conclusions on beach erosion in the presence of exotic *Casuarina* trees, however prelimanary studies would indicate that *Casuarina* affect beaches by changing back-beach shape at the local scale. The study demonstrates that *Casuarina* significantly changes substrate characteristics by significanlty lowering pH and temperature levels and therefore suggests that *Casuarina* trees have potentially negative impacts on sandy beaches and fauna such as sea turtles. Considering these effects, the study suggests that native species are preferable to *Casuarina* species as a dune stabilizer

REFERENCES

ACKERMAN, R. A. 1981. Oxygen consumption by sea turtle (*Chelonia*, *Caretta*) eggs during development. *Physiological Zoology* 54:316–324.

BARBIER, E., HACKER, S., KENNEDY, C., KOCH, E., STIER, A. and SILLIMAN, B. 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81:169–193.

BATISH, D. R., SINGH, H. P. and KOHLI, R. K. 2001. Vegetation exclusion under *Casuarina equisetifolia* L.: Does allelopathy play a role? *Community Ecology* 2:93–100.

BENEDET, L., FINKL, C.W., CAMPBELL, T., and KLEIN, A. 2004. Predicting the effect of beach nourishment and cross-shore sediment variation on beach morphodynamic assessment. *Coastal Engineering*, 51: 839-861.

BHALLA, R. S. 2007. Do bio-shields affect tsunami inundation? *Current Science* 93:831–833.

BLAUSTEIN, A. R., KIESECKER, J. M., CHIVERS, D. P., HOKIT, D. G., MARCO, A., BELDEN, L. K. and HATCH, A. 1998. Effects of ultraviolet radiation on amphibians field experiments. *American Zoologist* 38:799–812.

BLOTT, S. J. and PYE, K. 2001. Gradistat: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms* 26:1237–1248.

BOOMSMA, J. J. and DE VRIES, A. 1980. Ant species distribution in a sandy coastal plain. *Ecological Entomology* 5: 189-204.

BOUCHARD, S. S. and BJORNDAL, K. A. 2000. Sea turtles as biological transporters of nutrients and energy from marine to terrestrial ecosystems. *Ecology* 81:2305–2313.

BROWN, A. C. and MCLACHLAN, A. 2002. Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. *Environmental Conservation* 29:62–77.

BUEHLER, C. and RODGERS, J. 2012. Soil property differences between invaded casuarina (*Casuarina equisetifolia* L.) sites and non-casuarina sites in the Bahamas. *Physical Geography* 33:574–588.

CARROLL, D. 1962. Rainwater as a chemical agent of geologic processes: a review. US Government Printing Office.

CHAUDARI, S., PRASAD, K. D. and SHANKER, K. 2009. Impact of *Casuarina* plantations on Olive Ridley Turtle nesting along the Northern Tamil Nadu Coast , India. ATREE, Bangalore and MCBT, Mamallapuram, India. pp. 44.

COLOSIO, F., ABBIATI, M. and AIROLDI, L. 2007. Effects of beach nourishment on sediments and benthic assemblages. *Marine Pollution Bulletin* 54:1197–1206.

CONGRESS US. 1993. *Office of Technology Assessment. 1993. Harmful non-indigenous species in the United States*. OTA-F-565. US Government Printing Office, Washington, DC.

CORE TEAM. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

DAHL, E. 1952. Some aspects of the ecology and zonation of the fuana on sandy beaches. *Oikos* 4:1–27.

D'ANTONIO, C. and MEYERSON, L. A. 2002. Exotic plant species as problems and solutions in ecological restoration: A synthesis. *Restoration Ecology* 10:703–713.

DANIELSEN, F., SØRENSEN, M. K., OLWIG, M. F., SELVAM, V., PARISH, F., BURGESS, N. D., HIRAISHI, T., KARUNAGARAN, V. M., RASMUSSEN, M. S., HANSEN, L. B. AND QUARTO, A. 2005. The Asian tsunami: A protective role for coastal vegetation. *Science* 310:643-643.

DAS, S. and SANDHU, H., 2014. Role of Exotic Vegetation in Coastal Protection. *Economic and Political Weekly* 49: 42-50.

DEFEO, O. and CARDOSO, R. S. 2002. Macroecology of population dynamics and life history traits of the mole crab *Emerita brasiliensis* in Atlantic sandy beaches of South America. *Marine Ecology Progress Series* 239:169–179.

DEFEO, O. and MCLACHLAN, A. 2013. Global patterns in sandy beach macrofauna: Species richness, abundance, biomass and body size. *Geomorphology* 199:106-114.

DEFEO, O. and MCLACHLAN, A. 2005. Patterns, processes and regulatory mechanisms in sandy beach macrofauna: A multi-scale analysis. *Marine Ecology Progress Series*: 295:1-20.

DEFEO, O., MCLACHLAN, A., SCHOEMAN, D. S., SCHLACHER, T. A., DUGAN, J., JONES, A., LASTRA, M. and SCAPINI, F. 2009. Threats to sandy beach ecosystems: A review. *Estuarine, Coastal and Shelf Science* 81:1–12.

DEN HOLLANDER, J. and VAN HEERDT, P. F. 1981. Arthropod life in yellow dune habitats. In: Smit, C.J. (Ed.). *Wadden Sea Working Group Reports* 10: 88-94.

DOREN, R. F. AND JONES, D. T. 1997. Plant management in Everglades National Park. *Strangers in Paradise. D. Simberloff, DC Schmitz and TC Brown, eds. Island Press, Washington, DC*, pp.275-286.

DUGAN, J. E., DEFEO, O., JARAMILLO, E., JONES, A. R., LASTRA, M., NEL, R., PETERSON, C. H., SCAPINI, F., SCHLACHER, T. and SCHOEMAN, D. S. 2010. Give beach ecosystems their day in the sun. *Science* 329:1146.

DUNSON, W. A., WYMAN, R. L. and CORBETT, E. S. 1992. A symposium on amphibian declines and habitat acidification. *Journal of Herpetology* 26:349–352.

ECKRICH, C.E. AND OWENS, D.W. 1995. Solitary versus arribada nesting in the olive ridley sea turtles (*Lepidochelys olivacea*): A test of the predator-satiation hypothesis. *Herpetologica*: 51:349-354.

EMANUEL, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436:686–688.

EMERY, K.O. 1961. A simple method of measuring beach profiles. *Limnology and Oceanography* 6: 90-93.

FEAGIN, R. A., MUKHERJEE, N., SHANKER, K., BAIRD, A. H., CINNER, J., KERR, A. M., KOEDAM, N., SRIDHAR, A., ARTHUR, R., JAYATISSA, L. P., LO SEEN, D., MENON, M., RODRIGUEZ, S., SHAMSUDDOHA, M. and DAHDOUH-GUEBAS, F. 2010. Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters. *Conservation Letters* 3:1–11.

FEAGIN, R. A., SHERMAN, D. J. and GRANT, W. E. 2005 Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. *Ecological Society of America* 3:359–364.

FOLEY, A. M., PECK, S. A., HARMAN, G. R. and RICHARDSON, L. W. 2000. Loggerhead Turtle (*Caretta caretta*) nesting habitat on low-relief mangrove islands in Southwest Florida and consequences to hatchling sex ratios. *Herpetologica* 56:433–445.

GUEBAS, F. 2010. Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters. *Conservation Letters* 3:1–11.

GEORGES, A. 1989. Female turtles from hot nests: Is it duration of incubation or proportion of development at high temperature that matters? *Oecologia* 81:323–328.

GEORGES, A., LIMPUS, C. and STOUTJESDIJK, R. 1994. Hatchling sex in the marine turtle *Caretta caretta* is determined by proportion of development at a temperature, not daily duration of exposure. *The Journal of Experimental Zoology* 270:432–444.

GHABBOUR, S. I., DA FONSECA, J. C. AND MIKHAIL, W. Z. A. 1987. Seasonal differentiation of soil mesofauna in a littoral dune of the Egyptian Mediterranean coast. *Biology and Fertility of Soils* 3:75-80.

GOCHENAUR, S. E. 1975. Distributional patterns of mesophilous and thermophilous microfungi in two Bahamian soils. *Mycopathologia* 57:155–164.

GORDON, D. R., 1998. Effects of invasive, non-indigenous plant species on ecosystem processes: Lessons from Florida. *Ecological Applications* 8:975-989.

GOSWAMI, B. N., VENUGOPAL, V., SENGUPTA, D., MADHUSOODANAN, M. S. and XAVIER, P. K. 2006. Increasing trend of extreme rain events over India in a warming environment. *Science* 314:1442–1444.

HARDMAN, C. J., WILLIAMS, S., MANCO, B. N. and HAMILTON, M. A. 2012. Predicting the potential threat of *Casuarina equisetifolia* to three endemic plant species on the Turks and Caicos Islands. *Oryx* 46:204–212.

HARRIS, L., CAMPBELL, E. E., NEL, R. and SCHOEMAN, D. 2014. Rich diversity, strong endemism, but poor protection: Addressing the neglect of sandy beach ecosystems in coastal conservation planning. *Diversity and Distributions* 20:1120–1135.

HARRIS, L., NEL, R., HOLNESS, S. and SCHOEMAN, D. 2015. Quantifying cumulative threats to sandy beach ecosystems: A tool to guide ecosystem-based management beyond coastal reserves. *Ocean and Coastal Management* 110:12–24.

HARRIS, L. R. 2012. An ecosystem-based spatial conservation plan for the South African sandy beaches. PhD thesis, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

HAYS, G. C. and SPEAKMAN, J. R., 1993. Nest placement by loggerhead turtles, *Caretta caretta. Animal Behaviour*, *45*:47-53.

HAYS, G. C., MACKAY, A., ADAMS, C. R., MORTIMER, J. A., SPEAKMAN, J. R. and BOEREMA, M., 1995. Nest site selection by sea turtles. *Journal of the Marine Biological Association of the United Kingdom* 75:667-674.

IPCC. 2001. Intergovernmental Panel on Climate Change web site. www.grida.no/climate/ipcc_tar/wg2/index.htm. (accessed May 2018).

JADHAV, B. B. and GAYNAR, D. G. 1995. Effect of *Casuarina equisetiolia* J.R. leaf litter leachates on germination and seedling growth of rice and cowpea. *Allelopathy Journal* 2:105-108.

KAMEL, S. J. AND MROSOVSKY, N., 2004. Nest site selection in leatherbacks, *Dermochelys coriacea*: Individual patterns and their consequences. *Animal Behaviour* 68:357-366.

KATHIRESAN, K. and RAJENDRAN, N. 2005. Coastal mangrove forests mitigated tsunami. *Estuarine, Coastal and Shelf Science* 65:601–606.

KOOP, K. AND GRIFFITHS, C. L., 1982. The relative significance of bacteria, meio-and macrofauna on an exposed sandy beach. *Marine Biology* 66:295-300.

KLUKAS, R. W., 1969. Exotic terrestrial plants in South Florida with emphasis on Australian pine (*Casuarina equisetifolia*). *Homestead, Florida: Everglades National Park. Report*, (33030).

MARCANTONIO, M., ROCCHINI, D. and OTTAVIANI, G. 2014. Impact of alien species on dune systems: A multifaceted approach. *Biodiversity and Conservation* 23:2645–2668.

MASCARENHAS, A. and JAYAKUMAR, S. 2008. An environmental perspective of post-tsunami scenario along the coast of Tamil Nadu, India: Role of sand dunes and forests. *Journal of environmental management* 89:24–34.

MATSUZAWA, Y., SATO, K., SAKAMOTO, W. and BJORNDAL, K. A. 2002. Seasonal fluctuations in sand temperature: Effects on the incubation period and mortality of loggerhead sea turtle (*Caretta caretta*) pre-emergent hatchlings in Minabe, Japan. *Marine Biology* 140:639–646.

MAZZOTTI, F. J., OSTRENKO, W. and SMITH, A. T., 1981. Effects of the exotic plants *Melaleuca quinquenervia* and *Casuarina equisetifolia* on small mammal populations in the eastern Florida Everglades. *Florida Scientist* 44:65-71.

MCARDLE, S. B. and MCLACHLAN, A. 1992. Sandy beach ecology: Swash features relevant to the macrofauna. *Journal of Coastal Research* 8:398–407.

MCGWYNNE, L. E., MCLACHLAN, A. AND FURSTENBERG, J. P. 1988. Wrack breakdown on sandy beaches—its impact on interstitial meiofauna. *Marine Environmental Research* 25:213-232.

MCLACHLAN, A. 1977. Studies on the psammolittoral meiofauna of Algoa Bay, South Africa. II. The distribution, composition and biomass of the meiofauna and macrofauna. *African Zoology* 12:33-60.

MCLACHLAN, A. 1991. Ecology of coastal dune fauna. *Journal of Arid Environments* 21:229-243.

MILLER, J. D., LIMPUS, C. J. and GODFREY, M. H. 2003. Nest site selection, oviposition, eggs, development, hatching, and emergence of loggerhead turtles. In: Bolten, A.B. and Witherington, B. E. (eds). *Loggerhead Sea Turtles*, Smithsonian. pp. 125–143.

MCLACHLAN, A. and DORVLO, A. 2005. Global Patterns in sandy beach macrobenthic communities. *Journal of Coastal Research* 21:674–687.

MITCHELL, J., JURY, M. R. and MULDER, G. J. 2005. A Study of iSimangaliso beach morphodynamics. *South African Geographical Journal* 87:43–51.

MORTON, J. F. 1980. The Australian pine or beefwood (*Casuarina equisetifolia* L.), an invasive 'weed' tree in Florida. *Proceedings of the Florida State Horticultural Society* 93:87–95.

MUCINA, L., ADAMS, J. B., KNEVEL, I. C., RUTHERFORD, M. C., POWRIE, L. W., BOLTON, J. J., VAN DER MERWE, J. H., ANDERSON, R. J., BORNMAN, T. G., LE ROUX, A. AND JANSSEN, J. A. 2006. Coastal vegetation of South Africa. The vegetation of South Africa, Lesotho and Swaziland. *Strelitzia* 19:558-683.

MUKHERJEE, N., BALAKRISHNAN, M. and SHANKER, K. 2009. Bioshields and ecological restoration in tsunami-affected areas in India. In: Moksness, E., Dahl, E., and Støttrup, J. (eds). *Integrated Coastal Zone Management*, John Wiley and Sons, Oxford. pp. 131–144.

NEL, R. 2008. Sea turtles of KwaZulu-Natal: Data report for 2007/8 season. Report for Ezemvelo KwaZulu-Natal Wildlife: 1 – 32.

NEL, R., CAMPBELL, E.E., HARRIS, L., HAUSER, L., SCHOEMAN, D.S., MCLACHLAN, A., DU PREEZ, D.R., BEZUIDENHOUT, K. AND SCHLACHER, T.A. 2014. The status of sandy beach science: Past trends, progress, and possible futures. *Estuarine, Coastal and Shelf Science*, *150*:1-10.

PATIL, R. H., HUNSHAL, C. S. and ITNAL, C. J. 2002. Effect of casuarina litter leachates on crops. *Allelopathy Journal* 10:141–146.

PIERCE, B. A. 1985. Acid tolerance in amphibians. *BioScience* 35:239–243.

PILKEY, O. H., NEAL, W. J., KELLEY, J. T. and COOPER, J. A. G. 2011. The World's Beaches. University of California Press, Berkeley, CA.

POTGIETER, L. J., RICHARDSON, D. M. and WILSON, J. R. U. 2014. *Casuarina*: Biogeography and ecology of an important tree genus in a changing world. *Biological Invasions* 16:609–633.

POUGH, F. H. 1976. Acid precipitation and embryonic mortality of spotted slamanders, *Ambystoma maculatum*. *Science* 192:68–70.

POUGH, F. H. and WILSON, R. E. 1977. Acid precipitation and reproductive success of *Ambystoma* salamanders. *Water, Air, and Soil Pollution* 7:307–316.

SAMARAKOON, M. B., TANAKA, N. and IIMURA, K. 2013. Improvement of effectiveness of existing *Casuarina equisetifolia* forests in mitigating tsunami damage. *Journal of Environmental Management* 114:105–114.

SCHLACHER, T. A., DUGAN, J., SCHOEMAN, D. S., LASTRA, M., JONES, A., SCAPINI, F., MCLACHLAN, A. and DEFEO, O. 2007. Sandy beaches at the brink. *Diversity and Distributions* 13:556–560.

SCHLACHER, T. A., SCHOEMAN, D. S., DUGAN, J., LASTRA, M., JONES, A., SCAPINI, F. and MCLACHLAN, A. 2008. Sandy beach ecosystems: Key features, sampling issues, management challenges and climate change impacts. *Marine Ecology* 29:70–90.

SCHMELZ, G. W. and MEZICH, R. R. 1988. A preliminary investigation of the potential impact of Australian pines on the nesting activities of the loggerhead turtle. In: Schroeder, B. A. (compiler). *Proceedings of the eighth annual conference on sea turtle biology and conservation. NOAA Technical Memorandum NMFSSEFC-214. On file at South Florida Ecosystem Office, US Fish and Wildlife Service, Vero Beach, Florida*: 63-66.

SEALEY, N. 2006. The cycle of *Casuarina*-induced beach erosion - A case study from Andros, Bahamas. pp. 197–205, *The 12th Symposium on the Geology of the Bahamas and other Carbonate Regions (2004)*.

SHORT, A. D. 1999. Short, wave-dominated beaches. In: Short, A. D. (ed.). Handbook of Beach and Shoreface Morphodynamics, pp 173-203. Wiley, Chichester, UK.

SHORT, A. D. 2006. Australian beach systems - nature and distribution. *Journal of Coastal Research*, 22:11-27.

TANAKA, N. 2009. Vegetation bioshields for tsunami mitigation: review of effectiveness, limitations, construction, and sustainable management. *Landscape and Ecological Engineering* 5:71–79.

TANAKA, N. and THUY, N. B. 2010. Tsunami force mitigation by tropical coastal trees, *Pandanus odoratissimus* and *Casuarina equisetifolia*, considering the effect of tree breaking. *International Conference on Sustainable Built Environment (ICSBE-2010, Kandy, Sri Lanka* 13–14 December 2010, pp 7-14.

THUY, N. B., TANAKA, N. and TANIMOTO, K. 2012. Tsunami mitigation by coastal vegetation considering the effect of tree breaking. *Journal of Coastal Conservation* 16:111–121.

TUCEK, J. B. 2014. Comparison of the population growth potential of the South African loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtles. MSc dissertation, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

VAN WILGEN, B. W., REYERS, B., LE MAITRE, D. C., RICHARDSON, D. M. and SCHONEGEVEL, L. 2008. A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa. *Journal of Environmental Management* 89:336–349.

WEBSTER, P. J., HOLLAND, G. J., CURRY, J. A. and CHANG, H. R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309:1844–1846.

WHEELER, G. S., TAYLOR, G. S., GASKIN, J. F. and PURCELL, M. F. 2011. Ecology and management of Sheoak (*Casuarina* spp.), an Invader of Coastal Florida, U.S.A. *Journal of Coastal Research* 27:485–492.

WHITMORE, C. P. AND DUTTON, P. H., 1985. Infertility, embryonic mortality and nest-site selection in leatherback and green sea turtles in Suriname. *Biological Conservation* 34:251-272.

WOLANSKI, E. 2007. Synthesis of the protective functions of coastal forests and trees against natural hazards. *Coastal protection in the aftermath of the Indian Ocean tsunami: What role for forests and trees? Proceedings of the Regional Technical Workshop*:161–184.

WOOD, D. W. AND BJORNDAL, K. A. 2000. Relation of temperature, moisture, salinity, and slope to nest site selection in loggerhead sea turtles. *Copeia*, 2000:119-119.

YNTEMA C. L., and MROSOVSKY N. 1982. Critical periods and pivotal temperatures for sexual differentiation in loggerhead sea turtles. *Canadian Journal of Zoology* 60:1012-1016.

Chapter 3 : *Regional Assessment of the Vulnerability of Sea Turtle Nesting Beaches to* Casuarina *presence, sea level rise and storm activity throughout the Indian Ocean and South-East Asia*

ABSTRACT

The world's beaches are under severe pressure, because of anthropogenic modification and climate change. The most common coastal management approaches have focused largely on the protection of infrastructure, without considering the function of the beach and dune system as a natural protective barrier and a diverse ecosystem. Large scale plantations of non-native vegetation have been initiated in many countries as a coastal protection tool, but the use of exotic vegetation has been demonstrated to have negative impacts on sandy beach ecosystems, including the promotion of erosion in some instances and negative impacts on sea turtle nesting and hatchling sex-ratios. The extent of the use of exotic vegetation, specifically *Casuarina* trees, was assessed on 50 sea turtle nesting beaches of the Indian Ocean region, with a concomitant assessment of beach vulnerability to erosion (using a novel index) in the presence/absence of *Casuarina* trees. Beach vulnerability was classified according to four vulnerability categories: 1) High Risk-High Threat; 2) High Risk-Low Threat; 3) Low Risk-High Threat and 4) Low Risk-Low Threat. Overall, *Casuarina* trees occurred on 28% of beaches, occurring predominantly on beaches outside of their native ranges. The High Risk-High Threat category included 14% of the turtle nesting beaches, with olive ridley (*Lepidochelys olivacea*) beaches being particularly vulnerable. The study highlighted that *Casuarina* however could not be viewed as an indicator of erosion, and that several other beach features, like narrow back-beach width, are better indicators of erosion vulnerability. However, the study emphasizes the wide-spread occurrence of *Casuarina* on sea turtle nesting beaches and highlights increased erosion vulnerability for beaches with non-native *Casuarina* present. Where feasible the replacement of non-native *Casuarina* with native vegetation is recommended.

3.1 INTRODUCTION

Rapid global change and anthropogenic modification of natural habitats are threatening ecosystems across the globe (Crain et al. 2008, Halpern et al. 2008, Ban et al. 2010), and many of these threats and adverse impacts are concentrated on the world's coastlines (McLachlan and Brown 2006, Defeo et al. 2009, Dugan et al. 2010). Moreover, Crowell et al. (2007) noted that 20% of the global population lives within 25 km of the coastline and an estimated 40% within a 100 km. To accommodate such a large proportion of the global population and their related activities, the dynamic littoral active zone is frequently stabilized with hard engineering structures such as sea walls (Charlier et al. 2005, Bulleri and Chapman 2010) which disrupts coastal ecological processes. In fact, most natural coastal processes have become natural disaster risks to the anthropogenically-modified coasts (Schlacher et al. 2007, Rizzo et al. 2017). Coastal stabilization has led to "coastal squeeze" with modified shorelines unable to move according to changes in sea level (Brown and McLachlan 2002, Defeo et al. 2009). Furthermore, global change through global 'warming' exacerbates sea level rise (Feagin et al. 2005, Phillips and Crisp 2010). The combined impacts result in permanent/episodic inundation and coastal erosion (Gornitz 1991, Zhang et al. 2004, Özyurt and Ergin 2010), which may damage human settlements and degrade or destroy coastal habitats (Kennedy et al. 2002, Feagin et al. 2005, Harley et al. 2006, Fuentes et al. 2007).

To ensure the protection of coastlines, both as a physical landform and a functional ecosystem, alternative land-use strategies that account for global/climate change should be considered (Glick et al. 2011). Hard armouring structures, such as sea walls (Charlier et al. 2005) or 'soft' options like large-scale plantations of non-native bio-shields (Mukherjee et al. 2009, Tanaka 2009, Samarakoon et al. 2013) are some of the most popular mechanisms to protect developed coasts. Indeed, the popularity of green shelter belts have rapidly increased since the December 2004 tsunami event in the Indian Ocean and South-East Asian region. Extensive portions of the coastal habitat has been modified by planting exotic vegetation (Tanaka 2009, Feagin et al. 2010), such as *Casuarina equisetifolia*.

Casuarina trees (Australian pines or beefwoods) are fast-growing evergreen trees native to Australia, specific regions of Southeast Asia and the Pacific archipelagos (Wheeler et al. 2011). Two species, *C. equisetifolia* and *C. glauca,* recorded as invasive, are regularly used for coastal dune stabilization because they are specifically adapted to conditions that are arid, with high salinity and low soil fertility, like beaches (Chaudari et al. 2009, Potgieter et al. 2014). These *Casuarina* are now found globally across most tropical and sub-tropical regions, including China, India, Thailand, Kenya, Senegal and Tanzania (Potgieter et al. 2014) as they are actively planted in certain coastal regions of the Indian Ocean and South-East Asia (IOSEA) as a measure against erosion and episodic flooding events such as storms or tsunami's (Danielsen et al. 2005, Kathiresan and Rajendran 2005, Wolanski 2007, Mukherjee et al. 2009, Tanaka and Thuy 2010). The functionality of *Casuarina* as a coastal protection tool, however, has yet to be scientifically tested. Indeed studies have emerged disputing the sustainability of using non-native trees as dune stabilizers or storm protection measures. Bhalla (2007), as well as Das and Sandhu (2014), argues that there is no evidence to support the claim that *Casuarina* adequately functions as a storm protection measure and other studies have emphasized that *Casuarina* have adverse effects on sandy beach ecosystems, including the promotion of erosion in some instances and negative impacts on sea turtles (Morton 1980, Sealey 2006, Chaudari et al. 2009) (Described in Chapter 2).

The IOSEA hosts six of the seven sea turtle species, which migrates from widely dispersed feeding grounds to aggregate *en masse* on relatively small nesting beaches to reproduce (Bouchard and Bjorndal 2000). Some of the most important rookeries (based on highest abundance of nesting females per annum) occur throughout the IOSEA region. The IOSEA hosts a major leatherback rookery in Indonesia; approximately 700 leatherback females nest on the Jamursba medi beach (Hitipeuw 2006) and the largest loggerhead rookeries with approximately 30 000 females nesting annually on Masirah Island, Oman (Pilcher 2007). Seychelles and Western Australia host the largest hawksbill rookeries with Cousin Island totalling approximately 700 nesting females (Nature Seychelles 2008) and Rosemary Island more than 400 females (Pendoley et al. 2008). Flatback turtles nest exclusively on Australian beaches and the two largest rookeries, Crab Island and Cape Domett, occurs in northern Queensland with approximately 1000 -5000 (Limpus and Environmental Protection Agency 2009) and around 3000 nesting females (Whiting et al. forthcoming) per year, respectively. The largest olive ridley rookery in the IOSEA occurs on the Orissa coastline of India; approximately 150 000 – 200 000 females exhibit synchronised nesting at the Devi River mouth (includes Rushikulya and Gahirmatha rivers) (Shanker et al. 2004a). Green turtles however, have the widest distribution, with the most important rookeries in northern Queensland adjacent to the northern Great Barrier Reef, Australia. In fact, Raine Island with Moulter Cay and other sand cays (Northern Great Barrier Reef), hosts up to 70 122 nesting females per year. This is the largest remaining breeding assemblage of green turtles globally (Limpus et al. 2003). Other important locations include Europa Island and Farquhar Island in the south-western Indian Ocean (Rene and Roos 1996, Bourjea et al. 2007).

With demonstrated effects of *Casuarina* on sea turtle nesting in some regions (Chaudari et al. 2009) and the wide distribution of important sea turtle nesting beaches throughout the IOSEA region, it is necessary to estimate the extent of *Casuarina* occurrence within important rookeries, i.e. where does sea turtle nesting habitat and *Casuarina* occurrence overlap. Acknowledging that *Casuarina* have been shown to increase beach erosion (Sealey 2006), it is also important to establish the erosion vulnerability of these nesting beaches. A tool which can be used to assess erosion vulnerability of sea turtle nesting beaches are Vulnerability Assessments (VA's). VA's (described in Chapter 1) can highlight the balance between risks and threats and so expose vulnerable areas susceptible to erosion damage (UNDRO 1982). Furthermore, VA's can be used to prioritise regions where existing stressors/risks, such as the presence of exotic *Casuarina* trees might be exacerbated by climate change (Anfuso and Martínez Del Pozo 2009, Mclaughlin and Cooper 2010), and so inform suitable risk-management or planning strategies (Glick et al. 2011). Using VA methods such as the Coastal Vulnerability Index (CVI) originally created by Gornitz et al. (1994) (Di Paola et al. 2011) it is possible to conduct an assessment estimating the erosion potential of important sea turtle nesting beaches throughout the IOSEA.

The aim of this study is to assess the coastal vulnerability with a CVI for sea turtle nesting beaches in the Indian Ocean and South-East Asian (IOSEA) region, as indicated by physical beach features, such as back-beach condition, and threats such as sea-level rise, storm activity and development. Vulnerability in this study is defined as a measure of **Risk** (based on physical beach variables) and **Threat** (based on sea-level rise, storm intensity, storm frequency and coastal development). The cumulative scores allocated indicate overall vulnerability to erosion of the backshore (section above the high-water mark, including the incipient and primary dunes). *The objectives of the study are to identify the distribution of non-native* Casuarina *trees on sea turtle nesting beaches in the IOSEA and to create an erosion vulnerability score (risk vs. threat) for the nesting sites based on global data sets of certain indicators (back-beach width; beach orientation and protection, modal beach energy, state of the dune system, coastal development, sea level rise and storminess).* I hypothesize that non-native *Casuarina* will be present on beaches vulnerable to erosion and will therefore be a good indicator of erosion susceptibility for beaches.

3.2 METHODS

To meet the objectives for this study, the methods involved a three-step process: 1) identify a representative set of sea turtle nesting beaches (study sites) across the IOSEA region, 2) map the distribution (using presence/absence) of *Casuarina* trees and 3) calculate a cumulative CVI score based on *risk* and *threat* for these sea turtle nesting beaches.

3.2.1 Study sites

The conflicting approaches with regards to protecting turtle nesting beaches and *Casuarina* tree planting were identified under the IOSEA sea turtle MoU as a priority (R Nel 2016, personal communication, 19 January) and hence the IOSEA region was chosen as the study area. The IOSEA includes coastal countries of East Africa, the six adjacent island nations, both the Arabian Gulf and Bay of Bengal, extending across the south-eastern Asian countries, including Malaysia, Indonesia and Papua New Guinea, all the way to Australia (western Australia, northern territory and Queensland). Within this region, the 50 most important sea turtle rookeries (in terms of nesting female abundance) were selected for the six species that frequent the IOSEA region. Kemp's ridley (*Lepidochelys kempi*), native to the Gulf of Mexico, was thus excluded. The study sites/sea turtle nesting beaches were identified using female abundance data as reported in the State of the World's Sea Turtles (SWOT) database (http://seamap.env.duke.edu/swot) to ensure some standardization of data reported per site. Specific site information was further augmented from national reports as captured on the IOSEA MoU's website (IOSEA MoU website: http://www.ioseaturtles.org/).

Representative rookeries for each sea turtle nesting species were selected based on female nesting abundance. This allows for a balanced spread among turtle species, while having a representative selection of beaches across the region and countries. Some beaches host more than one species, but the most abundant species was used, unless it was already selected for one of the other (less abundant species). Then an additional beach was chosen for that species until a total of 50 beaches were selected. For very long beaches, for example in South Africa with a continuous rookery exceeding 150 km, monitoring data only exist for a subset of the coast i.e. Mabibi to Kosi lake, and hence only this section was included in the analyses.

3.2.2 *Casuarina* distribution

C. cunninghamiana, *C. equisetifolia* and *C. glauca*, are the only *Casuarina* species globally recorded as either naturalized or invasive in coastal regions (Potgieter et al. 2014). These species are adapted to arid conditions, low soil fertility and high salinity and thus are ideal bio-shields in coastal dune habitats (Chaudari et al. 2009, Potgieter et al. 2014). To establish their occurrence at turtle rookeries across the IOSEA region, several approaches on different scales were considered. First the global distribution and native ranges were established by making use of three global data sets: The Invasive Species Compendium (CABI International 2000, http://www.cabi.org/ISC/), Global Biodiversity Information Facility (GBIF 2008, http://www.gbif.org) and Atlas of Living Australia (http://www.ala.org.au/).

These datasets, however, do not allow for species identification at a very fine/local scale (i.e. beach level). A proximity analysis (generate near table) in ArcMap 10.5.1 with a radius of 30 km was attempted but identified only nine of the study sites as having *Casuarina* present and all within the native ranges. Ground truthing the data indicated this to be an unreliable source for non-native species distribution. Remote sensing imagery was considered, but the information was simply not available for most of the sites. An expert-derived WikiMapping (http://wikimapping.com/) exercise was attempted to source information from individuals throughout the IOSEA region but had very low levels of participation. Some data contributions were made and these were used to inform data for the relevant sites but was limited. Finally, the user-posted images on Google Earth (Pro 7.3.0.3832) Panoromio were most useful (e.g. **Figure 3.1**). Users upload geotagged images, which allowed for identifying *Casuarina* presence as well as extent along the back-beach, but no species identification was possible.

Only native vs non-native *Casuarina* presence and absence information was indicated with no assumptions about the species or impact on each of the different nesting beaches. Beaches were therefore defined according to *Casuarina* presence and origin with no quantitative assumptions made about impact for the different study sites. The purpose of indicating non-native *Casuarina* presence was to support the removal of invasive trees for beaches that are highlighted as highly vulnerable to erosion by the study outcome.

Figure 3.1: Panoramio images for Farquhar island (SC52) from Google Earth Pro 7.3.0.3832. The images indicate Casuarina *presence on a local scale (per nesting beach).*

3.2.3 CVI – Coastal Vulnerability Index assessment

The CVI method was used to calculate vulnerability as a measure of *risk* vs. *threat*. To calculate *risk* and *threat* indices, CVI variables were adapted. New score variables to interpret these metrics (for risk and threat) needed to be developed. To develop score categories per variable, a training data set published by Defeo and McLachlan (2013) was used (**Figure 3.2**). This training data set provided a representative global set of beaches (n= > 200) with comprehensive beach information available, from which score categories for variables could be developed. Scores were then applied to the study sites/sea turtle nesting beaches. If data could not be obtained for an indicator at certain sites, that datum was indicated as data deficient and, following Wallace et al. (2011), received the highest score of that category.

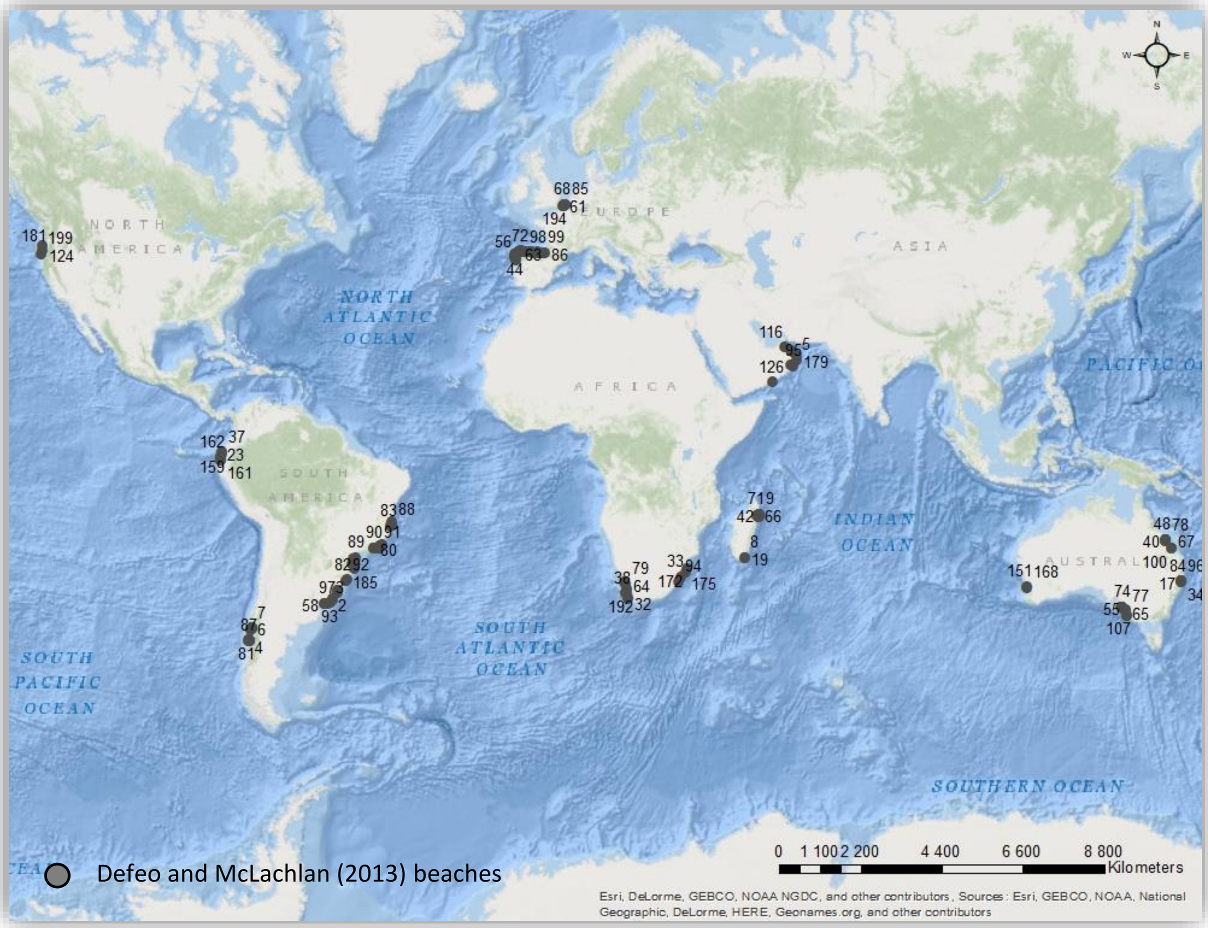


Figure 3.2: Distribution of the beaches used in the training data set published by Defeo and McLachlan (2013) (n= >200) to develop new risk/threat score categories. For a full list of the training data set beaches, refer to Appendix 3.1: Training data set.

A) Risk indicators

1. Back-beach width (BBW)

Following Rizzo et al. (2017) who highlighted dry beach width as an indicator of erosion, Google Earth (Pro 7.3.0.3832) was used to measure back-beach width in metres on the training data set. Back-beach width was defined as the section between the normal/modal high tide drift line and the edge of high shore structures, be it primary dunes or developments. Three measurements were taken for BBW, one in the middle, and two at the far sides of the beach and an average per beach was calculated. This was done irrespective of beach shape and beach length. A total of 204 mean measurements were taken across the beaches of the training data set and the distribution of the back-beach width values were plotted and the 20th, 40th, 60th, 80th and 100th percentiles provided the score categories (see **Appendix 3.2: Criteria and category development: Back-beach width** and **Table 3.5** for width criteria used). BBW scores were allocated to the study sites, where back-beach width values < 20th percentile (or 0 – 9 m wide) were given a score of five (high risk) and values > 80th percentile (>26 m wide) were allocated a score of one (low risk).

2. Orientation and protection

A number of studies (Bryan et al. 2001, Mclaughlin and Cooper 2010, Goodhue et al. 2012) highlighted the importance of wave exposure as an erosion risk indicator, so beach orientation/exposure was calculated for each nesting beach. Beach orientation and protection were characterised using current and historical aerial imagery on Google Earth (Pro 7.3.0.3832) and comprised of surf-zone width, image entropy, pressure of protective structures and estimated wave direction. Each was defined as:

- Surf-zone width: The higher the number of waves in the surf, the more exposed a beach is.
- Image entropy (image complexity): Indicators of disrupted water flow like choppy waters, white foam canopies, presence of rip currents or side currents etc.
- Protective structures: Any geomorphological structures like rocky outcrops or reefs, or man-made structures like harbours or groins that may shelter the beach from waves.
- Wave direction/beach orientation: The average wave direction across a week's predictions (with eight predictions per day) on Windy (www.windy.com) were considered to rate exposure of the beach to waves. Wave direction is more stable than wind direction and a week's response considered adequate following ground-truthing against known sites.

Scores for beach orientation and protection (in **Table 3.1**) were obtained from Harris (2012) and ranged from sheltered, calm beach obtaining a score of zero to shores facing into oncoming waves with wide surf zones with multiple breakers in the surf, with no shoreward protection, and with substructure suggesting currents or reef/bars scoring a value of 4. Half values were assigned if only part of the criteria was met. Where multiple beaches made up the sea turtle nesting habitat, i.e. for 22 sites, including 21 islands and one coastal area (multiple nesting beaches of Ras al Had, Oman), each beach's orientation and protection was rated and the average exposure for the island or coastal area was calculated.

Table 3.1: Orientation and protection score criteria adapted from Harris (2012)

Score	Classification
0	completely sheltered (*e.g.*, blocked by a rocky reef or breakwater)
1	sheltered
2	semi-exposed, more sheltered than exposed
3	semi-exposed, more exposed than sheltered
4	fully exposed

3. Modal Beach Energy

Most indices of erosion combine some metric of wave height with tide range to calculate a risk indicator (Gornitz et al. 1994, McLaughlin et al. 2002, Boruff et al. 2005, Abuodha and Woodroffe 2006, Kumar et al. 2010, Özyurt and Ergin 2010). Instead of simply using wave height and tide range, wind speed was added as a factor, because of the physical impact on the back shore. *Modal beach energy*, was therefore developed from the wave height, wind speed, and tide range score. Data per beach were generated from the predicted wave height and wind speeds from Windy (www.windy.com) for 30 (haphazardly selected) days over a year with eight recordings per day, (n = 240 per beach). The modal wind speed (knots) and wave height (m) value per beach was calculated.

Wave height, wind speed and tide range were first scored separately using existing published scales. Wave height was scored using the Douglas Sea Scale ratings (**Table 3.2**). The Beaufort scale was used to score wind speed (**Table 3.3**). Tide range was obtained from a map of global tide ranges by Davies (1980) modified by Masselink and Hughes (2003) (**Figure 3.3**). Tide range was scored according to Gornitz et al. (1994), where micro-tide range environments (tide = < 2 m) were allocated a score of one (low risk), meso-tide range environments (tide = 2-4 m) received a score of two (moderate risk) and macro-tide range environments (> 4 m) received a score of three (high risk). To create a final score out of 24, the three categories of modal beach energy were added, i.e. Modal beach energy = Wind speed score + Wave height score + Tide range score.

Table 3.2: The Douglas Sea Scale (Met Office 2017)

Douglas Sea Scale Score	Wave height (m)	Wave condition
0	No waves	Calm (glossy)
1	0 – 0.1	Calm (rippled)
2	0.1 – 0.5	Smooth
3	0.5 – 1.25	Slight
4	1.25 – 2.5	Moderate
5	2.5 – 4	Rough
6	4 – 6	Very rough
7	6 – 9	High
8	9 – 14	Very high
9	>14	Phenomenal

Table 3.3: The Beaufort wind force scale (Met Office 2017; Royal Meteorological Society, 2017)

Beaufort Scale Score	Wind speed (knots)	Wind condition
0	1 <	Calm
1	1 – 3	Light air
2	4 – 6	Light breeze
3	7 – 10	Gentle breeze
4	11 – 16	Moderate
5	17 – 21	Fresh breeze
6	22 – 27	Strong breeze
7	28 – 33	Moderate gale
8	34 – 40	Fresh gale
9	41 – 47	Strong gale
10	48 – 55	Whole gale
11	56 – 65	Storm
12	> 65	Hurricane

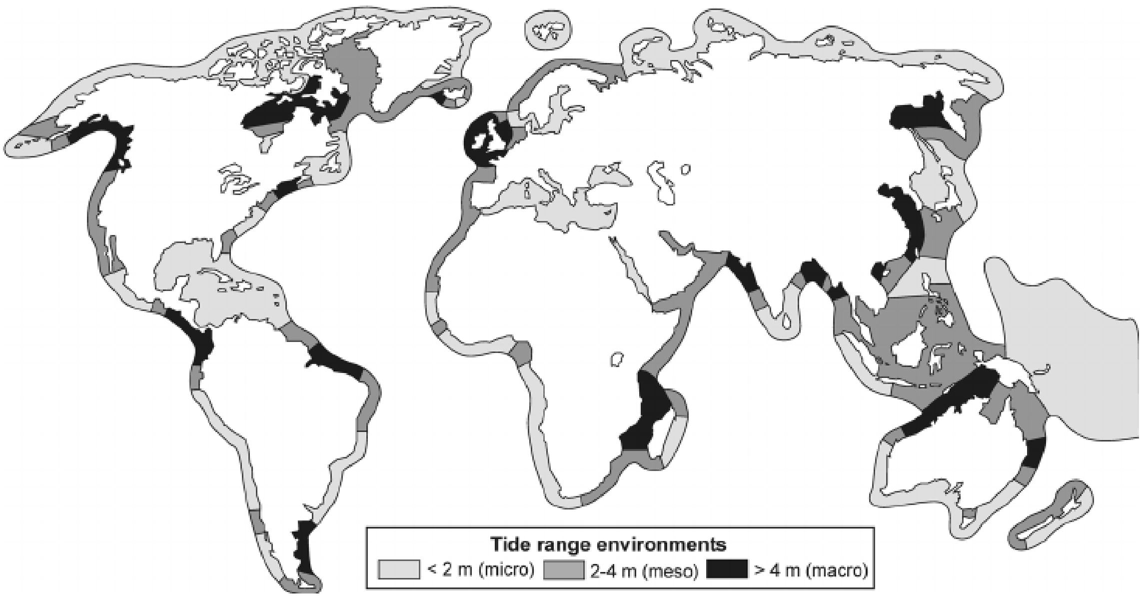


Figure 3.3: Global variation in tidal range (Davies 1980, modified by Masselink and Hughes 2003)

4. State of the dune system

CVI studies typically include dune systems, particularly dune height, as a risk indicator of erosion, (Abuodha and Woodroffe 2006). Coastlines with an intact dune systems have a low risk/susceptibility to erosion (Benassai et al. 2015; Rizzo et al. 2017) as do dunes with multiple sand dune ridges (Mclaughlin and Cooper 2010). Beaches with single sand dune ridges/gravel and boulder ridges and beaches with no dunes/mudflat/saltmarsh however have a higher susceptibility to erosion (Mclaughlin and Cooper 2010). In accordance with the Mclaughlin and Cooper (2010) ranking for dunes, beaches with multiple sand dune ridges were as low risk (score = one), beaches with a single sand dune ridge were scored two (moderate risk) and beaches with no dunes/developed dunes were scored three (high risk) (**Table 3.5**).

B) Threat indicators

I. Coastal development

Coastal development poses a threat to the integrity of the dune system (Benassai et al. 2015, Rizzo et al. 2017) and was identified as any human alteration of the back-beach, foredune and secondary dune. Any buildings or other hard structures such as sea walls, loffelstein blocks, dolosse/rubble, harbour breakwaters, tourism amenities, roads, and rocks, that are visible on Google Earth Pro 7.3.0.3832 imagery were used to score the extent of coastal development following Harris (2008). The categories were adapted to generate three different classification values; location (or position) of development across the beach, intensity (or density) of development, and longshore extent of the development. Each class was attributed a value from 0 – 3 according to the criteria in **Table 3.4**. The final score was calculated as the sum of the three classifications (location, intensity and extent) giving a final score out of nine.

Table 3.4: The characteristics of the back-beach and coastal development that was used to get an overall risk score for development

Classification	Score/Code	Description
Location of development	(0) None	No development present or the development is far away, i.e. not on the back-beach, foredune or secondary dune
	(1) Secondary dune	Development located anywhere on the secondary dune
	(2) Foredune	Development located anywhere on the foredune
	(3) Back-beach	Immediately behind the backshore beach
Intensity of development	(0) None	No development present or the development is far away, i.e. not on the back-beach, foredune, seconday
	(1) Low	Much higher proportion of vegetion compared to development
	(2) Medium	Patchy development with approximately equal proportions of natural vegetation and development
	(3) High	Many buildings located very close to one another such that only very small pathces of natural vegetation are present. May include hard armouring as well, such as: sea wall; loffelstein; dolosse/rubble; harbour breakwaters; tourism amenities; road; and rock.
Extent of development	(0) None	No development present or the development is far away, i.e. not on the back-beach, foredune, secondary
	(1) 1/3	Development covers approximately 1/3 of the beach extent
	(2) 2/3	Development covers approximately 2/3 of the beach extent
	(3) 3/3	Development covers approximately 3/3 of the beach extent

II. Sea level rise (SLR)

Feagin et al. (2005) emphasized the vulnerability of coastal dunes to shoreline erosion and retreat because of sea level rise. Rising sea levels are thus a primary driver of potential coastal erosion (Pethick 2001, Corbella and Stretch 2012) and has been included in almost all CVI studies (**APPENDIX 1: Table 0.1**). The IPCC Fifth Assessment Report 2014 used about 50 models to evaluate scenarios of sea level rise, and the CSIRO ACESS1.0 Coupled Model Intercomparison Project Phase 5 (CMIP5) model was chosen for the current study to model sea level rise estimates, because it provides consistent estimates across different regions, and in time (IPCC 2014). Representative concentration pathways (RCPs) are used to project future anthropogenic greenhouse gas emissions (GHG) and atmospheric concentrations. See IPCC 2014 report for details. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one extreme (but realistic) scenario with very high GHG emissions (RCP8.5), which portrays current global rate of GHG emission. RCPs 4.5 and 8.5 were selected to model sea level rise.

Two variables were extracted, “zos” and “zosga”. “Zos” provided an estimate of sea level at any point in space/time relative to the ocean geoid (i.e., a value relative to mean global sea level), “Zosga” provided estimates of average global sea-level rise. Adding the two variables together provided an estimate of the sea level into the future for individual points of interest. Monthly estimates between 2006 and 2100 were extracted for each of the training data set beaches, within a 1º x 1º grid. A bilinear interpolation along the x- and y-axes among adjacent grid cells were used to obtain an estimate at the point of interest, rather than assuming the sea-level response is the same across the entire grid cell. Mean sea level rise was estimated from 2020 to 2100 for the two scenarios RCP 4.5 and 8.5, and the average of the two scenarios obtained. Threshold values assigned scores for the 20th, 40th, 60th, 80th and 100th percentile for the training data set (n= 204) (**APPENDIX 3.2: Criteria and category development: Sea level rise**). These scores were then applied to the SLR values estimated in the same way for the turtle nesting beaches. Sea level rise values < 20th percentile (0.33 – 0.36 m by 2100) were scored as a low threat (score = one) and values > 80th percentile (> 0.48 m) were allocated a score of five as a high threat (**Table 3.5**). On this basis, sea-level rise estimates were calculated for the 50 turtle nesting beaches, and scored a value between 1 – 5.

III. Storminess

Considering the inconsistencies of storm projection models at a coarse scale (global models) (IPCC 2007), the study used historical storm track data for the last 170 years with the assumption that conditions will be similar over the next 80 years. The International Best Track Archive for Climate Stewardship (IBTrACS) Version 3 dataset from the NOAA National Climatic Data Center (data.noaa.gov) was used to assess storm effects. The IBTrACS dataset contains comprehensive track information from over 10 international forecast centres. The dataset reports the position, maximum sustained winds, minimum central pressure, and storm nature for every tropical cyclone recorded globally at 6-hr intervals in UTC (Coordinated Universal Time). Statistics are also provided such as number of centres tracking the storm, range in pressure, median wind speed, etc. The dataset period is from 1848 to 2018. Because of the resolution of the data, both storm frequency and intensity scores were estimated.

Storm frequency

After downloading the IBTrACS ver. 3 dataset shapefile, from the NOAA National Climatic Data Center (data.noaa.gov), storm frequency was calculated from the storm tracks as line features in ArcMap 10.5.1. With a Cylindrical Equal Area projection, the line density tool was used to calculate a magnitude-per-square kilometre for the storm tracks that fell within a specified radius around each cell. The output cell size was 250 km^2 and the default radius from the line density tool was used. Storm track density was therefore calculated at a sub-regional level as a likely indication of storm frequency.

The storm track density (per km^2) for the study sites were extracted from the line density raster using the ‘extract to table’ tool in ArcMap 10.5.1. The training data set could not be used to score storm track density values per nesting beach, as most sampled beaches (> 150 beaches) fell outside of storm ranges. Sea turtle nesting beach storm density values were therefore scored according to the nine equal interval categories presented by the line density output tool and not according to the training data set percentile ranges (**APPENDIX 3.2: Criteria and category development: Storminess**). Line density values lower than 0.208 were give a low score (0 – 2), while values between 0.208 – 0.416 were scored as moderate (3 - 5) and line density values higher than 0.416 were scored high (6- 9) (**Table 3.5**).

Storm intensity

Storm intensity was calculated from the IBTrACS ver. 3 dataset shapefile (data.noaa.gov). In ArcMap 10.5.1, storm intensity values were obtained using ‘feature to raster’ tool; a storm intensity raster layer with maximum sustained wind speed (knots) per 250 km^2 was created and the ‘extract to table’ tool, was used to generate a table of the storm intensity for the study sites were extracted. Similar to storm frequency, the training data set could not be used to score storm intensity per nesting beach, as most sampled beaches (> 150 beaches) fell outside of storm ranges. Sea turtle nesting beach storm intensity was therefore scored according to the nine equal interval categories presented by the feature to raster output tool and not according to the training data set percentile ranges (**APPENDIX 3: Criteria and category development: Storminess**). Maximum sustained wind speeds lower than 58 knots were give a low score (0 – 2), while values between 58 – 107 knots were scored as moderate (3 -5) and wind speed higher than 107 knots were scored high (6- 9) (**Table 3.5**).

Table 3.5: Scoring categories for various indicators

Beach vulnerability			
Risk Indictors	**Score**	**Threat Indicators**	**Score**
1) Back beach width *Based on the width from the high tide line to the foot of the primary dune or the first line of coastal development*	**1** = > 26 m **2** = 18 - 26 m **3** = 12 - 18 m **4** = 9 - 12 m **5** = 0 -9 m	**1) Projected sea level rise** *Average increase from the 2020's to the 2090's for both the 4.5 and 8.5 RCP scenarios*	**1** = 0.33 - 0.36 m **2** = 0.36 - 0.38 m **3** = 0.38 - 0.40 m **4** = 0.40 - 0.48 m **5** = > 0.48 m
2) Beach exposure *Based on surfzone entropy, geomorphological or other structures that may offer shelter and wave direction*	**0** = completely sheltered (blocked by a rocky reef or breakwater) **1** = sheltered **2** = semi-exposed, more sheltered than exposed **3** = semi-exposed, more exposed than sheltered **4** = fully exposed	**2) Storm frequency** *Storm frequency refers to line density of the NOAA archived storm track data (1848 to 2018) per km^2 (line density tool ArcMap 10.5.1)*	**0** = 0 **1** = < 0.69 **2** = 0.069 - 0.139 **3** = 0.139 - 0.208 **4** = 0.208 - 0.277 **5** = 0.277 - 0.347 **6** = 0.347 - 0.416 **7** = 0.416 - 0.486 **8** = 0.486 - 0.554 **9** = 0.554 - 0.624
3) Modal Beach energy *Based on the sum of the modal wave height, wind speed and tidal range*	**Waves** **0** = Calm (No waves) **1** = Calm (Ripples, 0 – 0.1 m) **2** = Smooth (0.1 – 0.5 m) **3** = Slight (0.5 – 1.25 m) **4** = Moderate (1.25 – 2.5 m) **5** = Rough (2.5 – 4 m) **6** = Very rough (4 – 6 m) **7** = High (6 – 9 m) **8** = Very High (9 – 14 m) **9** = Phenomenal (>14 m)	**3) Storm intensity** *Storm intensity refers to the maximum sustained winds (knots) extracted per km^2 from the NOAA archived strom track data (1848 to 2018)*	**0** = 0 **1** = 10 - 26 knots **2** = 26 - 42 knots **3** = 42 - 58 knots **4** = 58 - 74 knots **5** = 74 - 91 knots **6** = 91 - 107 knots **7** = 107 - 123 knots **8** = 123 - 139 knots **9** = 139 - 155 knots
	Wind **0** = Calm (< 1 knots) **1** = Light air (1 – 3 knots) **2** = Light breeze (4 – 6 knots) **3** = Gentle breeze (7 – 10 knots) **4** = Moderate (11 – 16 knots) **5** = Fresh breeze (17 – 21 knots) **6** = Strong breeze (22 – 27) **7** = Moderate gale (28 – 33 knots) **8** = Fresh gale (34 – 40 knots) **9** = Strong gale (41 – 47 knots) **10** = Whole gale (48 – 55 knots) **11** = Storm (56 – 65 knots) **12** = Hurricane (>65 knots)	**4) Coastal development** *Based on location, intensity and extent.*	**Location of development** **0** = None **1** = Secondary dune **2** = Foredune **3** = Back beach **Intensity of development** **0** = None **1** = Low **2** = Moderate **3** = High **Extent of development** **0** = None **1** = 1/3 **2** = 2/3 **3** = 3/3
	Tide 1 = micro-tidal (<2 m) 2 = meso-tidal (2-4 m) 3 = macro-tidal (>4 m)		
4) State of the dunes system *Based on the condition of the dune system*	1= multiple sand dune ridges 2= single sand dune ridge 3= developed or no dunes		

Calculating coastal vulnerability

Vulnerability was expressed as a measure of Risk (back-beach width, beach orientation and protection, modal beach energy and state of the dune system) and Threat (coastal development, future sea level rise, storm frequency and storm intensity). All Risk and Threat indicator variables were scored as per **Table 3.5**. Following Mclaughlin and Cooper (2010) and Benassai et al. (2015) no weights were applied to the variables in order to avoid subjective assessment. All scores for each indicator were ***normalized*** to give a value between ***zero*** and ***one*** (i.e. allocated score was divided by the total score of that category) and beach vulnerability was visualised by plotting the sum of normalized scores for risk variables (x-axis) against the sum of normalized scores for threat variables (y-axis). Scores fell within one of four quadrants that corresponded to four management prioritisation categories: 1) High Risk-High Threat; 2) High Risk-Low Threat; 3) Low Risk-Low Threat; 4) Low Risk-High Threat.

3.2.4 Difference in erosion vulnerability in the presence of *Casuarina*

To determine significant difference of vulnerability scores in the presence vs. absence of *Casuarina* trees, a two-sample t-Test assuming unequal variance was conducted; There were 18 beaches with and 32 beaches without *Casuarina*.

3.3 RESULTS

3.3.1 Study sites

Selected study sites included eight loggerhead (*Caretta caretta)*, seven green turtle (*Chelonia mydas)*, eight leatherback (*Dermochelys coriacea)*, nine hawksbill (*Eretmochelys imbricata)*, eleven olive ridley (*Lepidochelys olivacea)* and seven flatback (*Natator depressus)* nesting beaches (**Figure 3.4**). The map indicates strong regional biases for two nesting species, with flatback (*Natator depressus)* nesting exclusively in Australia and olive ridley (*Lepidochelys olivacea)* turtle nesting mainly along the east coast of India. Nesting sites for loggerhead (*Caretta caretta)*, green (*Chelonia mydas)*, hawksbill (*Eretmochelys imbricata)*, and leatherback (*Dermochelys coriacea)* turtles occurred across the Indian Ocean.

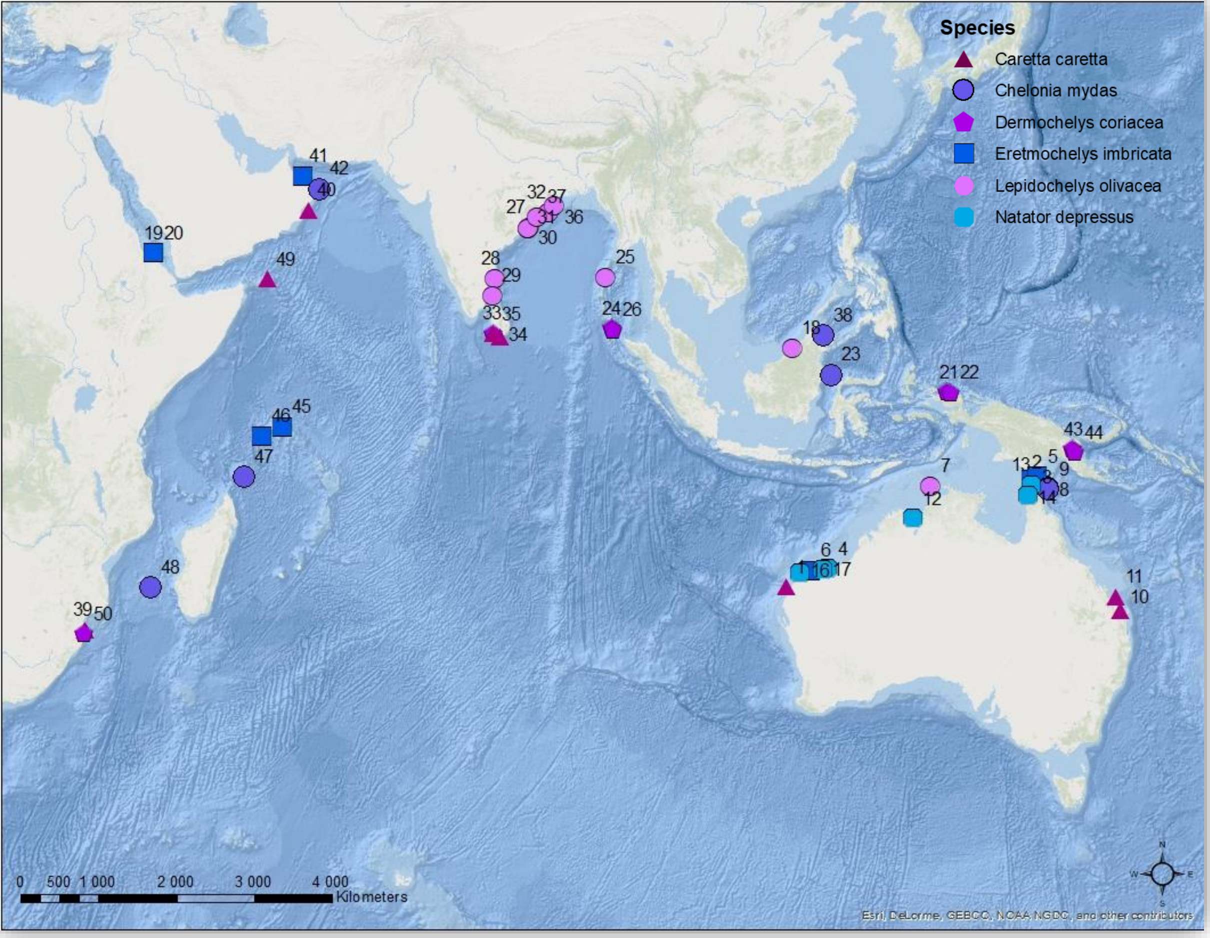
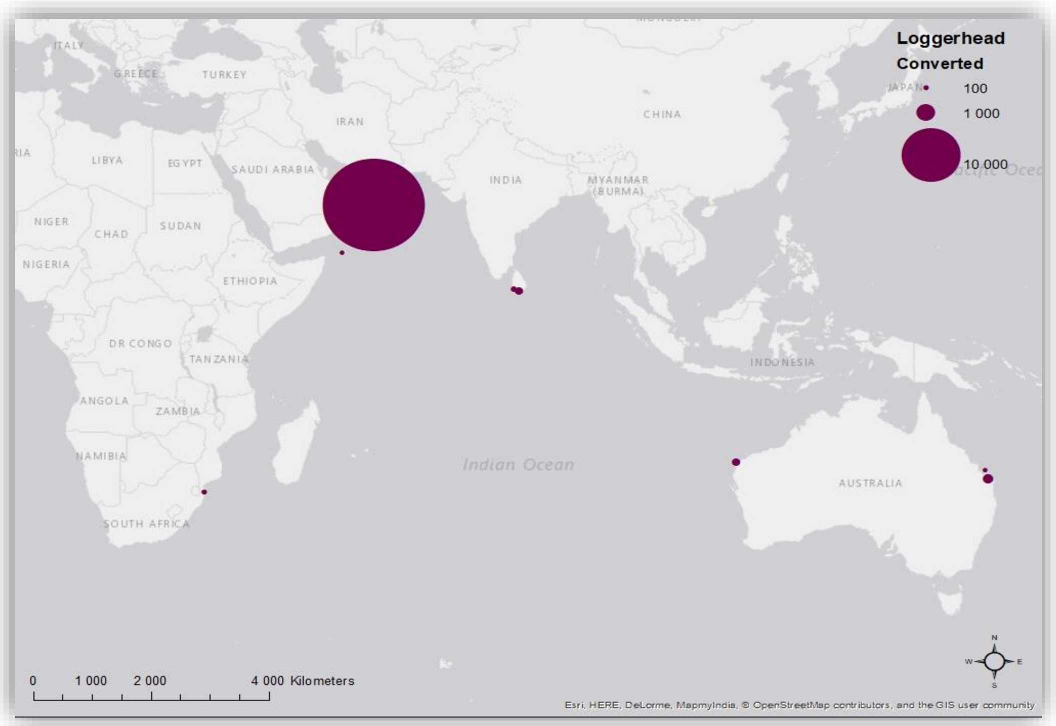


*Figure 3.4: Location of the 50 study sites (sea turtle nesting beaches). The colour and symbol represents the sea turtle species indicated in the map legend. The study sites are labelled with numbers corresponding to the site names in **Appendix 1: Study sites/sea turtle nesting beaches**. For species specific maps refer to figures below (**Figures 3. 5 – 10**).*



Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 3.5: Female nesting abundance for the Caretta caretta *nesting beaches. The highest* Caretta caretta *nesting female abundances occur on Masirah Island (OM02/#40), Oman*

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*Figure 3.6: Female nesting abundance for the green turtle (*Chelonia mydas*) nesting beaches. The highest Chelonia mydas nesting female abundances occur on Raine Island (AU309/#9), Australia.*

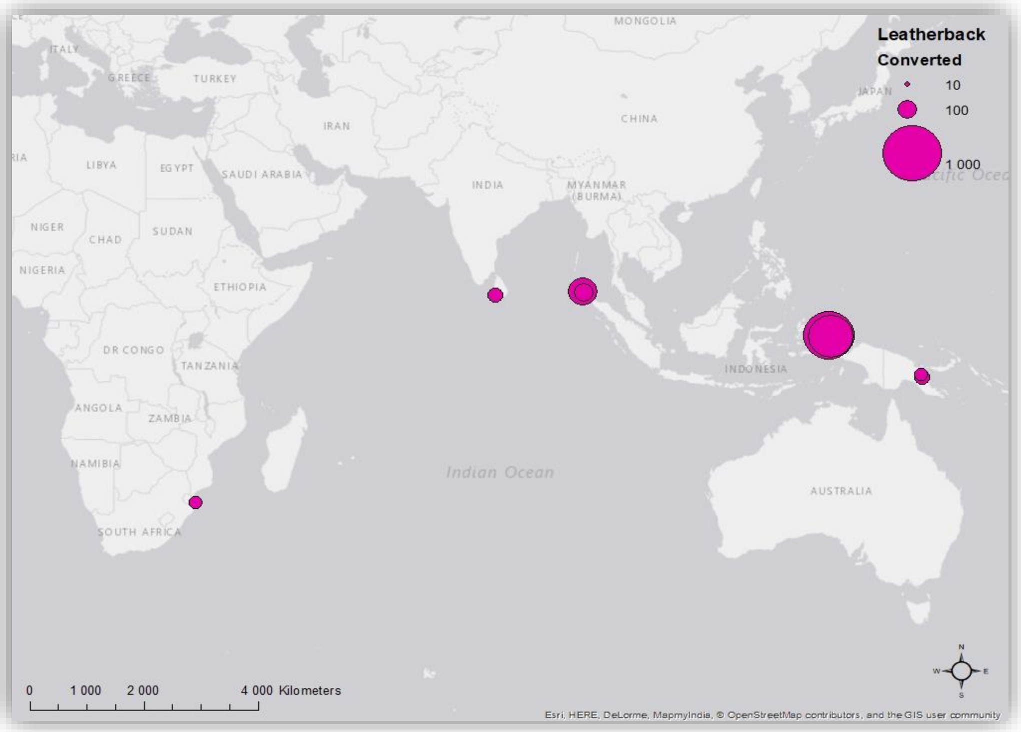


*Figure 3.7: Female nesting abundance for the leatherback (*Dermochelys coriacea*) nesting beaches. The highest* Dermochelys coriacea *nesting female abundances occur on the Jamursba Medi (ID02/#22), Indonesia.*

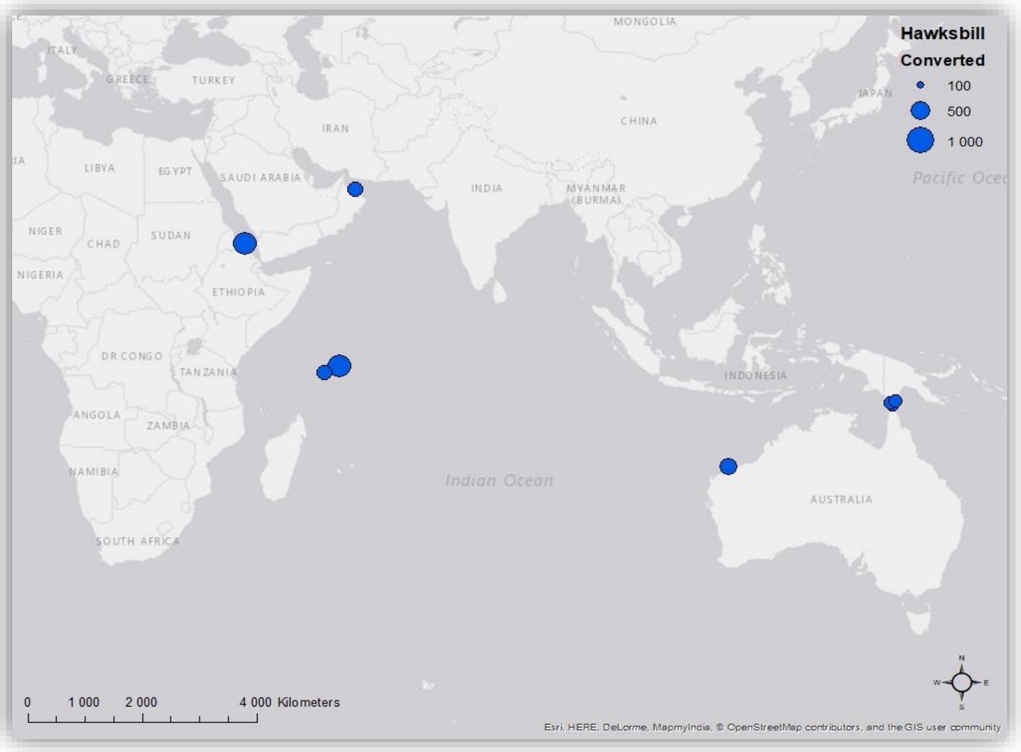


*Figure 3.8: Female nesting abundance for the hawksbill (*Eretmochelys imbricata*) nesting beaches. The highest* Eretmochelys imbricata *nesting female abundances occur on Dalmaniyat Island (OM11/#41), Oman.*

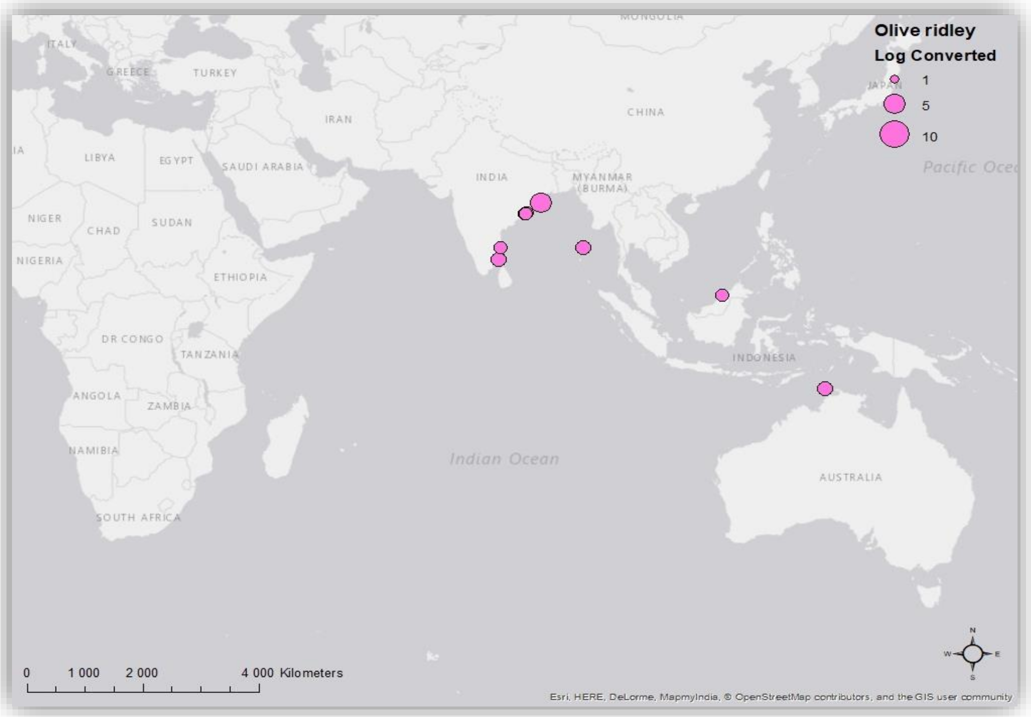


*Figure 3.9: Female nesting abundance for the olive ridley (*Lepidochelys olivacea*) nesting beaches. For mapping purposes nest abundances had to be log transformed to accommodate the high abundances of olive ridley nesting females. The highest* Lepidochelys olivacea *nesting female abundance occur at the Devi river mouth (IN76/#32), including the Rushikulya, Gahirmatha Rivers, Orissa, India, where between 150 000 – 200 000 nest annually*

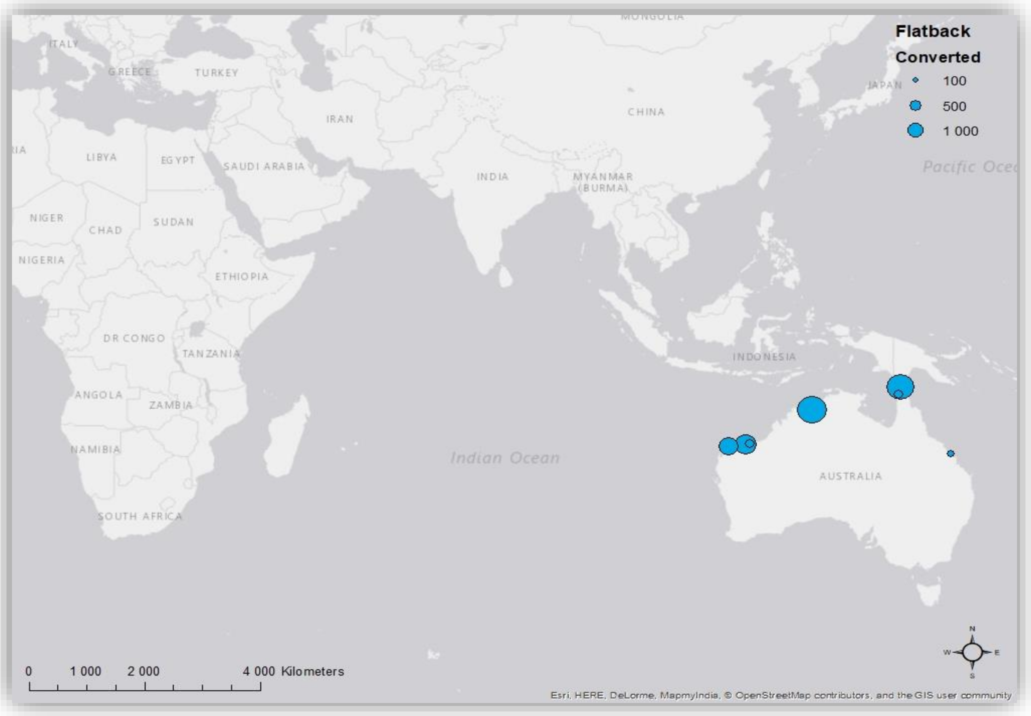


*Figure 3.10: Female nesting abundance for the flatback (*Natator depressus*) nesting beaches. The highest* Natator depressus *nesting female abundances occur at the Cape Domett beach (AU39/#12), Australia.*

3.3.2 *Casuarina* distribution

Casuarina species were present on 18 of the 50 turtle sites (**Figure 3.11**); four of these beaches had native *Casuarina* species including a site in Brunei (BNX/#11), one in Indonesia (ID02/#21) and two Australian sites (AU34/#11, AU70/#13). The 14 beaches with non-native/introduced *Casuarina* species occurred along the east coast of India and the (French) Scattered Islands north and west of Madagascar, as well as several Seychellois islands, and the South African rookery. One site in Sri Lanka, i.e., Rekawa (LK05/# 34), had a few introduced *Casuarina* covering less than 25% of the back-beach. The seven sites in India, namely Devi river mouth (IN76/#32), Gahirmatha (Murali_01/#36), Kalingapatnam (IN102/#27), Mamallapuram (IN126/#28), Nagapattinam (IN137/#29), Rushikulya (Murali_02/#37), Srikakulam (IN200/#31) and Srikurmam (IN180/#30), had extensive *Casuarina* strips covering more than 25% of the back-beach, very close to the high tide line (e.g. **Figure 3.12**).

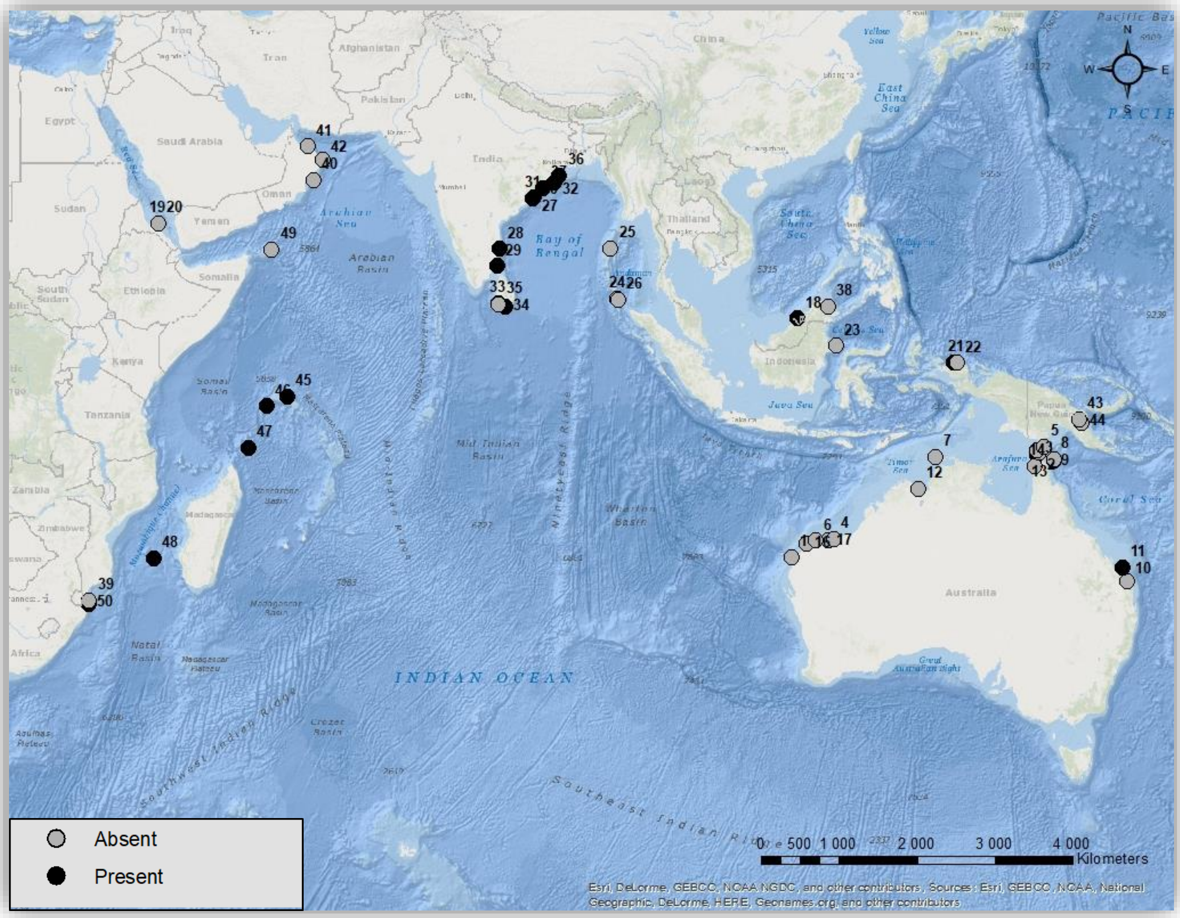


Figure 3.11: Casuarina *presence for the study sites/nesting beaches.*

Figure 3.12: Left: Rushikulya beach (Murali_02/#37) with extensive C. equisetifolia *plantations on the back-beach (IOSEA website: http://www.ioseaturtles.org). Right:* Lepidochelys olivacea *arribada on a beach in Orissa, India, with the backshore dominated by* Casuarina *trees (Photo: Kartik Shanker).*

Non-native *Casuarina* occurrence was extensive on two of the Seychelles study sites: Cousin Island Special Reserve (SC08/#45) and Farquhar Island (SC52/#47). Photos and Google Earth imagery show *Casuarina* were present directly on the back-beach for substantial portions of these two islands. For a full list of the study sites and their *Casuarina* presence/absence, refer to **Table 3.6**.

3.3.3 CVI – Coastal Vulnerability Impact Assessment

The risk and threat data are summarized in **Table 3.6** and **Table 3.7**. Note that these are the data per beach to which the allocation of scores were applied. Beach orientation and protection risk, as well as the development (threat) had no quantitative data and were directly allocated a score based on qualitative observations from Google Earth.

A) Risk indicators

1. Back-beach width

To score back-beach width for the sea turtle nesting beaches, score categories were created from the global training data set. Where back-beach width of the training data set range from approximately 9 to a 100 m (**Appendix 3.2**), the back-beach width of the sea turtle nesting beaches is extremely uniform as the majority of the beaches have a back-beach width smaller than 9 m (narrow back-beach) and were allocated a high-risk score (score = 5). The back-beach widths of the study sites ranged from 3.1 m to 107 m and median BBW was 13.9 m. The narrowest back-beach of approximately 3.1 m, was measured on a lower energy island beach off the coast on Turtle Islands, Sabah Malaysia (MY02/#38), while the widest recorded back-beach width of 106.9 m, was recorded on a higher energy beach in India, Kalingapatnam/Vamsadhara (IN102/#27). The widest back-beaches (> 26 m) (score = 1) were prevalent in the northern Indian Ocean, mainly including the beaches of the east coast of India and Oman (**Figure 3.13**). A few sites in northern Queensland (Australia) and western Australia also had wide back-beaches, but most of the Australian sites had narrow back-beaches.

Table 3.6: Risk indicator data per beach. The colour code per beach represents the final vulnerability score (low to high vulnerability) allocated for each beach as a measure of risk vs. threat. Green indicates low risk, orange indicates moderate risk and red indicates high risk.

Site ID	Beaches	Species	*Casuarina* presence	Risk Indicators									
				BBW (m)	Orientation and protection ratings					Modal beach energy			Dunes
					Sufzone	*Image entropy*	*Protection*	*Wave exposure*	*Final Score*	*Wind speed (knots)*	*Wave height (m)*	*Tide range*	
AU08	Bungelup	*Cc*	Absent	5.5	0	1.5	2.5	2	1.5	11	1.1	2-4 (meso)	Multiple
AU10	Dayman Island	*Ei*	Absent	8.4	0	1.5	2.5	2	1.5	11	0.1	2-4 (meso)	DD
AU11	Hawkesbury (Warral) Island	*Ei*	Absent	25.6	0	1	2	1	1	20	1	2-4 (meso)	None
AU119	Cemetery Beach	*Nd*	Absent	4.1	1	1.5	2.5	3	2	10	0.5	> 4 (macro)	Single
AU15	Long Island	*Ei*	Absent	7.3	1	1.5	2	1.5	1.5	20	1.1	2-4 (meso)	None
AU27	Rosemary Island	*Ei*	Absent	5.7	1	1	1	1	1	7	0.4	> 4 (macro)	Multiple
AU284	Cape Van Diemen	*Lo*	Absent	DD	DD	DD	2	2	2	10	0.5	> 4 (macro)	Single
AU300	Moulter Cay, north Great Barrier Reef	*Cm*	Absent	26.2	0	1	2	1	1	21	1.9	2-4 (meso)	None
AU309	Raine Island, north Great Barrier Reef	*Cm*	Absent	44.7	0	1	2	1	1	23	1.8	2-4 (meso)	None
AU33	Woongarra coast including Mon Repos	*Cc*	Absent	9.1	1.5	1.5	2.5	2.5	2	11	0.5	> 4 (macro)	Single
AU34	Wreck Island	*Cc*	Present**Native*	6.4	1	1	1	1	1	11	0.7	> 4 (macro)	None
AU39	Cape Domett	*Nd*	Absent	10.0	3	3.5	3.5	4	3.5	9	0.3	> 4 (macro)	Single
AU70	Crab Island	*Nd*	Present**Native*	52.9	1	1	1	1	1	12	0.4	2-4 (meso)	Single
AU71	Flinders Beach	*Nd*	Absent	15.8	1.5	2.5	2.5	3.5	2.5	10	0.2	2-4 (meso)	Single
AU80	Wild Duck	*Nd*	Absent	19.5	0	0	1	1	0.5	12	0.4	2-4 (meso)	Single
AU81	Barrow Island	*Nd*	Absent	28.1	2	2.5	2	1.5	2	10	0.5	2-4 (meso)	Multiple
AU82	Mundabullangana Beach	*Nd*	Absent	10.1	1.5	2	3	3.5	2.5	5	0.2	> 4 (macro)	Multiple
BNX	Brunei	*Lo*	Present **C.glauca* exotic **C.equisetifolia* native	15.1	3	3	4	4	3.5	4	0.3	2-4 (meso)	None
ER01	Aucan Island	*Ei*	Absent	8.1	0	1	1.5	1.5	1	9	0.3	< 2 (micro)	Multiple
ER02	Mojeidi Island	*Ei*	Absent	8.6	1.5	1.5	1.5	1.5	1.5	8	0.3	< 2 (micro)	Multiple
ID02	Jamursba Medi	*Dc*	Present**Native*	13.9	3	3	4	4	3.5	3	0.6	2-4 (meso)	None
ID14	Warmon	*Dc*	Absent	13.0	4	4	4	4	4	2	0.4	2-4 (meso)	None
ID27	Bilang-Bilangan	*Cm*	Absent	DD	1	1	1	1	1	5	0.3	2-4 (meso)	None
IN02	Beaches straddling the Alexandria and Dagmar Rivers	*Dc*	Absent	8.6	3.5	3	2	3.5	3	6	0.8	2-4 (meso)	Multiple
IN04	Cuthbert Bay	*Lo*	Absent	12.6	2	2	2.5	1.5	2	7	0.3	> 4 (macro)	None
IN05	Galathea Beach, Great Nicobar Island	*Dc*	Absent	7.5	2	2	2.5	1.5	2	10	1.7	2-4 (meso)	None
IN102	Kalingapatnam/Vamsadhara	*Lo*	Present	107.0	3.5	2	2.5	2	2.5	14	1.2	2-4 (meso)	Single
IN126	Mamallapuram - Pondi	*Lo*	Present	13.8	3	3	4	4	3.5	10	0.6	< 2 (micro)	None
IN137	Nagapattinam	*Lo*	Present	20.4	3	3	4	4	3.5	9	0.3	< 2 (micro)	None
IN180	Srikurmam	*Lo*	Present	62.7	4	4	4	4	4	14	1.4	2-4 (meso)	Multiple
IN200	Srikakulam	*Lo*	Present	53.6	4	4	4	4	4	13	1.6	2-4 (meso)	Multiple
IN76	Devi River mouth, Orissa	*Lo*	Present	51.0	1.5	2	2	2.5	2	15	0.8	2-4 (meso)	None
LK02	Bentota	*Dc*	Absent	41.5	4	3	3	4	3.5	8	1.6	< 2 (micro)	None
LK05	Rekawa	*Cc*	Present	28.9	3	3	3	3	3	11	1.3	< 2 (micro)	Single
LK21	Kosgoda	*Cc*	Absent	23.4	3	3	3	3	3	9	1.8	< 2 (micro)	None
Murali_01	Gahirmatha	*Lo*	Present	52.4	3	3	4	4	3.5	DD	DD	> 4 (macro)	Multiple
Murali_02	Rushikulya	*Lo*	Present	34.8	3	2.5	3.5	3	3	DD	DD	2-4 (meso)	Single
MY02	Turtle Islands, Sabah	*Cm*	Absent	3.1	1	1.5	2	1.5	1.5	5	0.2	2-4 (meso)	None
MZ07	Malongane	*Cc*	Absent	26.2	4	4	4	4	4	8	1.3	2-4 (meso)	Single
OM02	Masirah	*Cc*	Absent	41.4	2.5	2.5	1.5	1.5	2	17	0.6	2-4 (meso)	Multiple
OM11	Dalmaniyat	*Ei*	Absent	7.5	0	1.5	1.5	1	1	6	0.3	2-4 (meso)	Multiple
OM12	Ras al Had	*Cm*	Absent	46.5	2.5	2.5	1.5	1.5	2	8	0.5	2-4 (meso)	Multiple
PG02	Busama (Buli)	*Dc*	Absent	5.9	2.5	2.5	3.5	3.5	3	2	0.4	2-4 (meso)	DD
PG04	Kamiali Wildlife Management Area	*Dc*	Absent	4.9	1.5	2.5	3	3	2.5	2	0.3	2-4 (meso)	None
SC08	Cousin Island Special Reserve	*Ei*	Present	9.9	2	3.5	3.5	3	3	12	1.1	2-4 (meso)	None
SC10	D’Arros Island and St. Joseph Atoll	*Ei*	Present	7.0	1.5	1.5	1.5	1.5	1.5	14	1.4	2-4 (meso)	None
SC52	Farquhar Group	*Cm*	Present	9.2	0	0.5	1	0.5	0.5	17	1.9	2-4 (meso)	None
TF03	Europa	*Cm*	Present	9.8	1	1	1	1	1	10	2.1	2-4 (meso) to > 4 (macro)	Single
YE01	Abalhan Protected Area/ Socotra Man and Biosphere Reserve	*Cc*	Absent	17.0	2.5	3	3	3.5	3	4	0.3	2-4 (meso)	Multiple
ZA01	Mabibi to Kosi Lake/Bhanga Nek	*Dc*	Present	20.1	4	4	4		4	8	1.6	2-4 (meso)	Single to multiple

Table 3.7: Threat indicator data per beach. The table is colour coded so that green indicates low threat, orange indicates moderate threat and red indicates high threat. The colour code per beach is the final vulnerability score (low to high vulnerability) allocated for each beach as a measure of risk vs. threat.

Site ID	Beaches	Species	*Casuarina* presence	*Casuarina* presence	Threat Indicators						
					Development				Sea level rise (m)	Storm frequency (line density per km2)	Storm intensity (knots)
					Location	*Intensity*	*Extent*	*Final Score*			
AU08	Bungelup	*Cc*	Absent	Absent	0	0	0	0	0.31	0.036	50
AU10	Dayman Island	*Ei*	Absent	Absent	1	1	1	3	0.35	0.003	20
AU11	Hawkesbury (Warral) Island	*Ei*	Absent	Absent	0	0	0	0	0.34	0.001	15
AU119	Cemetery Beach	*Nd*	Absent	Absent	2	3	3	8	0.31	0.008	50
AU15	Long Island	*Ei*	Absent	Absent	0	0	0	0	0.35	0.000	20
AU27	Rosemary Island	*Ei*	Absent	Absent	0	0	0	0	0.31	0.005	35
AU284	Cape Van Diemen	*Lo*	Absent	Absent	0	0	0	0	0.32	0.136	20
AU300	Moulter Cay, north Great Barrier Reef	*Cm*	Absent	Absent	0	0	0	0	0.36	0.073	20
AU309	Raine Island, north Great Barrier Reef	*Cm*	Absent	Absent	0	0	0	0	0.36	0.003	20
AU33	Woongarra coast including Mon Repos	*Cc*	Absent	Absent	0	0	0	0	0.38	0.048	30
AU34	Wreck Island	*Cc*	Present*_Native_	Present*_Native_	0	0	0	0	0.38	0.087	40
AU39	Cape Domett	*Nd*	Absent	Absent	0	0	0	0	0.32	0.073	20
AU70	Crab Island	*Nd*	Present*_Native_	Present*_Native_	0	0	0	0	0.33	0.085	15
AU71	Flinders Beach	*Nd*	Absent	Absent	0	0	0	0	0.33	0.042	40
AU80	Wild Duck	*Nd*	Absent	Absent	0	1	1	2	0.38	0.014	0
AU81	Barrow Island	*Nd*	Absent	Absent	3	3	1	7	0.31	0.000	35
AU82	Mundabullangana Beach	*Nd*	Absent	Absent	0	0	0	0	0.31	0.000	50
BNX	Brunei	*Lo*	Present *_C.glauca_ exotic *_C.equisetifolia_ native	Present	1	2	3	6	0.33	0.075	0
ER01	Aucan Island	*Ei*	Absent	Absent	0	0	0	0	0.35	0.018	0
ER02	Mojeidi Island	*Ei*	Absent	Absent	0	0	0	0	0.35	0.005	0
ID02	Jamursba Medi	*Dc*	Present*_Native_	Present	0	0	0	0	0.32	0.000	0
ID14	Warmon	*Dc*	Absent	Absent	0	1	1	2	0.32	0.000	0
ID27	Bilang-Bilangan	*Cm*	Absent	Absent	0	1	1	2	0.33	0.073	0
IN02	Beaches straddling the Alexandria and Dagmar Rivers	*Dc*	Absent	Absent	0	0	0	0	0.33	0.002	0
IN04	Cuthbert Bay	*Lo*	Absent	Absent	0	0	0	0	0.34	0.136	25
IN05	Galathea Beach, Great Nicobar Island	*Dc*	Absent	Absent	0	0	0	0	0.33	0.008	0
IN102	Kalingapatnam/Vamsadhara	*Lo*	Present	Present	1	3	2	6	0.33	0.089	27
IN126	Mamallapuram - Pondi	*Lo*	Present	Present	2	2	1	5	0.33	0.136	45
IN137	Nagapattinam	*Lo*	Present	Present	2	2	1	5	0.31	0.136	35
IN180	Srikurmam	*Lo*	Present	Present	0	0	0	0	0.33	0.030	27
IN200	Srikakulam	*Lo*	Present	Present	0	0	0	0	0.33	0.055	27
IN76	Devi River mouth, Orissa	*Lo*	Present	Present	0	0	0	0	0.34	0.088	55
LK02	Bentota	*Dc*	Absent	Absent	2	3	3	8	0.32	0.000	35
LK05	Rekawa	*Cc*	Present	Present	3	3	1	7	0.35	0.048	25
LK21	Kosgoda	*Cc*	Absent	Absent	2	2	2	6	0.31	0.036	25
Murali_01	Gahirmatha	*Lo*	Present	Present	0	0	0	0	0.34	0.011	25
Murali_02	Rushikulya	*Lo*	Present	Present	0	0	0	0	0.33	0.011	27
MY02	Turtle Islands, Sabah	*Cm*	Absent	Absent	2	1	1	4	0.33	0.073	0
MZ07	Malongane	*Cc*	Absent	Absent	1	1	1	3	0.33	0.036	30
OM02	Masirah	*Cc*	Absent	Absent	3	2	1	6	0.34	0.080	45
OM11	Dalmaniyat	*Ei*	Absent	Absent	0	1	1	2	0.35	0.005	77
OM12	Ras al Had	*Cm*	Absent	Absent	2	1	1	4	0.34	0.011	77
PG02	Busama (Buli)	*Dc*	Absent	Absent	0	0	0	0	0.34	0.008	0
PG04	Kamiali Wildlife Management Area	*Dc*	Absent	Absent	1	1	1	3	0.35	0.019	25
SC08	Cousin Island Special Reserve	*Ei*	Present	Present	1	1	1	3	0.33	0.032	35
SC10	D'Arros Island and St. Joseph Atoll	*Ei*	Present	Present	2	1	1	4	0.33	0.005	20
SC52	Farquhar Group	*Cm*	Present	Present	1	1	1	3	0.33	0.006	20
TF03	Europa	*Cm*	Present	Present	0	0	0	0	0.31	0.078	30
YE01	Abalhan Protected Area/ Socotra Man and Biosphere Reserve	*Cc*	Absent	Absent	3	2	1	6	0.36	0.036	30
ZA01	Mabibi to Kosi Lake/Bhanga Nek	*Dc*	Present	Present	2	1	1	4	0.33	0.047	30

The south-western and south-eastern Indian Ocean, and the Eritrean sites (north-western Indian Ocean) were narrow and thus received a high back-beach width score. High risk scores (BBW < 9 m) were mainly allocated to islands, i.e. 10 of the 17 beaches allocated a back-beach width score of five, were islands with narrow beaches. Google Earth imagery for three of the beaches was of poor quality so that the high tide line could not be distinguished. Bilang-Bilangan (ID27/#23), Rushikulya (Murali_02/#32) and Cape Van Diemen (AU284/#7), were therefore scored as data deficient and the highest risk score for back-beach width (score = 5) was applied. To view the scores allocated to each study site, see **Table 3.6**.

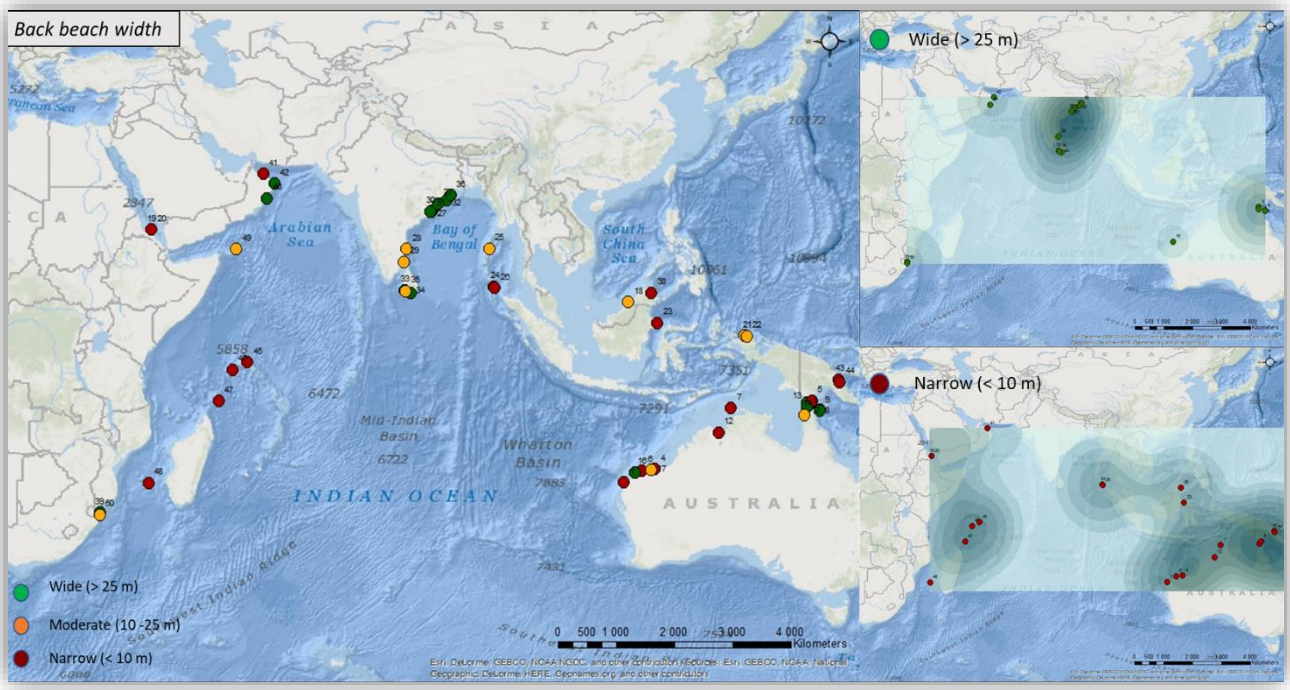


Figure 3.13: Beaches with wide (> 25 m), moderate (10-25 m) and narrow (< 10 m) back-beach widths for 50 sea turtle nesting beaches across the IOSEA region. A kernel density analysis represented by the blue contours indicate relative density of wide beaches (> 25 m; top right insert) and narrow beaches (> 25 m; top right insert. Beaches in the northern Indian Ocean (mainly along the eastern Indian coast) have the widest back-beaches (> 25 m; top right insert). Narrow back-beaches (<10 m) were spread across sites of the north-western, southern, western and eastern Indian Ocean regions (bottom right insert).

2. Orientation and protection

Orientation and protection were assessed according to four criteria; surf zone width, image entropy, level of physical protection and wave exposure. Most of the beaches had narrow surf zones (46%) and low image entropy (40%), with wider surf zones/higher image entropy occurring mainly for Indian, Sri-Lankan, Indonesian beaches, as well as the South African and Mozambiquen beaches. However, more beaches were unprotected (40%) than protected (13%). Protected beaches included mainly island nesting sites, such as the Australian islands: Wild duck (AU80/#15), Rosemary (AU27/#6, Wreck (AU34/#11) and Crab (AUand)/#13) island, as well as the Oman and Eritrean islands: Aucan (ER01/#19), Dalmaniyat (OM11/#41), Mojeidi (ER02/20) and Masirah (OM02/#40) island. The Seychelle-Farquhar island group (SC52/#47), D'Arros and St. Joseph Atoll Islands (SC10/#46) were also protected and two beaches Ras Al Had (OM12/42), Oman and Bilang-Bilangan (ID27/#23), Indonesia. Almost half of the beaches (44%) received direct wave action/impact.

Once all four categories were combined and the overall exposure rating for protection and orientation calculated (i.e. Final Score for Exposure and Orientation in **Table 3.5**), it is clear that the sea turtle nesting beach ratings were spread across a broad range. Two islands were rated as completely sheltered (0-0.5), Wild duck (AU80/#15) and Farquhar Group (SC52/#47). The majority of the beaches (20%) were rated as sheltered (1), 12% were rated between sheltered and semi- exposed and 18% were rated as semi-exposed (more sheltered than exposed). Some beaches (8%) were rated between semi-exposed (more sheltered than exposed) and semi-exposed (more exposed than sheltered). Approximately 14% were rated semi-exposed, more exposed than sheltered, and another 14% were rated between semi-exposed (more exposed than sheltered) and fully exposed. Approximately 10% of the beaches were rated as fully exposed (5); these include Srikakulam (IN200/#31), Srikurmam (IN180/#30), Warmon (ID14/#22), Malongane (MZ07/#39) and Mabibi to Kosi lake (ZA01/#50).

The geographic distribution of the sites with these scores do not provide any regional patterns, however some generalizations are that most of the more sheltered beaches were Australian sites (**Figure 3.14**) on account of higher protection for these nesting sites, which consisted mainly of island surrounded by reefs. Most of the exposed beaches occur in the northern Indian Ocean along the east Indian coast and the Sri-Lankan sites, with two more fully exposed sites in the south-eastern Indian Ocean on the coast of southern Africa (South Africa and Mozambique nesting sites). Several dispersed sites including the Indonesian sites, Brunei site, one Seychelles site (SC08/#45), the Yemen site (YE01/#49) and one Australian site (AU39/#12) were also considered as more exposed. To view the qualitative information and the scores per study site, see **APPENDIX 3.3: Dataset 1**.

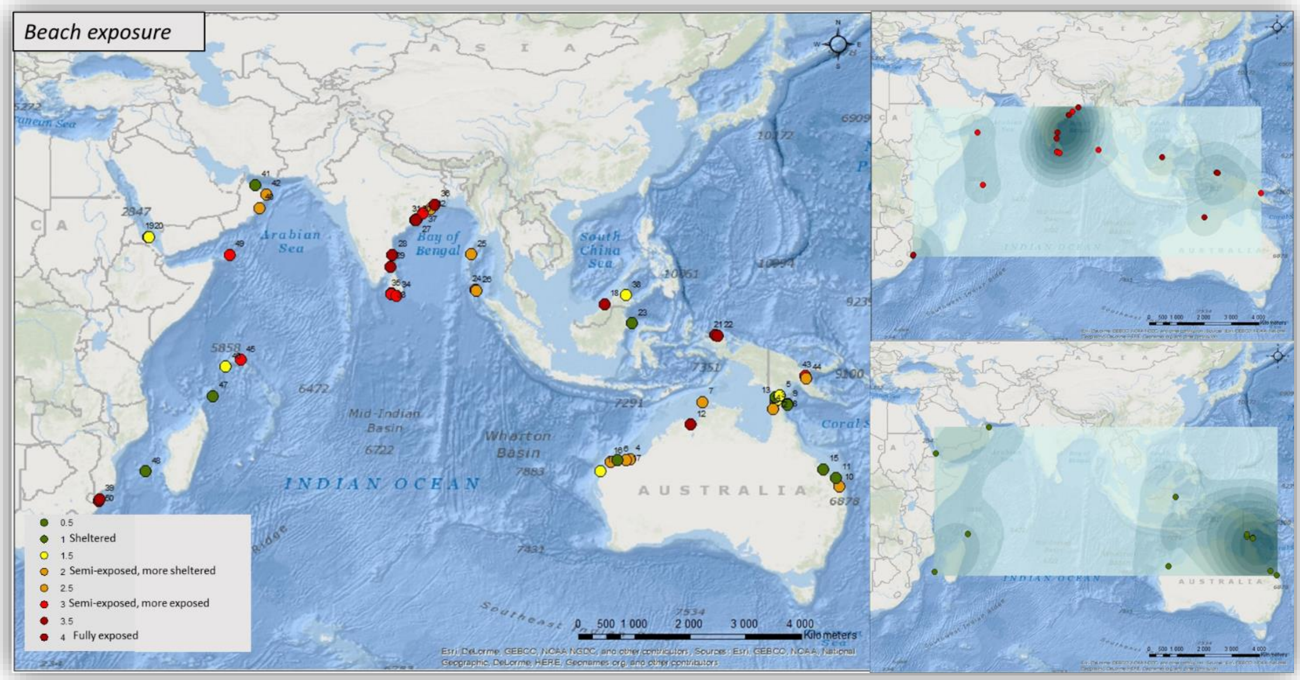


Figure 3.14: Distribution of the sea turtle nesting beaches with orientation and protection rating scores between 0.5 as very sheltered to 4 as very exposed. A Kernel density analysis represented by the blue contours indicate relative density of sheltered beaches (0.5 to 1 score; bottom right insert) and exposed beaches (3 to 4 score; top right insert.

3. *Modal beach energy*

Modal beach energy was calculated per three categories; wind speed (knots), wave height (m) and tide range (2 m bins). Seasonality (summer vs. winter conditions) were controlled for by randomly subsampling throughout the year. Modal (predicted) wind speeds across the study sites ranged from 2 – 23 knots, with a mean wind speed of 10 knots (SD±4.9 knots). The Papua New Guinea and Indonesia sites had the lowest modal wind speed (2 – 3 knots), including Busama (PG02/#43), Kamiali Wildlife Management Area (PG04/#44), Jamursba Medi (ID14/#22) and Warmon (ID02/#21). The highest modal wind speeds (21 and 23 knots, respectively) were calculated for islands of the northern Great Barrier Reef (Australia), Moulter Cay Island (AU300/#8) and Raine Island (AU309/#9) (**Figure 3.15**).

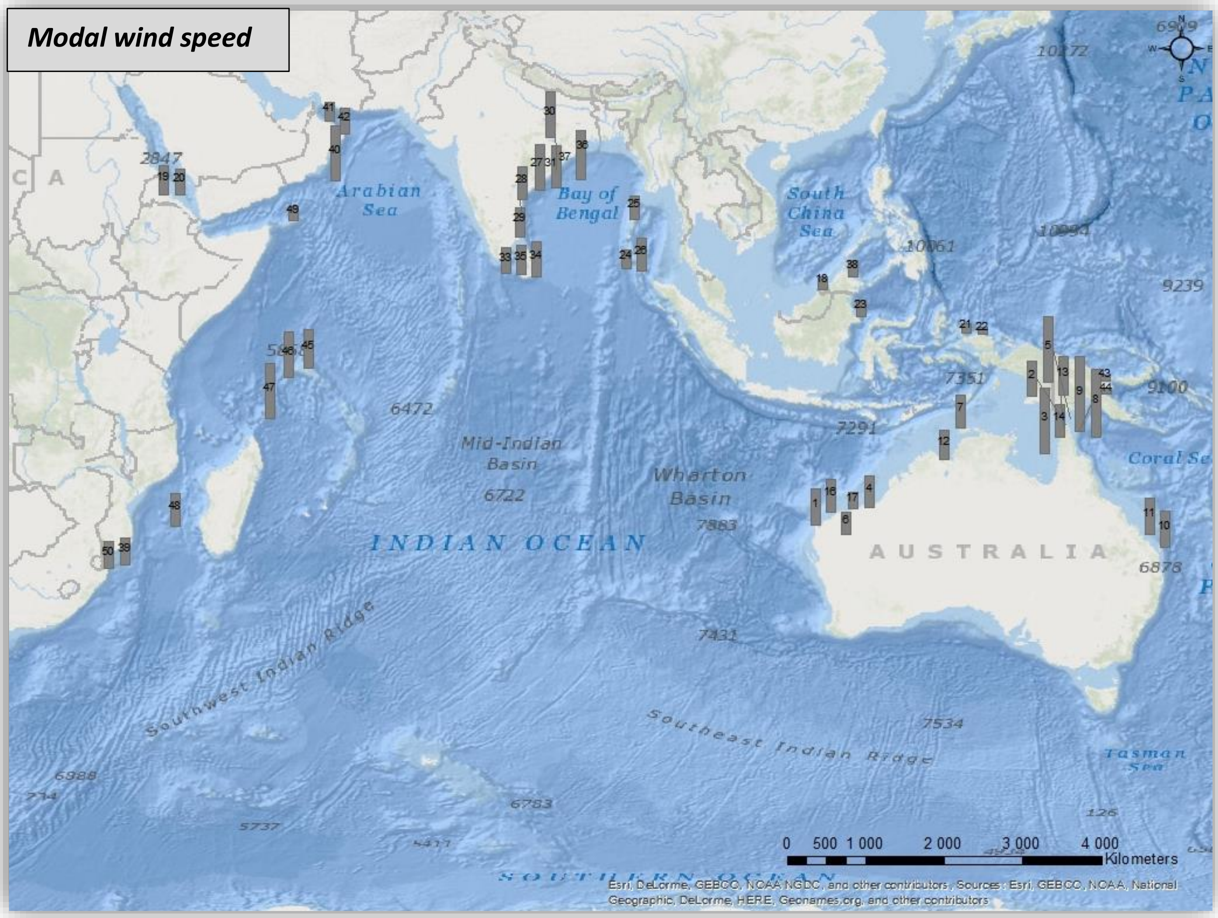


Figure 3.15: Modal (predicted) wind speed (knots) across 50 sea turtle nesting beaches. Modal wind speed (knots) is shown by bar charts per location. Numbers on bar charts indicates the site number (refer to **APPENDIX 3.1: Study sites**).

Modal (predicted) wave height of the study sites ranged from 0.1 - 2.1 m and mean wave height equalled 0.8 m (SD±0.6 m). The lowest modal wave heights (0.1 - 0.2 m) were recorded for Australian sites of Dayman island (AU10/#2), Flinders beach (AU71/#14), Mundabullangana beach (AU82/#17), and the Malaysian Island, Sabah (MY02/#38). The highest modal wave height of 2.1 m, was recorded for Europa island (TF03/#48 (**Figure 3.16**) in the Mozambique Channel. The third metric, i.e. tidal change, indicated that most of the beaches (66%) were meso-tidal (tide = 2 -4 m), while 14% was micro-tidal (tide < 2 m) and 20% were macro-tidal (tide > 4 m).

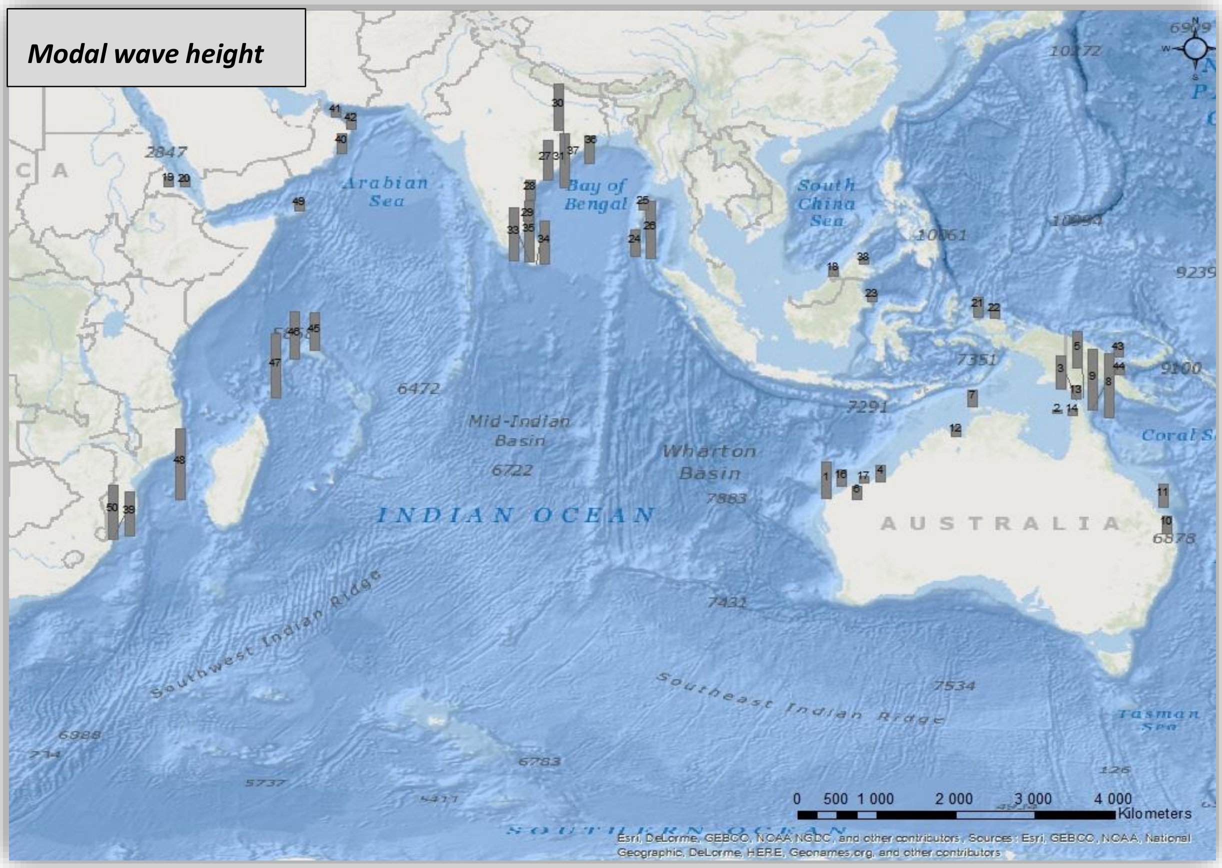


Figure 3.16: Modal (predicted) wave height (m) of sea turtle nesting beaches. Modal wave height (m) is shown by bar charts per location. Numbers on bar charts indicates the site number (refer to APPENDIX 3.1: Study sites).

Mapping the relative density of these categories (low, moderate or high) in ArcMap 10.5.1., Kernel density analysis showed a spread of both low and moderate energy beaches across the Indian Ocean (**Figure 3.17**); none of the beaches were allocated a high modal beach energy score of 24. The comparatively higher beach energy score (score = 12/24) was allocated to an Australian Island, Raine Island (AU309/#9). Another Australian island, Moulter Cay Island (AU300/#8), and a Seychelle Island, Farquhar Island (SC52/#47), also received comparatively higher modal beach energy scores (score = 11/24). Therefore, the south-east Australian sites are dominated by moderate energy beaches (excluding AU10/#2, AU71/#14, AU81/#16 and AU82/#17), as well as the rookeries in the south-western Indian Ocean including Europa Island, the Seychelle islands, South African and Mozambique sites. Gahirmatha (Murali_01/#36) and Rushikulya (Murali_02/#37), were added later during analysis based on local expert recommendation and data for modal wind speed and wave height had not been collected through Windy (www.windy.com) for these beaches. The wind and wave categories for modal beach energy were therefore scored as data deficient and as per the data deficiency rule stated in the methods section, received the highest possible score for those categories (12 + 9), so that Gahirmatha had a final score of 24 and Rushikulya had a final score of 23 (on account of different tide ranges).

The lowest modal beach energy scores (score = 5/24) were allocated to the Papua New Guinea and Indonesian sites: Warmon (ID14/#22), Busama (PG04/#43) and Kamiali Wildlife Management Area (PG04/#43). Therefore, the north-east Indian Ocean (excluding the beaches of the east coast of India), is dominated by low energy beaches including all the sites for Brunei, Indonesia, Malaysia and Papua New Guinea. The Arabian Peninsula beaches in the north-western Indian Ocean are also dominated by low energy beaches, including those from Eritrea, Oman (excluding MasirahOM02/#40) and Yemen.

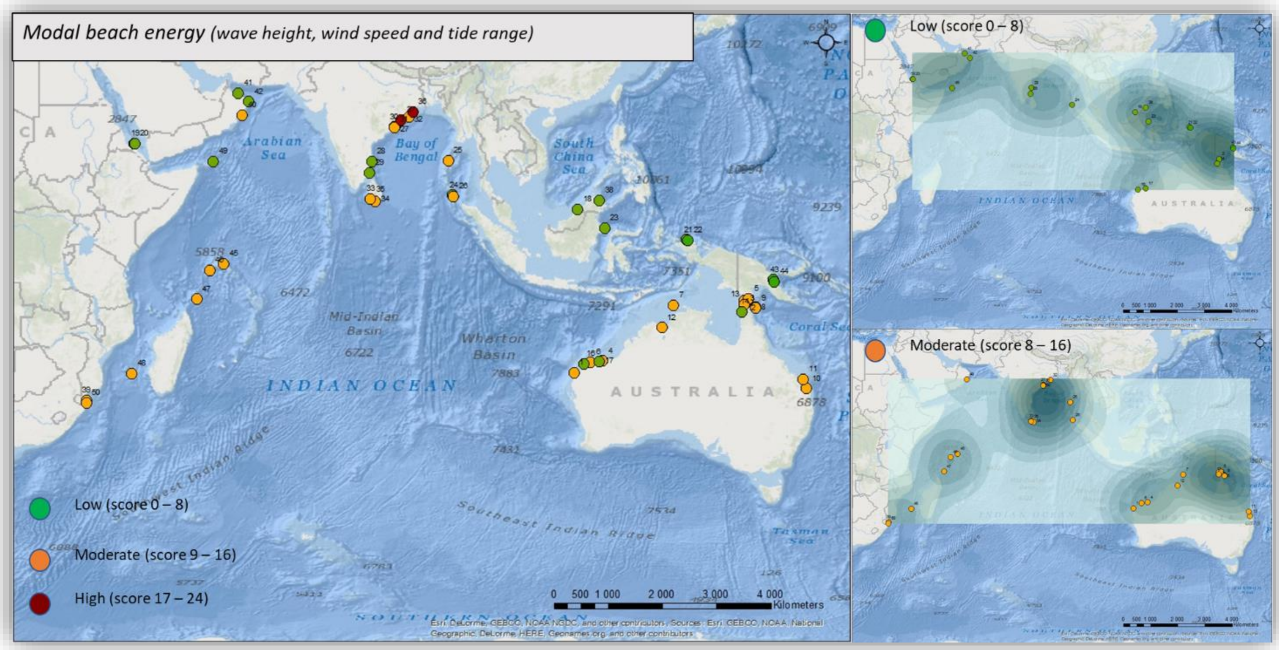


Figure 3.17: Geographic distribution of the modal beach energy scores obtained for the sea turtle nesting beaches. The map shows low (score = 0 – 8), moderate (score = 8 – 16) and high (score = 16 – 24) modal beach energy for the sites. Two beaches, Gahirmatha (site#36) and Rushikulya (site#37), were allocated high modal beach energy scores on account of data deficiency. A Kernel density analyses indicated by the blue contours for beaches with low (top right insert) and moderate (bottom right insert) modal beach energy are presented.

3. State of the dune system

Most study sites (23 of the 50 beaches) had no dune protection (**Table 3.6)**. One site, Dayman Island (AU10/#2), was scored as data deficient (score = 3) as it was very difficult to judge the state of the dune system from the Google Earth image. The lowest risk score (score = 1) was allocated to 14 of the sites that had multiple sand dune ridges. The geographic distribution of the dune systems revealed a strong patterns; The north-western Indian Ocean characteristically consisted of beaches with multiple sand dune ridges, including the sites for Eritrea, Oman and Yemen (ER01/#19, ER02/#20, OM02/#40, OM11/#41, OM12/#42 and YE01/#49) (**Figure 3.18**). Along the east coast of India, a mix of beaches with different dune systems occurred, with beaches along the north-east coast having single to multiple dune ridges and the south-east coast having no dunes. This could be explained by the different tide ranges, where the southern beaches were micro-tidal (tides = < 2 m) and the northern beaches were meso- to macro-tidal (tide range > 2 m). The beaches of north-western Australia were also characterised with multiple sand dune ridges, for example Mundabullangana beach (**Figure 3.19**), while the beaches of north-eastern Australia (Queensland) were characterised by no dunes or single dune ridges. The sites with no dune system consisted mainly of islands (12 of the 23 sites were low lying islands) and included islands of the eastern and western Indian Ocean, such as the Indian islands (IN04/#24, IN04#25, IN05/#26) and the Seychelle Islands (SC08/#45, SC10/#46 and SC52/#47). Low energy beaches in the eastern Indian Ocean, such as, the Indonesian and Papua New Guinea (ID02/#21, ID14/#22, ID27/#23, PG02/#44 and PG04/#44) sites were also characterised by beaches with no dune systems (e.g. **Figure 3.20**). In general, beaches closest to the equator had fewer dune ridges and the number of dune ridges increased with latitude.

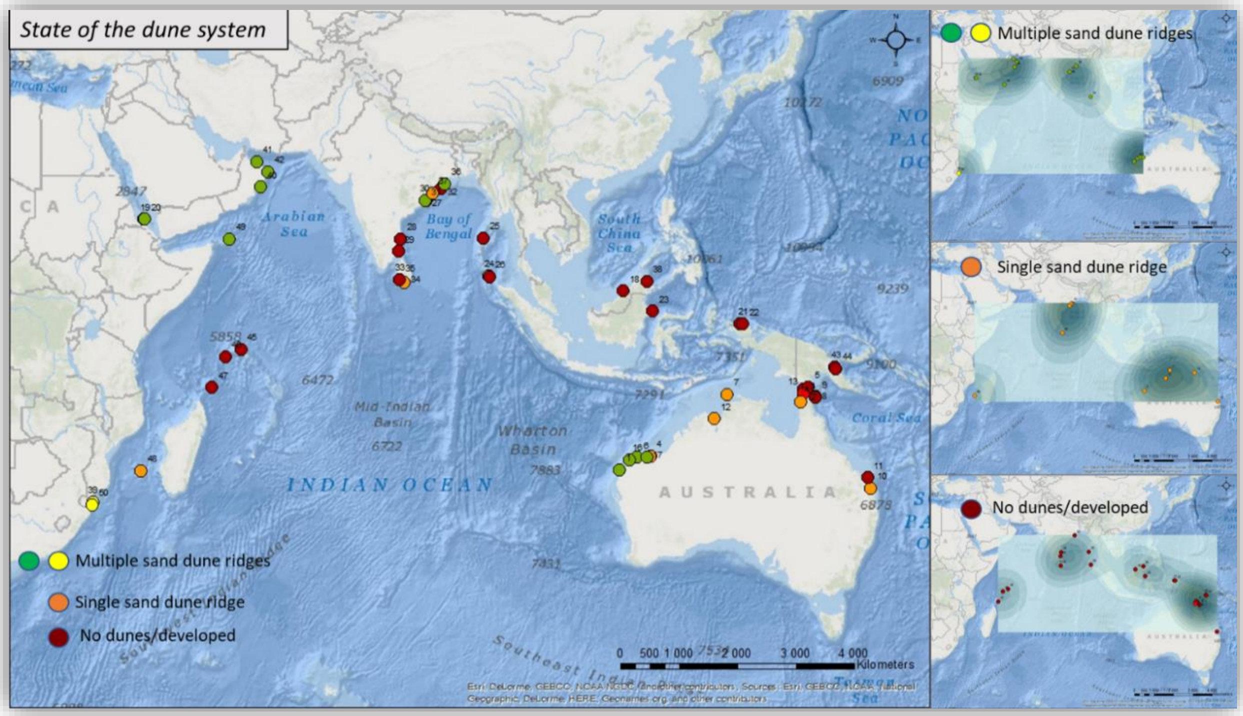


Figure 3.18: Geographic distribution of the scores/state of the dune system for the sea turtle nesting beaches. There is a strong geographic pattern; beaches around the equator have few dune ridges and as distance increased north and south, the number of dune ridges increases. A Kernel density analyses indicated by the blue contours for beaches with multiple dunes (top right insert), single dune (middle right insert) and no dunes (bottom right insert) are presented.

Figure 3.19: Mundabullangana Beach, western Australia. The sites/beaches of western Australia are characterised by multiple sand dunes behind the back-beach, constituting to a lower risk score for these beaches.

Figure 3.20: Turtle Islands, Sabah, Malaysia. The majority of the islands of this study has no dunes, contributing to a higher risk score for these sites.

B) Threat indicators

I. Coastal development

Coastal development was calculated per three categories; location, intensity and extent. Most beaches had low development intensity as 72% of the beaches had a score of 0-1. If development occurred the extent was limited; i.e. 90% were allocated a low development extent score of 0 – 1, and beaches were developed mainly behind the secondary dunes as 60% of the beaches had no development on back-beach or foredunes. Therefore, most of the sea turtle nesting beaches had low development levels with 26 of the 50 study sites having a development score of zero (**Figure 3.21; Table 3.7**). Two beaches, however, including Cemetery beach, Australia (AU119/#4) and Bentota beach, Sri Lanka (LK02/#33), had high development scores (8/9) and another two beaches, Barrow Island (AU81/#16) and Rekawa (LK05/#34) also in Australia and Sri Lanka scored 7/9. The other 20 sites had values ranging from 1 – 6.

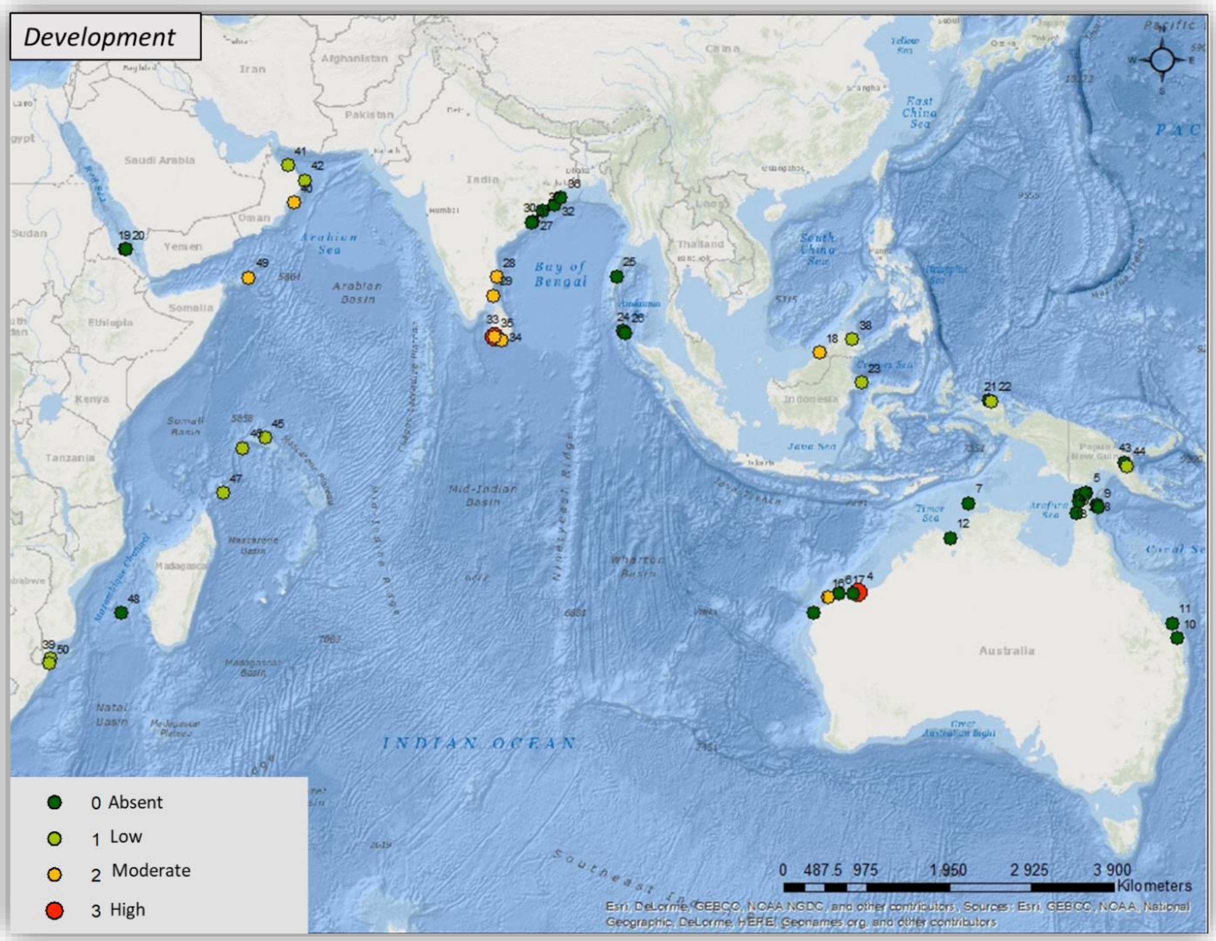


Figure 3.21: Levels of development for the sea turtle nesting beaches. Most of the beaches had no development (score = zero).

II. Sea level rise

To score sea level rise for the sea turtle nesting beaches, categories were created from the global training data set. The sea level rise values (SLR) obtained from the global training data set ranged from 0.30 – 0.60 m by the year 2100 (**Appendix 3.2**) but SLR values for the sea turtle nesting beaches were extremely uniform and ranged between 0.31 - 0.38 m (**Table 3.7**). The mean SLR value across the nesting beaches was 0.33 m, where 44 of the 50 beaches had an estimated SLR < 0.36 m. Only Mon Repos (AU33/#10), Wreck Island (AU34/#11) and Wild Duck Island (AU80/#15) had higher SLR values of 0.38 m.

III. Storminess

Storminess was described using two variables; storm frequency and storm intensity (sections below) and score categories for both storm frequency and intensity were created using ArcGIS line density and feature to raster output tool, respectively. The global storm frequency (line density per km^2 calculated from NOAA archived storm track data, 1848 to 2018) ranged from 0 – 0.62 per km^2, while the storm intensity (maximum sustained winds) ranged from 10 – 155 knots. A global map of the NOAA archived storm track data (1848 to 2018) in ArcMap 10.5.1, showed frequent (track density = 0.56 - 0.62 per km^2) and sometimes intense storms (139 – 155 knots) over the North Atlantic and North Pacific Ocean; the storm track line density was highest immediately adjacent to the west and east of North America and the maximum sustained wind (knots) raster showed some of these storms to have been very intense (**Figure 3.22)**. Globally the map showed that more intense storms occurred to the north of the equator than to the south. Lower storm frequency was indicated for the Indian Ocean. However, some intense storms occurred across the Indian Ocean, and impacted on the sea turtle nesting beaches.

A. Storm frequency

The study sites generally had low storm frequency scores (**Table 3.7**; **Figure 3.22**). Track density ranged from 0 to 0.14 per km^2. Therefore, the highest allocated score was 2/9 (track density range = 0.07 – 0.14 per km^2) given to 15 of the study sites, including the sites of the north-eastern Indian coast (IN04/#25, IN102/#27, IN126/#28, IN137/#29 and IN76/#32), some northern Queensland sites, Australian (AU284/#7, AU300/#,8 AU34/#11, AU39/#12 and AU70/#13), several sites north of Australia including a Brunei, Indonesian and Malaysian sites (BNX/#18, ID27/#23, MY02/#38). Europa Island (TF03/48) and Masirah Island (OM02/#40) were also allocated a score of 2/9. Most sites (31 beaches) received a score of 1/9 (track density range = 0.001 – 0.06 km^2). Several sites close to the equator scored 0 (AU81/#16, ID02/#21, AU15/#5 and AU82/#17), indicating that no storms were recorded by the NOAA National Climatic Data Center (data.noaa.gov) for these sites.

B. Storm intensity

The study sites received low to moderate intensity scores (**Table 3.7)**, where the maximum sustained winds ranged from 0 – 77 knots (**Figure 3.22**). The Oman sites comparatively had the most intense storms. Two sites in Oman, Dalmaniyat (OM11) and Ras al Had (OM12) received moderate scores for storm intensity based on maximum sustained winds of 77 knots (score = 5/9). Other sites received relatively low intensity scores: five sites, including the Queensland, Australian sites (AU08/#1, AU119/#4 and AU82/#17) and Masirah Island (OM02/#40) received a score of 3/9 (wind speed range = 45 – 55 knots); 18 sites received a score of 2/9 (27 – 40 knots); 14 sites received a score 1/9 (15 – 25 knots); and 11 sites received a score of 0.

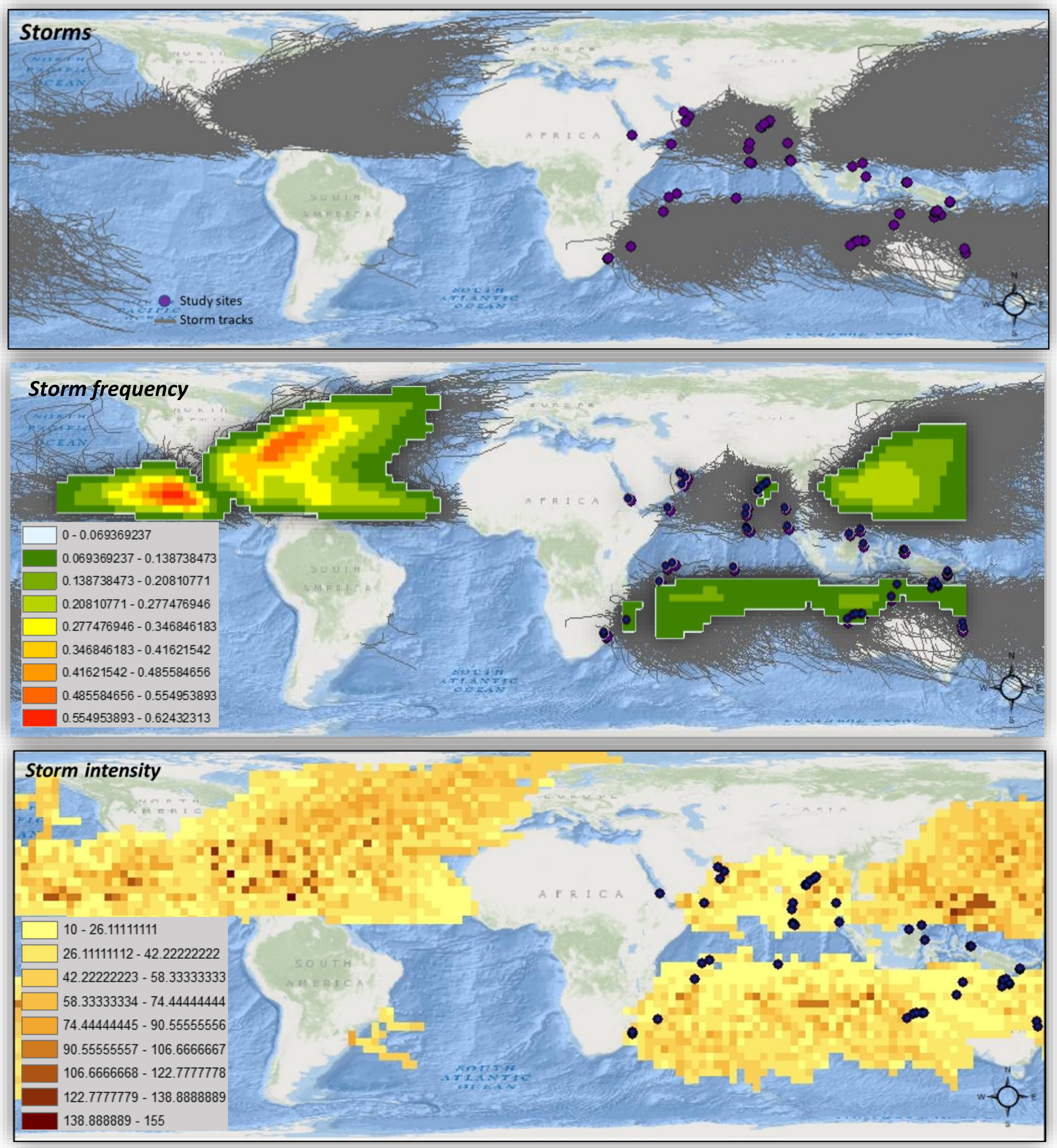


Figure 3.22: Top: Geographic distribution of global storm tracks (from the IBTrACS Version 3 storm track dataset from the NOAA National Climatic Data Center) between 1848 and 2018, and 50 important turtle nesting sites across the IOSEA. Storm tracks are indicated by grey lines and for all the maps sea turtle nesting beaches are indicated by purple dots. Middle: Distribution of storm frequency based on line density per km^2, ranging from 0 to 0.14 per km^2. Bottom: Distribution of global storm intensity based on maximum sustained winds (knots) per km^2, ranging from 0 – 155 knots.

Coastal vulnerability Index assessment

The vulnerability assessment indicated sites to fit into management priority categories as they relate to erosion vulnerability: 1) High risk-High threats, 2) High risk-Low threats, 3) High threats-Low risk and 4) Low risk-Low threats (**Figure 3.23)**. By adding the normalised risk and threat scores a final erosion vulnerability score was calculated for each study site (**Table 3.8**). Seven of the study sites are categorised as having High risk-High threat management priority and were quantified as having high vulnerability to erosion. Beaches within the High risk-High threats category were ranked according to their vulnerability score as follows: Mamallapuram – Pondi beach (IN126/#28) (**Figure 3.25**), Cemetery beach (AU119/#4), Bentota beach (LK02/#33), Brunei beach (BNX/#18), Nagapattinam (IN137/#29), Wreck Island (AU34/#11) and Kosgoda beach (LK21/#35) (**Figure 3.24**). As all the study sites (50 beaches) had low to moderate modal beach energy and storm intensity, as well as low sea-level rise and storm frequency, High risk – High threat beaches generally had several of the following characteristics: narrow back-beach width (< 10 m), high beach orientation and protection (exposed to fully exposed), no dune system and/or high development.

Nine of the study sites were categorised as having a Low risk-Low threat conservation priority and were quantified as having low vulnerability to erosion (**Figure 3.24** and **Table 3.8**). Beaches within the Low risk-Low threat category include: Wild duck (AU80/#15), Moulter Cay (AU300/#8), Raine Island (AU309/#9), Srikurmam (IN180/#30), Srikakulam (IN200/#31), Rosemary Island (AU27/#6), Crab Island (AU70/#13), Mojeidi Island (ER02/#20) and Aucan Island (ER01/#19) (**Figure 3.26**).

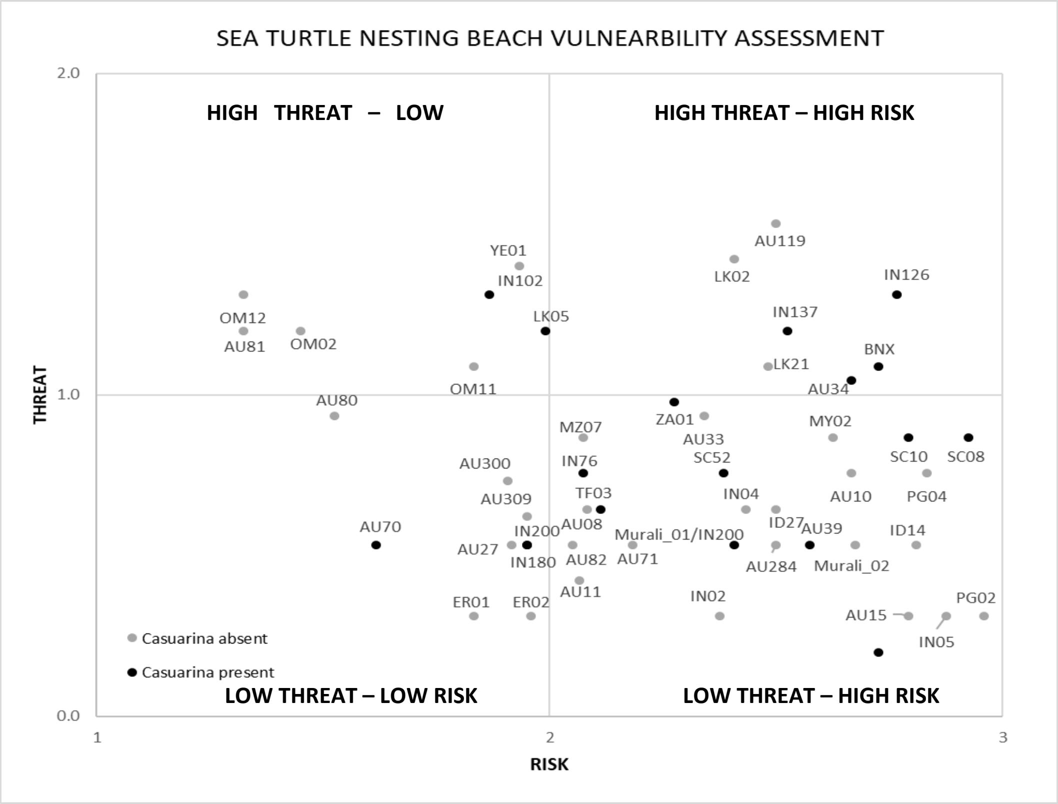


Figure 3.23: Vulnerability categories for 50 turtle nesting beaches based on risk (x-axis) and threat (y-axis) scores. The beaches are grouped into four categories are: High risk-High threat, High risk-Low threat, Low risk-High threat and Low risk-low threat. Sites where Casuarina *occur have been inidcated with a black dot and sites where* Casuarina *are absent are inidcated with a grey dot.*

Several study sites within the High risk - High threats category had non-native *Casuarina* present to an extent of more than 25% along the back-beach or dunes. Both, Mamallapuram - Pondi (IN126/#28), the site with the highest vulnerability rating, and Nagapattinam (IN137/#29), had non-native *Casuarina* trees present on the back-beach. The other study site, Brunei (BNX/#18), also within the High risk-High threats category, has *Casuarina* trees present on the back-beach, but it was not possible to distinguish between the native *Casuarina* species, *C. equisetifolia* and the non-native species, *C. gluaca*. Further investigation as to the species of *Casuarina* occurring on the beach is necessary. Non-native *Casuarina* occur at two of the study sites within the Low risk-Low threat categories: Srikurmam and Srikakulam, Andhra Pradesh, India. Although the beaches were categorised as having low vulnerability to erosion, prioritising the removal of non-native *Casuarina* will increase the suitability of these important *Lepidochelys olivacea* rookeries.

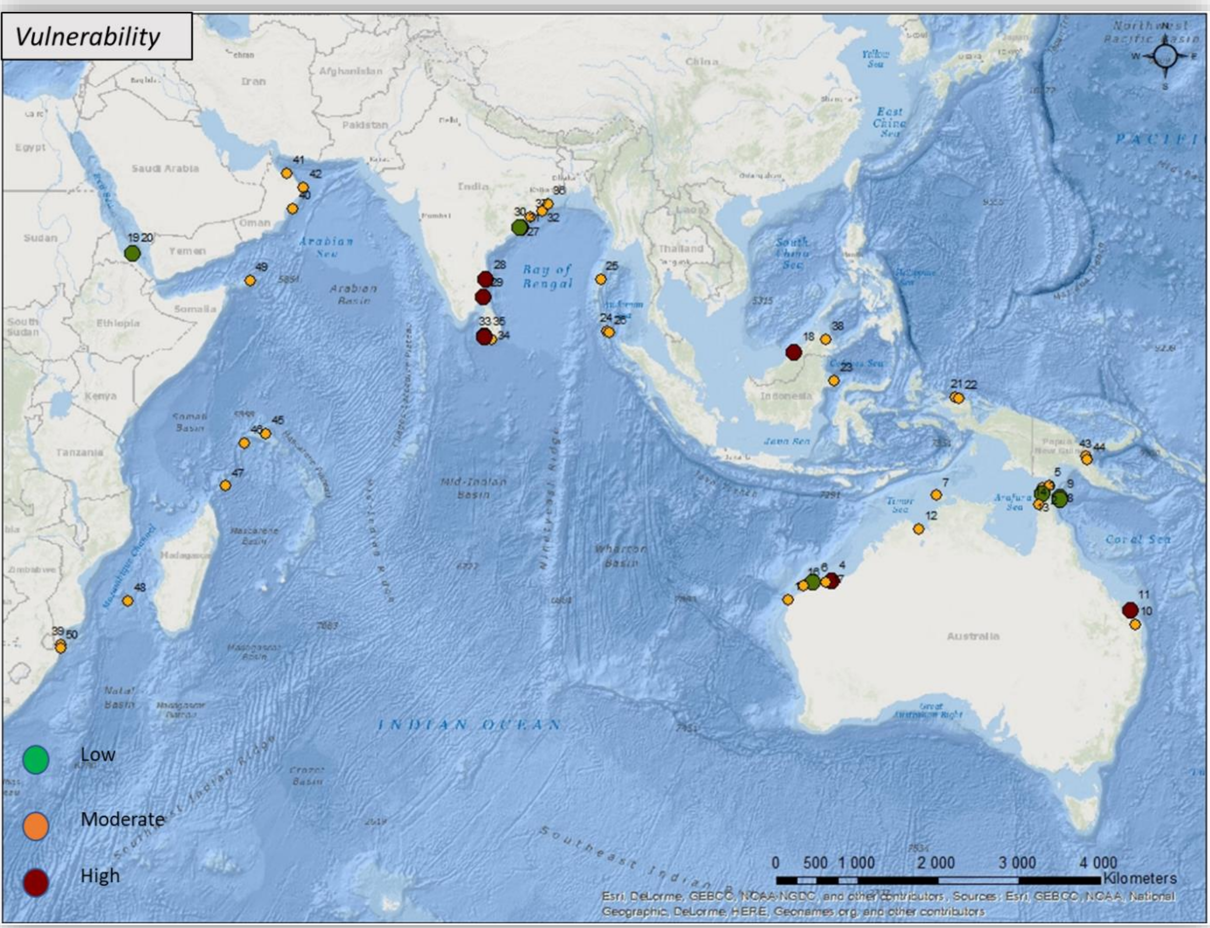


Figure 3.24: Geographic distribution of 50 turtle nesting sites with their respective vulnerability scores (low, moderate or high vulnerability)

The results suggest that 25% of the *Lepidochelys olivacea* selected nesting sites, are categorised as High threat-High risk (see **Figure 3.27**). High threat-Low risk/Low threat included 58% of the sites and 16% of the sites were categorised as Low risk-Low threat. The *L. olivacea* rookery with the highest number of nesting females (150 000 – 200 000) (Shanker et al. 2004a), Devi river mouth, Orissa (IN76/#32), is categorised as High risk-Low threat and received a moderate vulnerability score (ranked #36 out of 50).

Table 3.8: Vulnerability score (normalised risk score + threat score) assigned to each of the study sites. Sites are listed in order of vulnerability (highest to lowest).

Site number	Site ID	Beaches	Summed risk score	Summed threat score	Vulnerability
28	IN126	Mamallapuram - Pondi	2.77	1.31	4.08
4	AU119	Cemetery Beach	2.50	1.53	4.03
33	LK02	Bentota	2.41	1.42	3.83
18	BNX	Brunei	2.73	1.09	3.81
45	SC08	Cousin Island Special Reserve	2.93	0.87	3.79
29	IN137	Nagapattinam	2.53	1.20	3.73
11	AU34	Wreck Island	2.67	1.04	3.71
46	SC10	D'Arros Island and St. Joseph Atoll	2.79	0.87	3.66
44	PG04	Kamiali Wildlife Management Area	2.83	0.76	3.59
35	LK21	Kosgoda	2.48	1.09	3.57
38	MY02	Turtle Islands, Sabah	2.63	0.87	3.49
2	AU10	Dayman Island	2.67	0.76	3.42
22	ID14	Warmon	2.81	0.53	3.34
49	YE01	Abalhan Protected Area/Socotra Man and Biosphere Reserve	1.93	1.40	3.33
10	AU33	Woongarra coast including Mon Repos	2.34	0.93	3.28
43	PG02	Busama (Buli)	2.96	0.31	3.27
50	ZA01	Mabibi to Kosi Lake/Bhanga Nek	2.28	0.98	3.25
12	AU39	Cape Domett	2.68	0.53	3.21
34	LK05	Rekawa	1.99	1.20	3.19
26	IN05	Galathea Beach, Great Nicobar Island	2.88	0.31	3.19
27	IN102	Kalingapatnam/Vamsadhara	1.87	1.31	3.18
23	ID27	Bilang-Bilangan	2.50	0.64	3.14
47	SC52	Farquhar Group	2.38	0.76	3.14
37	Murali_02	Rushikulya	2.58	0.53	3.11
5	AU15	Long Island	2.79	0.31	3.10
25	IN04	Cuthbert Bay	2.43	0.64	3.08
7	AU284	Cape Van Diemen	2.50	0.53	3.03
36	Murali_01	Gahirmatha	2.41	0.53	2.94
39	MZ07	Malongane	2.08	0.87	2.94
21	ID02	Jamursba Medi	2.73	0.20	2.93
41	OM11	Dalmaniyat	1.83	1.09	2.92
32	IN76	Devi River mouth, Orissa	2.08	0.76	2.83
48	TF03	Europa	2.11	0.64	2.76
1	AU08	Bungelup	2.08	0.64	2.73
14	AU71	Flinders Beach	2.18	0.53	2.72
24	IN02	Beaches straddling the Alexandria and Dagmar Rivers	2.38	0.31	2.69
40	OM02	Masirah	1.45	1.20	2.65
8	AU300	Moulter Cay, north Great Barrier Reef	1.91	0.73	2.64
42	OM12	Ras al Had	1.33	1.31	2.64
17	AU82	Mundabullangana Beach	2.05	0.53	2.58
9	AU309	Raine Island, north Great Barrier Reef	1.95	0.62	2.57
16	AU81	Barrow Island	1.33	1.20	2.53
3	AU11	Hawkesbury (Warral) Island	2.07	0.42	2.49
30	IN180	Srikurmam	1.95	0.53	2.48
31	IN200	Srikakulam	1.95	0.53	2.48
15	AU80	Wild Duck	1.53	0.93	2.46
6	AU27	Rosemary Island	1.92	0.53	2.45
20	ER02	Mojeidi Island	1.96	0.31	2.27
13	AU70	Crab Island	1.62	0.53	2.15
19	ER01	Aucan Island	1.83	0.31	2.14

Figure 3.25: Mamallapuram beach, India. Mamallapuram beach (IN126#28), an important rookery for Lepidochelys olivacea *(600 nesting females) (Shanker et al. 2004b) received the highest overall vulnerability score (risk + threat).* Casuarina *trees have been planted on the back-beach and covers a moderate portion (> 25 m) along the coast. Beach characteristics such as high wave exposure and low protection (the beach is fully exposed) and lack of an intact dune system (no dunes) added to the high risk score. A portion of the back-beach has been hardened with a sea wall, adding to the high erosion threat.*

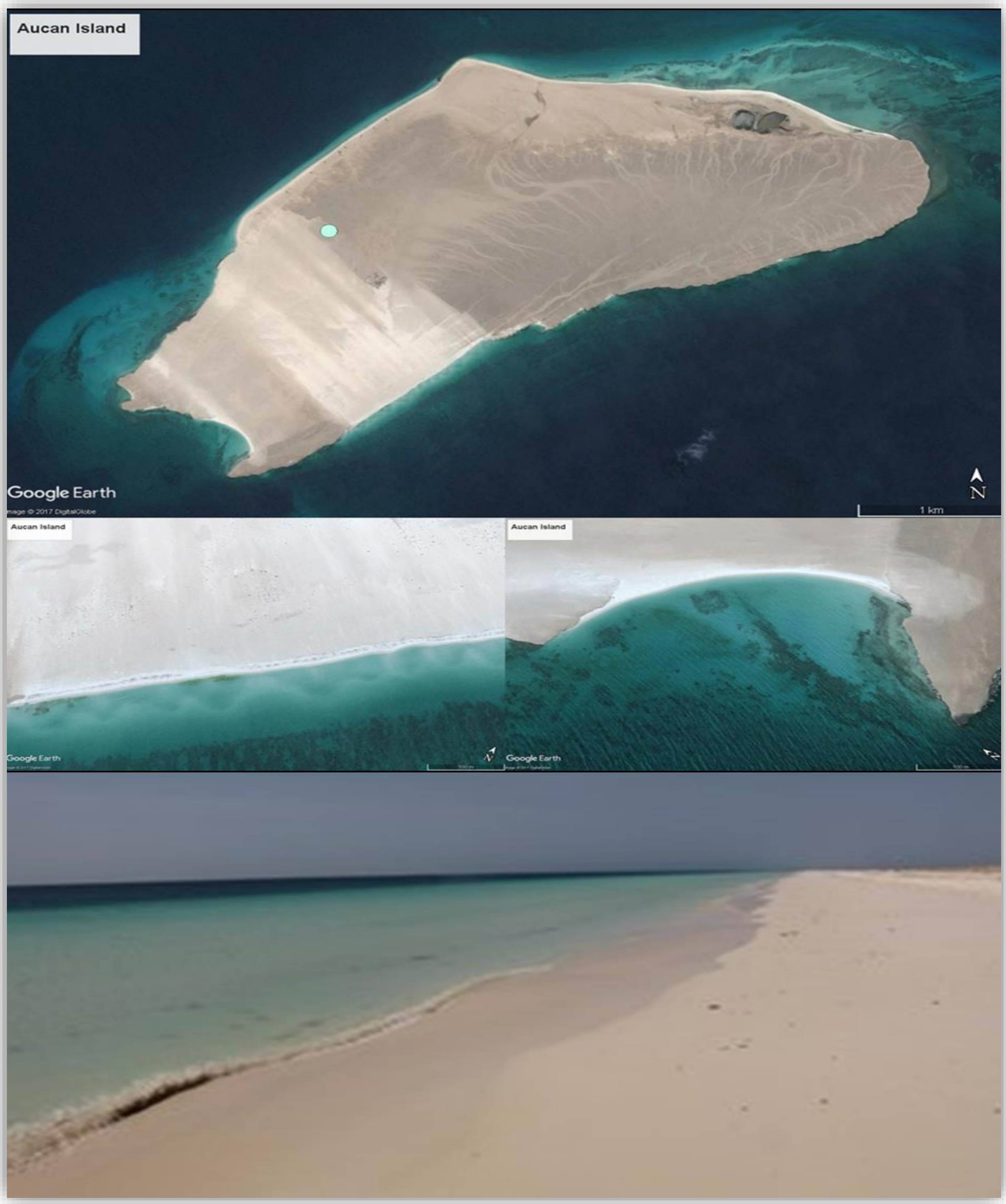


Figure 3.26: Aucan Island, Eritrea. Aucan Island (ER01), an important rookery for Eretmochelys imbricata *(735 nesting females) (Goitom et al. 2006), received the lowest overall vulnerability score (risk + threat). The island is characterised by halophytes and a few mangroves and no* Casuarina *occur here. Beach characteristics such as low wave exposure and high protection (beach is sheltered, low modal beach energy, and an intact dune system with multiple dune ridges contributed to the low risk score. There is no development on the island and very few storms with low intensity occur here. The sea level is predicted to have an average increase of 0.35 mm over the period of 2020's – 2100's, which is a relatively low increase compared to the sea level rise estimates of the global training data set.*

Of the *Natator depressus* selected nesting sites, 14% were categorised as High threat-High risk (**Figure 3.27**). Most of the study sites (57%) were categorised as High threat-Low risk/Low threat-High risk and 28% of the sites were categorised as Low risk-Low threat. The *N. depressus* rookery with the highest number of nesting females (3250 females) (Jayathilaka et al. 2016), Cape Domett (AU39/#12), is categorised as High risk-Low threat and received a moderate vulnerability score (ranked #18 out of 50). The high-risk score is mainly attributed to a narrow back-beach (score = 4/5)) and high exposure/orientation and exposure (score = 3.5/4), but the beach experiences only moderate modal beach energy (score = 8/24) and from this study it is apparent that the beach is quite pristine. There is no development, which means the beach can move landwards with low sea level rise and few storms contribute to erosion or disruption of the nesting females. Very little published information is available for the Cape Domett beach and further research on its stability as a nesting site is paramount to inform its management.

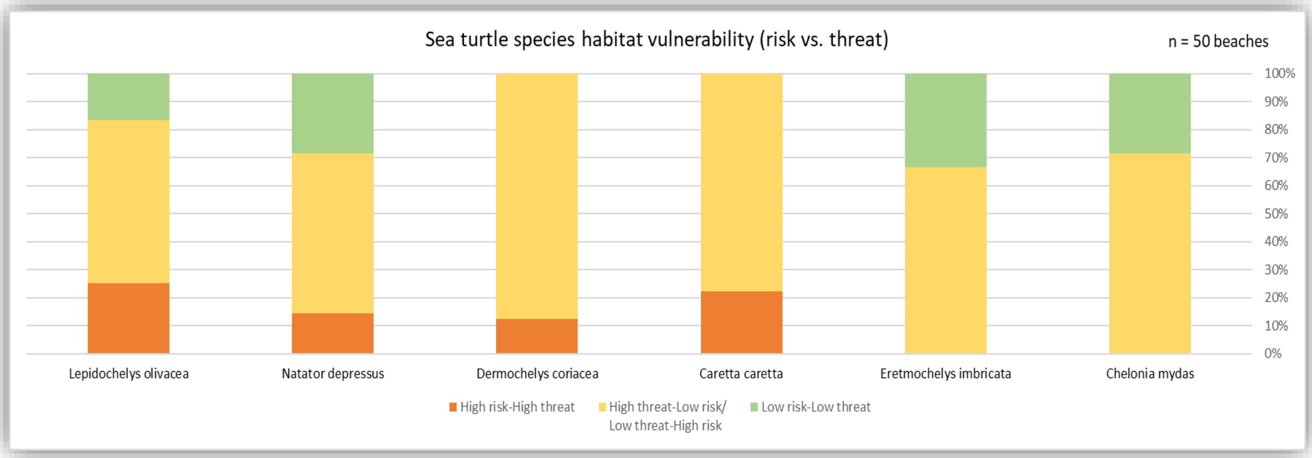


*Figure 3.27: Vulnerability categories (High risk-High threat, High risk-Low threat, Low risk-High threat and Low risk-Low threat) of the study sites for six of the sea turtle nesting species (*Chelonia mydas, Eretmochelys imbricata, Caretta caretta, Dermochelys coriacea, Natator depressus and Lepidochelys olivacea*). The highest proportion of* Lepidochelys olivacea*, were categorised as High risk-High threat. Non-native* Casuarina *occurrence is also most dominant on the* Lepidochelys olivacea *study sites, because of extensive plantations on the east coast of India in response to the December 2004 tsunami event.*

Of the *Dermochelys coriacea* selected nesting sites, 12.5% were categorised as High threat-High risk and the rest of the sites were all categorised as High threat-Low risk/Low threat-High risk (**Figure 3.27**). None of the sites were categorised as Low risk-Low threat. The *D. coriacea* rookery with the highest number of nesting females (721 females) (Hitipeuw 2006), Jamursba Medi (ID02/#21), was categorised as High risk-Low threat with a moderate vulnerability score (#30 out of 50). Beach characteristics such as beach orientation and protection and lack of a dune system puts the beach at risk of erosion.

Of the *Caretta caretta* nesting sites, 22% were categorised as High risk-High threat and all other sites were categorised as High threat-Low risk/Low threat-High risk (**Figure 3.27**). None of the sites were categorised as Low risk-Low threat. The *C. caretta* nesting site with the highest number of nesting females (30 000 females) (Pilcher 2007; Baldwin et al. 2003), Masirah (OM02/#40), was categorised as High threat-Low risk with a relatively low vulnerability score (ranked #37 out of 50). Moderate development exists on the island and the island is exposed to some storm events.

None of the *Eretmochelys imbricata* nesting beaches were categorised as High risk-High threat (**Figure 3.27**). Most of the sites (67%) were categorised as High threat-Low risk/Low threat-High risk and 33 % were categorised as Low risk-Low threat. The *E. imbricata* rookery, with the highest number of nesting females (793 females), (Nature Seychelles 2008), Cousin Island Special reserve (SC08/#45), was categorised High risk – Low threat with a high vulnerability score (ranked #5 out of 50).

The results show that none of the *Chelonia mydas* nesting beaches are categorised as High risk-High threat (**Figure 3.27**). The majority (71.5%) of the *C. mydas* nesting beaches were categorised as High threat-Low risk/Low threat-High risk and 28.5% were categorised as Low risk-Low threat. The *C. mydas* rookery with the highest number of nesting females (70 122 nesting females) (Limpus et al. 2003), Raine Island (AU309/#9), was categorised as Low risk – Low threat and concern over possible erosion on the island might be unfounded. These results are supported by a study by Dawson and Smithers (2014), which demonstrated that Raine island showed net growth (6% area, 4% volume) between 1967 and 2007.

3.3.4 Difference in erosion vulnerability in the presence of *Casuarina*

There was no significant difference between vulnerability mean in the presence (M = 3.2, SD = 0.3) vs. absence (M = 3, SD = 0.2) of *Casuarina* trees; t (31) = 1.7, p = 0.1 for the nesting beaches.

3.4 DISCUSSION

The aim of the study was to assess erosion vulnerability as a measure of risk and threat for important sea turtle nesting beaches in the IOSEA region, as indicated by the presence of non-native *Casuarina* trees, physical beach features such as the back-beach condition and threats such as sea-level rise, storm activity and development. The study established that non-native *Casuarina* occurred on 28% of the representative sea turtle nesting beaches selected for this study. Furthermore, several of these nesting beaches showed high vulnerability to erosion, because of physical beach characteristics, back-beach condition and development. Half of the beaches considered to be highly vulnerable (High risk – High threat) have introduced *Casuarina* on the back-beach. However, the study highlighted that *Casuarina* presence alone could not be viewed as an indicator of erosion and that several other indicators also explain high erosion vulnerability for beaches, but *Casuarina* trees are a contributing factor.

3.4.1 Erosion vulnerability of IOSEA turtle nesting beaches

The most vulnerable beaches, i.e. High risk-High threat beaches include Mamallapuram – Pondi beach (IN126/#28), Cemetery beach (AU119/#4), Bentota beach (LK02/#33), Brunei beach (BNX/#18), Nagapattinam (IN137/#29), Wreck Island (AU34/#11) and Kosgoda beach (LK21/#35), of which Mamallapuram – Pondi beach (IN126/#28), Brunei beach (BNX/#18) and Nagapattinam (IN137/#29) have introduced *Casuarina* present. Because the sea turtle nesting beaches showed low to moderate modal beach energy, sea level rise, storm frequency and intensity, the High risk-High threat beaches generally had the following characteristics: narrow back-beach width (< 10 m), high beach exposure, no dune system and/or high(er) levels of development. These characteristics increases the erosion potential of beaches; Back-beach or dry beach width acts a buffer zone against wave action, therefore wider back-beach sections will offer more protection (Anfuso and Martínez Del Pozo 2009, Rangel-Buitrago and Anfuso 2015), indicating the narrow back-beach sections would make the majority of the sea turtle nesting beaches more vulnerable to oncoming waves (Rizzo et al. 2017). High beach exposure means beach orientation and low/no physical protection allows for direct wave action making beaches more susceptible to sand loss (Bryan et al. 2001, Mclaughlin and Cooper 2010, Goodhue et al. 2012). If the dune system is compromised through development or if no dunes occur, sand loss might be permanent as dunes act as sand reserves that replenish the beaches sand budget (Tinley 1985, Tsoar 2001, Abuodha and Woodroffe 2006). The beaches of the study are therefore overall more vulnerable to erosion as a result of characteristics that increases the risk of beach inundation/flooding processes (Gornitz et al. 1994).

3.4.2 Casuarina *presence and vulnerable nesting species*

Mamallapuram – Pondi beach (IN126/#126) and Nagapattinam (IN137/#29) are two important *Lepidochelys olivacea* nesting beaches with non-native *Casuarina* occurrence to an extent of more than 25% along the back-beach or dunes. The study showed that the highest proportion of olive ridley nesting beaches, were categorised within the High risk-High category, concurring with findings of Fuentes et al. (2013) and Wallace et al. (2011), which indicated that the olive ridley populations of the west and north-east Indian ocean are some of the least resilient/most vulnerable marine turtle regional management units (RMU's). Furthermore, non-native *Casuarina* species are most dominant on *L. olivacea* study sites (attributed to large scale plantations of *C. equisetifolia* on the Indian coastline), including Devi river mouth with 150 000 – 200 000 nesting females (Shanker et al. 2004a). The physical characterises of the Devi river mouth makes the nesting site vulnerable to episodic inundation and possible erosion (Kumar et al. 2010) and superimposed on this is the occurrence of extensive *Casuarina* spp. plantations near the river mouth.

The presence of *Casuarina* at the Devi river mouth has been flagged as a hindrance to the nesting of *L. olivacea* and a threat to the dynamism of the beach system (IOSEA website: http://www.ioseaturtles.org/feature_detail.php?id=551). Several other studies have reiterated the importance of removing invasive *Casuarina* trees along the coast of India; Chaudari et al. (2009) highlighted the potential negative impacts of *Casuarina* trees on *L. olivacea* turtles along the Tamil Nadu coast, demonstrating the effect of *Casuarina* trees on temperature and showed that fewer turtles nest in the presence of *Casuarina* trees. Das and Sandhu (2014) reviewed ecosystem services provided by *Casuarina* trees along the Odisha coastline and found that natural vegetation/native species such as mangroves and mixed cashew nut forests afforded more storm protection than *Casuarina* and questioned the policy of planting *Casuarina* as storm buffers. Bhalla (2007) tested the assumption that *Casuarina equisetifolia* bio-shields offer tsunami protection along the Coromandel coast and found no significant relationship between the Normalised Difference Vegetation Index (NDVI) and inundation distance. The results of this and the above-mentioned studies question the large-scale use of exotic *Casuarina* species for storm protection along the east coast of India.

3.4.3 CVI method limitations and success

The variables considered in this study were mainly dictated by availability of data at an ocean-based scale and variables like elevation (Kumar et al. 2010, Gornitz et al. 1994) and shoreline change (Thieler and Hammer-Klose 2000, Boruff et al. 2005, Pendleton et al. 2010) that are commonly used in CVI assessments had to be omitted. Indeed rates of shoreline erosion/accession establishes reliable data on spatial variation of erosion processes and relative vulnerability and can substitute other overlapping secondary indicators (Williams et al. 2001, Rangel-Buitrago and Anfuso 2015); Long term monitoring of shoreline change can definitively describe whether a beach has been eroding or accreting (Corbella and Stretch 2012), where elevation gives a good indication of a beach's ability to withstand or recover from episodic events such as storms or future threats, such as sea level rise, because if a beach is elevated the risk of flooding/wave inundation decreases (Abuodha and Woodroffe 2006). Therefore, it is recommended that elevation and shoreline change should be included in CVI studies.

Analysing local scale (beach) vulnerability to storms using International Best Track Archive for Climate Stewardship (IBTrACS Version 3 dataset) potentially compromised the integrity of the results; The IBTrACS storm data were not normally distributed and included extreme outliers over a very large time frame (170 years). This means the storm intensity and frequency score categories generated by ArcGIS were not representative of mean storm conditions and included some of the most extreme events over the past century. Using these score categories, most nesting beaches were allocated low storm scores despite studies indicating frequent and intense storm events for some of these regions (De et al. 2005, Webster et al. 2005, Goswami et al. 2006). Another consideration regarding the spatial analysis of the storms is the resolution at which storm values (frequency and intensity) were estimated. The output cell size was extremely coarse (cell size equalled 250 km^2) and could potentially attribute storm values to beaches outside of the storm's influence. Output cell size was based on the minimum (100 km) and maximum (2200 km) storm diameter reported by Merrill (1984) and was not based on the IBTrACS storm circumferences, which could potentially give a better indication of actual storm sizes for different regions.

The applied CVI also did not adequately address recovery potential of beaches. Even though the assessment incorporates some indicators of system resilience (for example, back-beach width or integrity of dune system), it does not give a good indication of temporal adaption of the beach system. An approach by Pethick and Crooks (2000), is recommended, which relates disturbance event frequency to relaxation time (the time taken for the littoral component to recover its shape). Thereby providing an approximation of temporal variability of coastal features. However, this approach can only be applied to local scale studies and was therefore excluded from this study.

The applied CVI method should only be considered as a first level vulnerability assessment of beaches based on proneness to erosion and should not be accepted as a precise indication of a beach's resilience or recovery potential when considering SLR and storm impact (Abuodha and Woodroffe

2006, Goodhue et al. 2012). Although every care has been taken to ensure the integrity of the assessment, the limitations of the tool need to be considered. The CVI assessment is not an indication of present or historic erosion, nor does it make absolute predictions of potential future erosion. The success of the original CVI (Gornitz et al. 1994) and adapted versions, including this study and others such as Mclaughlin and Cooper (2010), Di Paola et al. (2011) and Rizzo et al. (2017), lies in the illumination of beaches at risk to potential erosion for further local assessments by modelling more analytical and numerical data (e.g. Mahendra et al. 2011) that measures actual erosion or shoreline change. Despite the omitted variables the assessment can be considered a useful tool to estimate beach erosion vulnerability, based on several physical beach characteristics and drivers: the back-beach width (Rizzo et al. 2017), beach orientation and protection (Bryan et al. 2001, Mclaughlin and Cooper 2010, Goodhue et al. 2012), the dune system (Benassai et al. 2015, Rizzo et al. 2017), wave height and tide range (Gornitz et al. 1994, Boruff et al. 2005, Abuodha and Woodroffe 2006), coastal development (Kumar et al. 2010, Mclaughlin and Cooper 2010), sea level rise (Gornitz et al. 1994) and storminess (Özyurt and Ergin 2010, Li and Li 2011).

3.4.4 Conclusion

The study emphasized the presence and extensive use of non-native *Casuarina* species in coastal regions throughout the IOSEA. Furthermore, the study used a novel vulnerability index based on long term global data sets (rather than local) to highlight high erosion vulnerability of seven important sea turtle nesting beaches. The study showed that beaches with *Casuarina* present were not more prone to erosion than beaches without.

REFERENCES

ABUODHA, P. A. and WOODROFFE, C. D. 2006. Assessing vulnerability of coasts to climate change: A review of approaches and their application to the Australian coast. *GIS for the Coastal Zone: A selection of Papers from CoastGIS 2006*:458.

ANFUSO, G. and MARTÍNEZ DEL POZO, J. Á. 2009. Assessment of coastal vulnerability through the use of GIS tools in south Sicily (Italy). *Environmental Management* 43:533–545.

BALDWIN, R., HUGHES, G. R. and PRINCE, R. I. T., 2003. Loggerhead turtles in the Indian Ocean. In: Bolton, A. B. and Witherington, B. E. (eds). Loggerhead Sea Turtles. Smithsonian. pp. 218–232.

BAN, N. C., ALIDINA, H. M. and ARDRON, J. A. 2010. Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. *Marine Policy* 34:876–886.

BATISH, D. R., SINGH, H. P. and KOHLI, R. K. 2001. Vegetation exclusion under *Casuarina equisetifolia* L.: Does allelopathy play a role? *Community Ecology* 2:93–100.

BELL, C., MORO, D. and PENDOLEY, K. 2014. Patterns and pathways: Marine construction and patterns of dispersal in hatchling flatback turtles at Barrow Island. Proceedings of the Second Western Australian Marine Turtle Symposia: 14.

BENASSAI, G., DI PAOLA, G. and AUCELLI, P. P. C. 2015. Coastal risk assessment of a micro-tidal littoral plain in response to sea level rise. *Ocean and Coastal Management* 104:22–35.

BHALLA, R. S. 2007. Do bio-shields affect tsunami inundation? *Current Science* 93:831–833.

BORUFF, B. J., EMRICH, C. and CUTTER, S. L. 2005. Erosion hazard vulnerability of US coastal counties. *Journal of Coastal Research* 215:932–942.

BOUCHARD, S. S. and BJORNDAL, K. A. 2000. Sea turtles as biological transporters of nutrients and energy from marine to terrestrial ecosystems. *Ecology* 81:2305–2313.

BOURJEA, J., LAPEGUE, S., GAGNEVIN, L., BRODERICK, D., MORTIMER, J.A., CICCIONE, S., ROOS, D., TAQUET, C. and GRIZEL, H., 2007. Phylogeography of the green turtle, *Chelonia mydas*, in the Southwest Indian Ocean. *Molecular Ecology*, 16:175-186.

BROOKS, N. 2003. Vulnerability, risk and adaptation: A conceptual framework. *Tyndall Centre for Climate Change Research* Working Paper 38: p16.

BROWN, A. C. and MCLACHLAN, A. 2002. Sandy shore ecosystems and the threats facing them: Some predictions for the year 2025*. Environmental Conservation* 29:62–77.

BROWN, A. C., MCLACHLAN, A., JACKSON, N. L. and SHERMAN, D. J. 2008. Sandy shores of the near future. In: Polunin, N. V. C. (ed.). *Aquatic Ecosystems; Trends and Global Prospects*. Cambridge University Press, New York, pp. 263-280.

BRYAN, B. A., HARVEY, N., BELPERIO, T. and BOURMAN, B. 2001. Distributed process modelling for regional assessment of coastal vulnerability to sea-level rise. *Environmental Modelling and Assessment* 6:57–65.

BULLERI, F. and CHAPMAN, M. G. 2010. The introduction of coastal infrastructure as a driver of change in marine environments. *Journal of Applied Ecology* 47:26–35.

CAB International. 2000. Forestry compendium global module. CAB International Wallingford

CHARLIER, R. H., CHAINEUX, M. C. P. and MORCOS, S. 2005. Panorama of the history of coastal protection. *Journal of Coastal Research* 21:79–111.

CHAUDARI, S., PRASAD, K. D. and SHANKER, K. 2009. Impact of *Casuarina* plantations on Olive Ridley Turtle nesting along the Northern Tamil Nadu Coast , India. ATREE, Bangalore and MCBT, Mamallapuram, India. pp. 44.

CORBELLA, S. and STRETCH, D. D. 2012. Decadal trends in beach morphology on the east coast of South Africa and likely causative factors. *Natural Hazards and Earth System Science* 12:2515–2527.

COSTAS, S., FERREIRA, O. and MARTINEZ, G. 2015. Why do we decide to live with risk at the coast? *Ocean and Coastal Management* 118:1–11.

CRAIN, C. M., KROEKER, K. and HALPERN, B. S. 2008. Interactive and cumulative effects of multiple human stressors in marine systems. *Ecology Letters* 11:1304–1315.

CROWELL, M., EDELMAN, S., COULTON, K. and MCAFEE, S. 2007. How many people live in coastal areas? *Journal of Coastal Research* 23:iii–vi.

DANIELSEN, F., SØRENSEN, M. K., OLWIG, M. F., SELVAM, V., PARISH, F., BURGESS, N. D., HIRAISHI, T., KARUNAGARAN, V. M., RASMUSSEN, M. S., HANSEN, L. B. and QUARTO, A. 2005. The Asian tsunami: A protective role for coastal vegetation. *Science 310*: 643.

DAS, S. and SANDHU, H., 2014. Role of exotic vegetation in coastal protection. *Economic and Political Weekly* 49: 43.

DAVIES J. L. 1980. *Geographical Variation to Coastal Development*, 2nd Edition, Longman (Pearson Education Limited).

DAWSON, J. L. and SMITHERS, S. G., 2010. Shoreline and beach volume change between 1967 and 2007 at Raine Island, Great Barrier Reef, Australia. *Global and Planetary Change* 72:141-154.

DEFEO, O. AND MCLACHLAN, A. 2013. Global patterns in sandy beach macrofauna: Species richness, abundance, biomass and body size. *Geomorphology* 199:106-114.

DEFEO, O., MCLACHLAN, A., SCHOEMAN, D. S., SCHLACHER, T. A., DUGAN, J., JONES, A., LASTRA, M. and SCAPINI, F. 2009. Threats to sandy beach ecosystems: A review. *Estuarine, Coastal and Shelf Science* 81:1–12.

DE LANGE, H. J., SALA, S., VIGHI, M. and FABER, J. H. 2010. Ecological vulnerability in risk assessment - A review and perspectives. *Science of the Total Environment* 408:3871–3879.

DI PAOLA, G., IGLESIAS, J., RODRIGUEZ, G., BENASSAI, G., AUCELLI, P. and PAPPONE, G. 2011. Estimating coastal vulnerability in a meso - tidal beach by means of quantitative and semi-quantitative methodologies. *Journal of Coastal Research* 61:1–7.

DUGAN, J. E., DEFEO, O., JARAMILLO, E., JONES, A. R., LASTRA, M., NEL, R., PETERSON, C. H., SCAPINI, F., SCHLACHER, T. and SCHOEMAN, D. S. 2010. Give beach ecosystems their day in the sun. *Science* 329:1146.

EMANUEL, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436:686–688.

FEAGIN, R. A., MUKHERJEE, N., SHANKER, K., BAIRD, A. H., CINNER, J., KERR, A. M., KOEDAM, N., SRIDHAR, A., ARTHUR, R., JAYATISSA, L. P., LO SEEN, D., MENON, M., RODRIGUEZ, S., SHAMSUDDOHA, M. and DAHDOUH-GUEBAS, F. 2010. Shelter from the storm? Use and misuse of coastal vegetation bio-shields for managing natural disasters. *Conservation Letters* 3:1–11.

FEAGIN, R. A., SHERMAN, D. J. and GRANT, W. E. 2005. Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. *Ecological Society of America* 3:359–364.

FEKETE, A., DAMM, M. and BIRKMANN, J. 2010. Scales as a challenge for vulnerability assessment. *Natural Hazards* 55:729–747.

FUENTES, M. M. P. B., PIKE, D. A., DIMATTEO, A. and WALLACE, B. P. 2013. Resilience of marine turtle regional management units to climate change. *Global Change Biology* 19:1399–1406.

FUENTES, M. M. P. B., LIMPUS, C. J., HAMANN, M. AND DAWSON, J. 2010. Potential impacts of projected sea-level rise on sea turtle rookeries. *Aquatic Conservation: Marine and Freshwater Ecosystems* 20:132-139.

GBIF. 2008. Global Biodiversity Information Facility (GBIF) Work programme 2009–2010. Available: http://www2.gbif.org/WP2009-10.pdf. Accessed 21 Feb 2017, UK.

GLICK, P., STEIN, B. A. and EDELSON, N. A. (eds). 2011. Scanning the conservation horizon: A guide to climate change vulnerability assessment. National Wildlife Federation, Washington, D.C.

GOITOM, M., TECLEMARIAM, Y., and MENGSTU, T. 2006. Field Trip Report on Sea Turtle Nesting Assessment on the Islands of Mojeidi and Aucan. Massawa, Eritrea: Ministry of Fisheries. Unpublished report

GOODHUE, N., ROUSE, H., RAMSAY, D., BELL, R., HUME, T. AND HICKS, M. 2012. Coastal adaptation to climate change: Mapping a New Zealand coastal sensitivity index. *A report prepared as part of the Coastal Adaptation to Climate Change Project under contract (CO1XO802) to MBIE, NIWA, Hamilton, New Zealand. 43p*.

GORDON, D. R. 1998. Effects of invasive , non-indigenous plant species on ecosystem processes : Lessons from Florida. *Ecological Applications* 8:975–989.

GORNITZ, V. M. 1991. Global coastal hazards from future sea-level rise. *Global and Planetary Change* 89:379–398.

GORNITZ, V. M., DANIELS, R. C., WHITE, T. W. and BIRDWELL, K. R. 1994. The development of a coastal risk assessment database: Vulnerability to sea-level rise in the U.S. southeast. *Journal of Coastal Research.* Special issue 12:327–338.

GOSWAMI, B. N., VENUGOPAL, V., SENGUPTA, D., MADHUSOODANAN, M. S. and XAVIER, P. K. 2006. Increasing trend of extreme rain events over India in a warming environment. *Science* 314:1442–1444.

HALPERN, B. S., MCLEOD, K. L., ROSENBERG, A. A. and CROWDER, L. B. 2008. Managing for cumulative impacts in ecosystem-based management through ocean zoning. *Ocean and Coastal Management* 51:203–211.

HARDMAN, C. J., WILLIAMS, S., MANCO, B. N. and HAMILTON, M. A. 2012. Predicting the potential threat of *Casuarina equisetifolia* to three endemic plant species on the Turks and Caicos Islands. *Oryx* 46:204–212.

HARLEY, C. D. G., HUGHES, A. R., HULGREN, K. M., MINER, B. G., SORTE, C. J. B., THORNBER, C. S., RODRIGUEZ, L. F., TOMANEK, L. and WILLIAMS, S. L. 2006. The impacts of climate change in coastal marine systems. *Ecology Letters* 9:228–241.

HARRIS, L., NEL, R., HOLNESS, S. and SCHOEMAN, D. 2015. Quantifying cumulative threats to sandy beach ecosystems: A tool to guide ecosystem-based management beyond coastal reserves. *Ocean and Coastal Management* 110:12–24.

HARRIS, L. R. 2012. An ecosystem-based spatial conservation plan for the South African sandy beaches. PhD thesis, Nelson Mandel Metropolitan University, Port Elizabeth, South Africa.

HARRIS, L.R. 2008. The ecological implications of sea-level rise and storms for sandy beaches in Kwazulu-Natal. MSc thesis, Nelson Mandel Metropolitan University, Port Elizabeth, South Africa.

HITIPEUW, C., WWF INDONESIA. 2006. Leatherback nesting in Papua, Indonesia: Personal communication. In The State of the World’s Sea Turtles Report, vol. 1 (2006).

HUGHES, P. and BRUNDRIT, G. B. 1992. An index to assess South Africa's vulnerability to sea- level rise. *South African Journal of Science* 88:308–311.

IONESCU, C., KLEIN, R. J. T., HINKEL, J., KAVI KUMAR, K. S. and KLEIN, R. 2009. Towards a formal framework of vulnerability to climate change. *Environmental Modelling and Assessment* 14:1–16.

IPCC. 2007. Climate change 2007: The physical science basis. Contribution of Working Group 1 to the Fourth Assessment Report of the *Intergovernmental Panel on Climate Change*. Solomon S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H. L. (eds). Cambridge University Press. United Kingdom and New York, NY, USA. pp, 727–728.

IPCC. 2014: Climate Change 2014: Synthesis Report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151.

JAYATHILAKA, R. A. M., PERERA, H. A. C. C. and HAPUTHANTHRI, S. S. K. 2016. Marine turtles of Sri Lanka; Status, issues, threats and conservation strategies. National Resources Research and Development Agency (NARA), Scientific Sessions.

JULIUS, S. H., WEST, J. M., JOYCE, L. A., KAREIVA, P., KELLER, B. D., PALMER, M. AND PETERSON, C. 2008. Preliminary review of adaptation options for climate-sensitive ecosystems and resources. *National Parks*, *1*(6).

KASPERSON, J. X., KASPERSON, R. E. AND TURNER, B. L. 1995. *Regions at risk*. United Nations University Press.

KATHIRESAN, K. and RAJENDRAN, N. 2005. Coastal mangrove forests mitigated tsunami. *Estuarine, Coastal and Shelf Science* 65:601–606.

KEANE, R. M. and CRAWLEY, M. J. 2002. Exotic plant invasions and the enemy release hypothesis. *Trends in Ecology and Evolution.* 17:164–170.

KENNEDY, V. S., TWILLEY, R. R., KLEYPAS, J. A, COWAN, J. H. and HARE, S. R. 2002. Coastal and marine ecosystems and global climate change: potential effects on U.S. resources. Pew Research Center, Available at: http://www.c2es.org/docUploads/marine_ecosystems.pdf

KLUKAS, R.W. 1969. Exotic terrestrial plants in South Florida with emphasis on Australian pine (*Casuarina equisetifolia*). *Homestead, Florida: Everglades National Park. Report*, (33030).

KOT, C. Y., FUJIOKA, E., DIMATTEO, A. D., WALLACE, B. P., HUTCHINSON, B. J., CLEARY, J., HALPIN, P. N. and R. B. MAST. 2015. The state of the world's sea turtles online database: Data provided by the SWOT Team and hosted on OBIS-SEAMAP. Oceanic Society, Conservation International, IUCN Marine Turtle Specialist Group (MTSG), and Marine Geospatial Ecology Lab, Duke University. http://seamap.env.duke.edu/swot.

KUMAR, T., MAHENDRA, R., NAYAK, S., RADHAKRISHNAN, K. and SAHU, K. 2010. Coastal vulnerability assessment for Orissa State, east coast of India. *Journal of Coastal Research* 26:523–534.

LI, K. and LI, G. S. 2011. Vulnerability assessment of storm surges in the coastal area of Guangdong Province. *Natural Hazards and Earth System Science* 11:2003–2010.

LIMPUS, C., MILLER, J., PARMENTER, C. and LIMPUS, D. 2003. The green turtle, *Chelonia mydas*, population of Raine Island and the northern Great Barrier Reef: 1843-2001. *Memoirs of the Queensland Museum* 49:349–440.

LIMPUS, C. J., and ENVIRONMENTAL PROTECTION AGENCY, STATE OF QUEENSLAND. 2009. Flatback nesting in Queensland: Personal communication. In SWOT Report—The State of the World's Sea Turtles, vol. 4 (2009).

LOICZ. 1995. Coastal zone resources assessment guidelines. LOICZ, Manila

MAHENDRA, R. S., MOHANTY, P. C., BISOYI, H., KUMAR, T. S. and NAYAK, S. 2011. Assessment and management of coastal multi-hazard vulnerability along the Cuddalore-Villupuram, east coast of India using geospatial techniques. *Ocean and Coastal Management* 54:302–311.

MASSELINK, G. and HUGHES, M. G. 2003. Introduction to coastal processes and geomorphology. Oxford University Press.

MCLACHLAN, A. and BROWN, A. C. 2006. *Ecology of sandy shores*. Academic Press.

MCLAUGHLIN, S. and COOPER, J. A. G. 2010. A multi-scale coastal vulnerability index: A tool for coastal managers? *Environmental Hazards* 9:233–248.

MCLAUGHLIN, S., MCKENNA, J. and COOPER, J. A. G. 2002. Socio-economic data in coastal vulnerability indices: Constrains and opportunities. *Journal of Coastal Research* 497:487–497.

MET OFFICE. 2017. Beaufort wind force scale. [ONLINE] Available at: https://www.metoffice.gov.uk/binaries/content/assets/mohippo/pdf/b/7/fact_sheet_no._6.pdf. [Accessed 23 October 2017].

MORTON, J. F. 1980. The Australian pine or beefwood (*Casuarina equisetifolia* L.), an invasive 'weed' tree in Florida. *Proceedings of the Florida State Horticultural Society* 93:87–95.

MUKHERJEE, N., BALAKRISHNAN, M. and SHANKER, K. 2009. Bioshields and ecological restoration in tsunami-affected areas in India. In: Moksness, E., Dahl, E., and Støttrup, J. (eds). *Integrated Coastal Zone Management*, John Wiley and Sons, Oxford. pp. 131–144.

NATURE SEYCHELLES. 2008. Hawksbill nesting on Cousin Island, Seychelles. In SWOT Report—The State of the World's Sea Turtles 3 (2008).

NICHOLLS, R. J., WONG, P. P., BURKETT, V., WOODROFFE, C. D. and HAY, J. 2008. Climate change and coastal vulnerability assessment: Scenarios for integrated assessment. *Sustainability Science* 3:89–102.

ÖZYURT, G. and ERGIN, A. 2010. Improving coastal vulnerability assessments to sea-level rise: A new indicator-based methodology for decision makers. *Journal of Coastal Research* 262:265–273.

PATWARDHAN, A., SEMENOV, S., SCHNIEDER, S., BURTON, I., MAGADZA, C., OPPENHEIMER, M., PITTOCK, B., RAHMAN, A., SMITH, J., SUAREZ, A. and SUKUMAR, R. 2007. Assessing key vulnerabilities and the risk from climate change. *Climate change* p. 779-810.

PENDLETON, E. A., THIELER, E. R. and WILLIAMS, S. J. 2010. Importance of coastal change variables in determining vulnerability to sea- and lake-level change. *Journal of Coastal Research* 261:176–183.

PENDOLEY, K., HOWITT, L., SPEIRS, M., and VITERNBERGS, A. 2008. Hawksbill nesting in Western Australia. In SWOT Report—The State of the World's Sea Turtles, vol. 3 (2008). Nesting Beach: Bivalve Beach, Pilbara, Western Australia.

PERNAS, T., WHEELER, G., LANGELAND, K., GOLDEN, E., PURCELL, M., TAYLOR, J., BROWN, K., TAYLOR, S. D. and ALLEN, E. 2013. Australian pine management plan for Florida. Florida Exotic Pest Plant Council, www.fleppc.org.

PETHICK, J. 2001. Coastal management and sea-level rise. *Catena* 42:307–322.

PETHICK, J. and CROOKS, S. 2000. Development of a coastal vulnerability index: a geomorphological perspective. *Environmental Conservation* 27:359–367.

PHILLIPS, M. and CRISP, S. 2010. Sea level trends and NAO influences: The Bristol Chanel/Seven Estuary. *Global Planet Change* 73:211–218

PILCHER, N. 2007. Loggerhead nesting on Masirah Island, Oman: Personal communication. In SWOT Report—State of the World's Sea Turtles, vol. 2 (2007).

POTGIETER, L. J., RICHARDSON, D. M. and WILSON, J. R. U. 2014. *Casuarina*: Biogeography and ecology of an important tree genus in a changing world. *Biological Invasions* 16:609–633.

RANGEL-BUITRAGO, N. and ANFUSO, G. 2015. Risk assessment of storms in coastal zones: Case studies from Cartagena (Colombia) and Cadiz (Spain). *SpringerBriefs in Earth Sciences* Book Series, Springer, Berlin. pp7–14.

RENE, F. AND ROOS, D. 1996. The status of sea turtle conservation in French Territories of the Indian Ocean: Isles Eparces. *Status of Sea Turtle Conservation in the Western Indian Ocean. UNEP Regional Seas Reports and Studies*, 165: 151-155.

RIZZO, A., AUCELLI, C. P. C., GRACIA, F. J. and ANFUSO, G. 2017. A novelty coastal susceptibility assessment method: application to Valdelagrana area (SW Spain). *Journal of Coastal Conservation*: https://doi.org/10.1007/s11852-017-0552-2.

ROYAL METEOROLOGICAL SOCIETY. 2017. Beaufort scale. [ONLINE] Available at: https://www.rmets.org/weather-and-climate/observing/beaufort-scale. [Accessed 23 October 2017].

SAMARAKOON, M. B., TANAKA, N. and IIMURA, K. 2013. Improvement of effectiveness of existing *Casuarina equisetifolia* forests in mitigating tsunami damage. *Journal of Environmental Management* 114:105–114.

SCHLACHER, T. A., DUGAN, J., SCHOEMAN, D. S., LASTRA, M., JONES, A., SCAPINI, F., MCLACHLAN, A. and DEFEO, O. 2007. Sandy beaches at the brink. *Diversity and Distributions* 13:556–560.

SEALEY, N. 2006. The cycle of *Casuarina*-induced beach erosion - A case study from Andros, Bahamas. pp. 197–205, *The 12th Symposium on the Geology of the Bahamas and other Carbonate Regions (2004)*.

SHANKER, K., PANDAV, B. and CHOUDHURY, B. C. 2004a. An assessment of the olive ridley turtle (*Lepidochelys olivacea*) nesting population in Orissa, India. *Biological Conservation* 115:149–160.

SHANKER, K., RAMADEVI, J., CHOUDHURY, B. C., SINGH, L. and AGGARWAL, R. K. 2004b. Phylogeography of olive ridley turtles (*Lepidochelys olivacea*) on the east coast of India: Implications for conservation theory. *Molecular Ecology* 13:1899–1909.

TANAKA, N. 2009. Vegetation bio-shields for tsunami mitigation: Review of effectiveness, limitations, construction, and sustainable management. *Landscape and Ecological Engineering* 5:71–79.

TINLEY, K. . 1985. Coastal dunes of South Africa. South African National Scientific Programmes Report No 109, CSIR. p 300.

THIELER, E. R. and HAMMER-KLOSE, E. S. 2000. National assessment of coastal vulnerability to sea-Level rise: Preliminary results for the US Pacific coast. Woods Hole, MA: United States Geological Survey (USGS), Open File Report 00-178, 1.

TSOAR, H. 2001. Types of Aeolian Sand Dunes and their formation. In: Balmforth, N. J. and Provenzale, A. (eds). *Geomorphological Fluid Mechanics. Lecture Notes in Physics* vol 582:403–429. Springer, Berlin.

UNDRO. 1982: *Natural disasters and vulnerability analysis.* Geneva: Office of the United Nations disaster relief CO-ORDINATOR.

WALLACE, B. P., DIMATTEO, A. D., BOLTEN, A. B., CHALOUPKA, M. Y., HUTCHINSON, B. J., ABREU-GROBOIS, F. A., MORTIMER, J. A., SEMINOFF, J. A., AMOROCHO, D., BJORNDAL, K. A. AND BOURJEA, J. 2011. Global conservation priorities for marine turtles. *PloS one*, 6(9) e24510, https://doi.org/10.1371/journal.pone.0024510.

WEBSTER, P. J., HOLLAND, G. J., CURRY, J. A. and CHANG, H. R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309:1844–1846.

WHEELER, G. S., TAYLOR, G. S., GASKIN, J. F. and PURCELL, M. F. 2011. Ecology and management of Sheoak (*Casuarina* spp.), an Invader of Coastal Florida, U.S.A. *Journal of Coastal Research* 27:485–492.

WHITING, A. U., THOMSON, A., CHALOUPKA, M. Y., and LIMPUS, C.J. 2009. Seasonality, abundance, and breeding biology of one of the largest populations of nesting flatback turtles, *Natator depressus*: Cape Domett, Western Australia. *Australian Journal of* Zoology 56:297-303.

WILLIAMS, A. T., ALVEIRINHO-DIAS, J., NOVO, F. G., GARCIA-MORA, M. R., CURR, R. AND PEREIRA, A. 2001. Integrated coastal dune management: checklists. *Continental Shelf Research*, 21:1937-1960.

WILLIAMS, S. L. and GROSHOLZ, E. D. 2008. The invasive species challenge in estuarine and coastal environments: Marrying management and science. *Estuaries and Coasts* 31:3–20.

WOLANSKI, E. 2007. Synthesis of the protective functions of coastal forests and trees against natural hazards. *Coastal protection in the aftermath of the Indian Ocean tsunami: What role for forests and trees? Proceedings of the Regional Technical Workshop*:161–184.

ZHANG, K., DOUGLAS, B. C. and LEATHERMAN, S. P. 2004. Global warming and coastal erosion. *Climate Change* 64:41–58.

Chapter 4 : *Conclusions and implications for beach management policies*

The main aim of the study was to investigate the potential use of non-native *Casuarina* trees as a coastal protection measure within sea turtle nesting habitat. The study suggests that even though some characteristics remain unaffected (sand moisture and shade density), *Casuarina* affect the back-beach and the primary foredune negatively, and coastal functioning is different from native/natural vegetation conditions. *Casuarina* affects the back-beach and dune environment by (i) creating a concave back-beach shape; (ii) by lowering the substrate pH levels; and (iv) lowering *in situ* sand temperature at sea turtle nest depth (around 50 cm). The study showed that at a regional scale, back-beach environment and coastline response were not altered in the presence of non-native *Casuarina* trees as opposed to native or no vegetation conditions, but that *Casuarina* had negative local scale effects. The use of *Casuarina* trees as a coastal protection measure is therefore questionable, especially in areas where these species are considered exotic.

4.1 Bio-shield policy

The study demonstrated that *Casuarina* trees were present throughout the Indian Ocean and South-East Asia, predominantly on beaches outside of their native range; Non-native *Casuarina* trees occurred on approximately 28% of the study beaches, concurring with other studies demonstrating extensive introduction of exotic *Casuarina* throughout the Indian Ocean (Danielsen et al. 2005, Bhalla 2007, Feagin et al. 2010, Tanaka and Thuy 2010, Mathiventhan and Jayasingum 2014, Riyasahamed 2017). Studies advocating (Danielsen et al. 2005, Kathiresan and Rajendran 2005, Olwig et al. 2009, Tanaka 2009, Tanaka and Thuy 2010, Samarakoon et al. 2013, Mathiventhan and Jayasingum 2014, Riyasahamed 2017) and opposing (Kerr et al. 2006, Bhalla 2007, Kerr and Baird 2007, Feagin et al. 2010, Pernas et al. 2013, Awale and Phillott 2014, Das and Sandhu 2014) the use of *Casuarina* as a coastal protection tool against the inundation and erosion impacts by extreme episodic events were reviewed. This study's findings supports the opposition of the unmitigated use of exotic vegetation, based on the lack of empirical evidence demonstrating the effectiveness of exotic *Casuarina* for coastal protection and demonstrated negative impacts of *Casuarina* trees on sandy beaches and sensitive species such as sea turtles by this study and others (Morton 1980, Jadhav and Gaynar 1995, Gordon 1998, Batish et al. 2001, Patil et al. 2002, Sealey 2006, Chaudari et al. 2009, Buehler 2010, Wheeler et al. 2011, Hardman et al. 2012).

The promotion of bio-shields on beaches for the purpose of protection against extreme events devalues the other benefits offered by a functional sandy beach and dune ecosystems (Feagin et al. 2010). Beaches support of a variety of fauna and flora, serving as an important habitat to a unique spectrum of animals and vegetation (Barbier et al. 2011), including endangered species such as sea turtles (Miller et al. 2003). Beaches also offer other invaluable benefits that include processes like the breakdown of organic materials and pollutants, water filtration and purification, nutrient mineralisation and recycling (Defeo et al. 2009) and includes, but is not limited to protection against sea level rise and increased storm activity (Pilkey et al. 2011). Sandy beach and dune ecosystems are therefore of critical importance to support a range of specialized biotic assemblages and provide irreplaceable ecosystem services (Barbier et al. 2011), but bio-shield policies focused only on forest protection services, essentially ignores the fact that natural/native vegetation and a consequential intact dune system can offer protection against erosion and flooding events (Bradshaw et al. 2007; Vuik et al. 2016).

The key drivers behind decision making processes need to be transparent and scientific evidence as to the effectiveness of the initiative need to be demonstrated (Kerr and Baird 2007). Feagin et al. (2010) suggest long-standing political agendas as key drivers in bio-shield policy implementation, especially in developing countries and shows contradictory policies with regards to bio-shield implementation initiated by international institutions (e.g., FAO and CIFOR), where pre-determined policy outcomes would allow for both the a) understatement of the ability of bio-shield forests to reduce rainfall-induced flood frequency in order to promote a political agenda of deforestation and harvesting (Alila et al. 2009) and b) overstating the benefits of coastal vegetation during extreme events to save costs. Coastal policy decisions cannot operate within economic and social spheres in isolation, science needs to be incorporated to account for environmental resilience; which means that beaches should be considered as ecosystems vulnerable to anthropogenic modifications and global change, where changes in ecosystem functioning caused by, for example, the introduction of exotic vegetation/bio-shields, can increase the vulnerability of beaches.

4.2 Global snapshot of beach vulnerability

Regional (IOSEA) erosion vulnerability of 50 sea turtle nesting beaches were estimated by utilizing global indicator data sets and seven beaches were demonstrated to be highly vulnerable to erosion (**Figure 3.24**); Mamallapuram – Pondi beach (IN126/#28), Cemetery beach (AU119/#4), Bentota beach (LK02/#33), Brunei beach (BNX/#18), Nagapattinam (IN137/#29), Wreck Island (AU34/#11) and Kosgoda beach (LK21/#35) fell within the High risk-High threat category. A recent study by Luijendijk et al. (2018) evaluated global erosion trends for sandy beaches and identified erosion hot spots of coastal erosion/accretion. Six of the seven beaches identified as highly vulnerable to erosion by this study (**Figure i**), fell within erosion hotspots identified by Luijendijk et al. (2018). Luijendijk et al. (2018)

did not include small islands in the analysis, therefore Wreck Island (AU34/#11) (the 7th beach) is excluded.

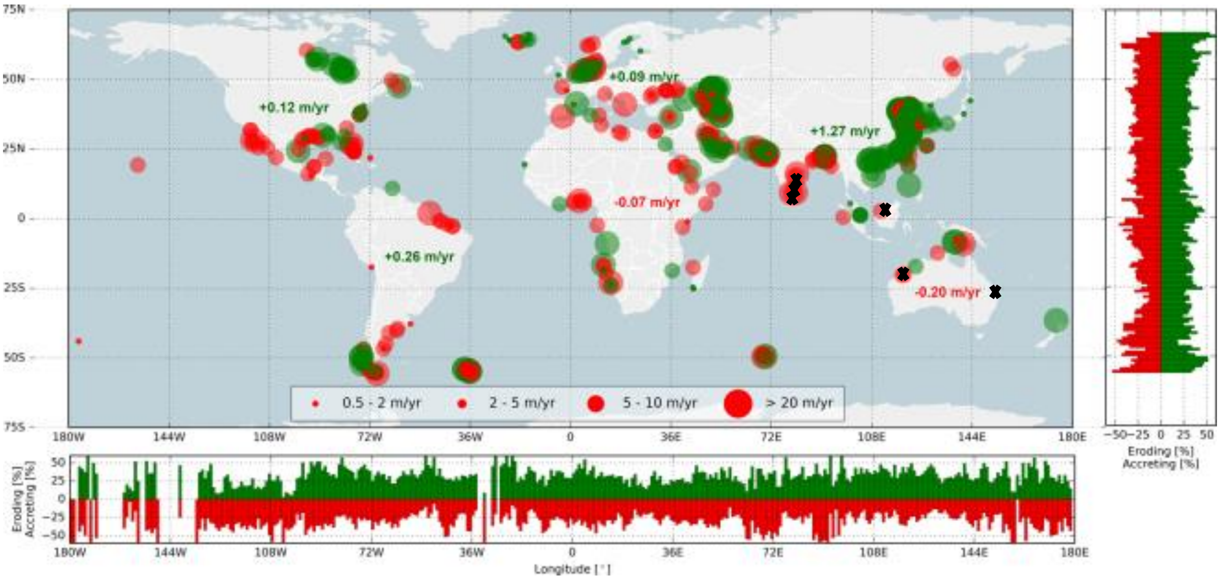


Figure i: Global hotspots of beach erosion/accretion by Luijendijk et al. (2018) and sea turtle nesting beaches highly vulnerable to erosion (this study); the red circles indicate erosion and the green circles indicate accretion for the four relevant shoreline dynamic classifications (see legend). The black crosses indicate the sea turtle nesting beaches demonstrated to be highly vulnerable to erosion. The bar plots to the right and at the bottom present the relative occurrence of eroding (accreting) sandy shorelines per degree latitude and longitude, respectively. The numbers presented in the main plot represent the average change rate for all sandy shorelines per continent.

Beach erosion showed relatively low latitudinal variation (Luijendijk et al. 2018), but certain indicators used to quantify erosion vulnerability for the sea turtle nesting beaches have been shown to have strong latitudinal and therefore regional variation. With regards to climate change, strong regional patterns emerge for sea level rise (Church et al. 2013) and storms (Webster et al. 2005); Generally, regional patterns show that the Indian Ocean is comparatively less threatened by SLR than the North Atlantic and Pacific Ocean regions (Church et al. 2013); **Figure ii**; Analysis of the global training data set showed the highest density of beaches with high sea-level rise (>0.48 m) occurred on the European Coastline (North Atlantic Ocean; **Figure A3.2: 0.2**), while beaches closer to the equator in South America (Brazil, Chile, Ecuador, Uruguay) have low and moderate SLR (0.33 – 0.4). The beaches of the Indian Ocean and South-East Asia had comparatively moderate to low sea level rise values (0.36 – 0.40 m). This is true for the IOSEA sea turtle nesting beaches as well, as the sea level rise values of theses sea turtle nesting beaches ranged from 0.31 - 0.38 m.

The NOAA archived storm track data (1848 to 2018), showed frequent (track density = 0 – 0.62 per km^2) and sometimes intense (0 – 155 knots) storms over the North Atlantic and North Pacific Ocean (**Figure 3.22**). Lower storm frequency was indicated for the Indian Ocean (track density = 0 – 0.28 per km^2) and very low frequencies were recorded for the nesting sites (0 – 0.14 per km^2; **Figure A3.2: 0.3**). Some intense storms occur across the Indian Ocean (0 – 155 knots), but comparatively less intense storms were recorded for the nesting beaches (0 - 77 knots; **Figure A3.2: 0.4**). Therefore, the study/nesting beaches of the IOSEA are not as threatened by climate change (sea level rise or frequent and intense storms) like the beaches of the North Atlantic and North Pacific Ocean, including important sea turtle populations, such as the North Pacific loggerhead population, the North Central Pacific greens and hawksbills populations and the Northwest Atlantic Kemps ridley population (Wallace et al. 2011, Fuentes et al. 2013).

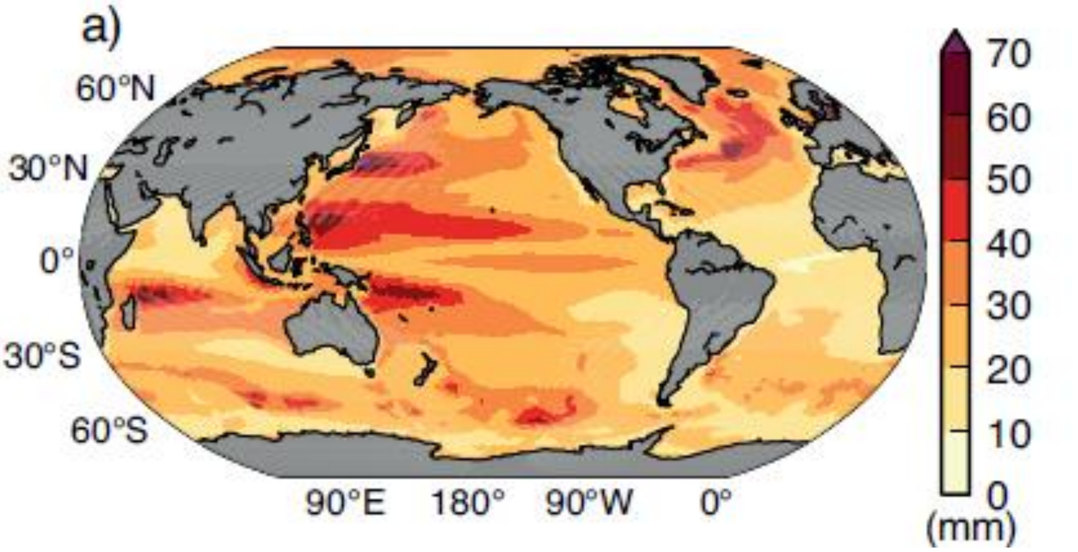


Figure ii: Map by Church et al. (2013), showing root-mean square interannual dynamic sea level rise (mm) variability in a CMIP5 multi-model ensemble (1951 – 2005).

While the sea turtle nesting beaches have been shown to be under low threat to sea level rise and storminess, they are at risk from climate change on account of narrow back beach width and lack of a dune system; The majority of the sea turtle nesting beaches had a narrow back-beach (< 10 m) with no dunes. This trend might be explained by the different wave climates, as wind and wave energy drives the formation of the surf, backshore and dune ridges (McArdle and McLachlan 1992; Short 1993, Short 1999); Wave height is highest in the Indian sector of the Indian Ocean and southwest

Australia (Semedo et al. 2013), corresponding to the wider back beaches with single or multiple dune ridges of the nesting beaches occurring along the east India coast and southwest Australia. Wave heights are, on average, lower in the tropical and subtropical regions and in sheltered fetch limited areas, such as the Indonesian Archipelago (Semedo et al. 2013), correlating with the narrow back beaches without dunes for the tropical and sub-tropical nesting islands of the study. Therefore, small, tropical low-lying islands are at risk from flooding and inundation impacts of climate change (Fuentes et al. 2007) on account of their narrow back beaches and no dunes.

Combining the results from localised impacts (Chapter 2), and regional drivers of erosion (Chapter 3), the study recognises the limits of exotic *Casuarina* as an erosion mitigation tool. The value of intact sandy beach dune ecosystems should be realised, and bio-shield policy should favour native vegetation species to increase the resilience of these ecosystems.

REFERENCES

AWALE, D. and PHILLOTT, A. D. 2014. A review of the adverse effects of *Casuarina* spp. on coastal ecosystems and sea turtle nesting beaches. *Indian Ocean Turtle Newsleter* 19:15–19.

BARBIER, E., HACKER, S., KENNEDY, C., KOCH, E., STIER, A. and SILLIMAN, B. 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81:169–193.

BATISH, D. R., SINGH, H. P. and KOHLI, R. K. 2001. Vegetation exclusion under *Casuarina equisetifolia* L.: Does allelopathy play a role? *Community Ecology* 2:93–100.

BHALLA, R. S. 2007. Do bio-shields affect tsunami inundation? *Current Science* 93:831–833.

BRADSHAW, C.J., SODHI, N.S., PEH, K.S.H. AND BROOK, B.W. 2007. Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology 13*: 2379-2395.

BUEHLER, C. and RODGERS, J. 2012. Soil property differences between invaded casuarina (*Casuarina equisetifolia* L.) sites and non-casuarina sites in the Bahamas. *Physical Geography* 33:574–588.

CHAUDARI, S., PRASAD, K. V. and SHANKER, K. 2009. Impact of *Casuarina* plantations on Olive Ridley Turtle nesting along the Northern Tamil Nadu Coast , India. ATREE, Bangalore and MCBT, Mamallapuram, India. pp. 44.

CHURCH, J. A., CLARK, P. U., CAZENAVE, A., GREGORY, J. M., JEVREJEVA, S., LEVERMANN, A., MERRIFIELD, M. A., MILNE, G. A., NEREM, R., NUNN, P. D., PAYNE, A. J., PFEFFER, W. T., STAMMER, D. and UNNIKRISHNAN, A. S. 2013. Sea level change. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change:1137–1216.

DANIELSEN, F., SØRENSEN, M. K., OLWIG, M. F., SELVAM, V., PARISH, F., BURGESS, N. D., HIRAISHI, T., KARUNAGARAN, V. M., RASMUSSEN, M. S., HANSEN, L. B. and QUARTO, A. 2005. The Asian tsunami: A protective role for coastal vegetation. *Science 310*: 643.

DAS, S. and SANDHU, H., 2014. Role of exotic vegetation in coastal protection. *Economic and Political Weekly* 49: 43.

DE, U.S., DUBE, R.K. AND RAO, G.P. 2005. Extreme weather events over India in the last 100 years. *Journal of Indian Geophysical Union*, *9*: 173-187.

DEFEO, O., MCLACHLAN, A., SCHOEMAN, D. S., SCHLACHER, T. A., DUGAN, J., JONES, A., LASTRA, M. and SCAPINI, F. 2009. Threats to sandy beach ecosystems: A review. *Estuarine, Coastal and Shelf Science* 81:1–12.

FEAGIN, R. A., MUKHERJEE, N., SHANKER, K., BAIRD, A. H., CINNER, J., KERR, A. M., KOEDAM, N., SRIDHAR, A., ARTHUR, R., JAYATISSA, L. P., LO SEEN, D., MENON, M., RODRIGUEZ, S., SHAMSUDDOHA, M. and DAHDOUH-GUEBAS, F. 2010. Shelter from the storm? Use and misuse of coastal vegetation bio-shields for managing natural disasters. *Conservation Letters* 3:1–11.

FUENTES, M. M. P. B., PIKE, D. A., DIMATTEO, A. and WALLACE, B. P. 2013. Resilience of marine turtle regional management units to climate change. *Global Change Biology* 19:1399–1406.

FUENTES, M. M. P. B., LIMPUS, C. J., HAMANN, M. AND DAWSON, J. 2010. Potential impacts of projected sea-level rise on sea turtle rookeries. *Aquatic Conservation: Marine and Freshwater Ecosystems* 20:132-139.

GORDON, D. R. 1998. Effects of invasive , non-indigenous plant species on ecosystem processes : Lessons from Florida. *Ecological Applications* 8:975–989.

HARDMAN, C. J., WILLIAMS, S., MANCO, B. N. and HAMILTON, M. A. 2012. Predicting the potential threat of

Casuarina equisetifolia to three endemic plant species on the Turks and Caicos Islands. *Oryx* 46:204–212.

JADHAV, B. B. and GAYNAR, D. G. 1995. Effect of *Casuarina equisetiolia* J.R. leaf litter leachates on germination and seedling growth of rice and cowpea. *Allelopathy Journal* 2:105-108.

KATHIRESAN, K. and RAJENDRAN, N. 2005. Coastal mangrove forests mitigated tsunami. *Estuarine, Coastal and Shelf Science* 65:601–606.

KERR, A. M. and BAIRD, A. H. 2007. Natural barriers to natural disasters. *BioScience* 57:102–103.

KERR, A. M., BAIRD, A. H. and CAMPBELL, S. J. 2006. Comments on 'Coastal mangrove forests mitigated tsunami' by K. Kathiresan and N. Rajendran [Estuar. Coast. Shelf Sci. 65 (2005) 601-606]. *Estuarine, Coastal and Shelf Science* 67:539–541.

LUIJENDIJK, A., HAGENAARS, G., RANASINGHE, R., BAART, F., DONCHYTS, G. AND AARNINKHOF, S. 2018. The state of the world's beaches. *Scientific Reports* 8:1-11

MATHIVENTHAN, T. and JAYASINGAM, T. 2014. Coastal green belt in Batticaloa district, Sri Lanka: Is *Casuarina* a success? *International Journal of Marine Science* 4: doi: 10.5376/ijms.2014.04.0055.

MCARDLE, S. B. and MCLACHLAN, A. 1992. Sandy beach ecology: Swash features relevant to the macrofauna. *Journal of Coastal Research* 8:398–407.

MERRILL, R.T. 1984. A comparison of large and small tropical cyclones. *Monthly Weather Review*, 112: 1408-1418.

MILLER, J. D., LIMPUS, C. J. and GODFREY, M. H. 2003. Nest site selection, oviposition, eggs, development, hatching, and emergence of loggerhead turtles. In: Bolten, A.B. and Witherington, B. E. (eds). *Loggerhead Sea Turtles*, Smithsonian. pp. 125–143.

MORTON, J. F. 1980. The Australian pine or beefwood (*Casuarina equisetifolia* L.), an invasive 'weed' tree in Florida. *Proceedings of the Florida State Horticultural Society* 93:87–95.

OLWIG, M. F., SØRENSEN, M. K., RASMUSSEN, M. S., DANIELSEN, F., SELVAM, V., HANSEN, L. B., NYBORG, L., VESTERGAARD, K. B., PARISH, F. and KARUNAGARAN, V. M. 2009. Using remote sensing to assess the protective role of coastal woody vegetation against tsunami waves. *International Journal of Remote Sensing* 30:3817–3820.

PATIL, R. H., HUNSHAL, C. S. and ITNAL, C. J. 2002. Effect of casuarina litter leachates on crops. *Allelopathy Journal* 10:141–146.

PERNAS, T., WHEELER, G., LANGELAND, K., GOLDEN, E., PURCELL, M., TAYLOR, J., BROWN, K., TAYLOR, S. D. and ALLEN, E. 2013. Australian pine management plan for Florida. Florida Exotic Pest Plant Council, www.fleppc.org.

PILKEY, O. H., NEAL, W. J., KELLEY, J. T. and COOPER, J. A. G. 2011. The World's Beaches. University of California Press, Berkeley, CA.

RIYASAHAMED, A. M. 2017. Coastal bio-shields in Ampara District, Sri Lanka : Evaluation of greenbelt plantation. *Trends in Biosciences* 10:3369–3374.

SAMARAKOON, M. B., TANAKA, N. and IIMURA, K. 2013. Improvement of effectiveness of existing *Casuarina equisetifolia* forests in mitigating tsunami damage. *Journal of Environmental Management* 114:105–114.

SEALEY, N. 2006. The cycle of *Casuarina*-induced beach erosion - A case study from Andros, Bahamas. pp. 197–205, *The 12th Symposium on the Geology of the Bahamas and other Carbonate Regions (2004)*.

SEMEDO, A., WEISSE, R., BEHRENS, A., STERL, A., BENGTSSON, L. and GÜNTHER, H. 2013. Projection of global wave climate change toward the end of the twenty-first century. *Journal of Climate* 26:8269–8288.

SHORT, A. D. (ed.) 1993. Beach and surf zone morphodynamics. *Journal of Coastal Research, Special Issue no. 15.* Coastal Education and Research Foundation, Lawrence, USA: pp 231.

SHORT, A. D. 1999. Short, wave-dominated beaches. In: Short, A. D. (ed.). Handbook of Beach and Shoreface Morphodynamics, pp 173-203. Wiley, Chichester, UK.

TANAKA, N. 2009. Vegetation bio-shields for tsunami mitigation: Review of effectiveness, limitations, construction, and sustainable management. *Landscape and Ecological Engineering* 5:71–79.

TANAKA, N. and THUY, N. B. 2010. Tsunami force mitigation by tropical coastal trees, *Pandanus odoratissimus* and *Casuarina equisetifolia*, considering the effect of tree breaking. *International Conference on Sustainable Built Environment (ICSBE-2010, Kandy, Sri Lanka* 13–14 December 2010, pp 7-14.

VUIK, V., JONKMAN, S.N., BORSJE, B.W. AND SUZUKI, T. 2016. Nature-based flood protection: the efficiency of vegetated foreshores for reducing wave loads on coastal dikes. *Coastal engineering*, *116*, pp.42-56.

WALLACE, B. P., DIMATTEO, A. D., BOLTEN, A. B., CHALOUPKA, M. Y., HUTCHINSON, B. J., ABREU-GROBOIS, F. A., MORTIMER, J. A., SEMINOFF, J. A., AMOROCHO, D., BJORNDAL, K. A. AND BOURJEA, J. 2011. Global conservation priorities for marine turtles. *PloS One*, 6(9) e24510, https://doi.org/10.1371/journal.pone.0024510.

WEBSTER, P. J., HOLLAND, G. J., CURRY, J. A. and CHANG, H. R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309:1844–1846.

WHEELER, G. S., TAYLOR, G. S., GASKIN, J. F. and PURCELL, M. F. 2011. Ecology and management of Sheoak (*Casuarina* spp.), an Invader of Coastal Florida, U.S.A. *Journal of Coastal Research* 27:485–492.

APPENDIX 1: Summary of existing CVI’s

Table 0.1: Summary of vulnerability indices, their geographical application and the variables needed to implement them. Adapted from Abuodha and Woodroffe (2006) and Goodhue et al. (2012).

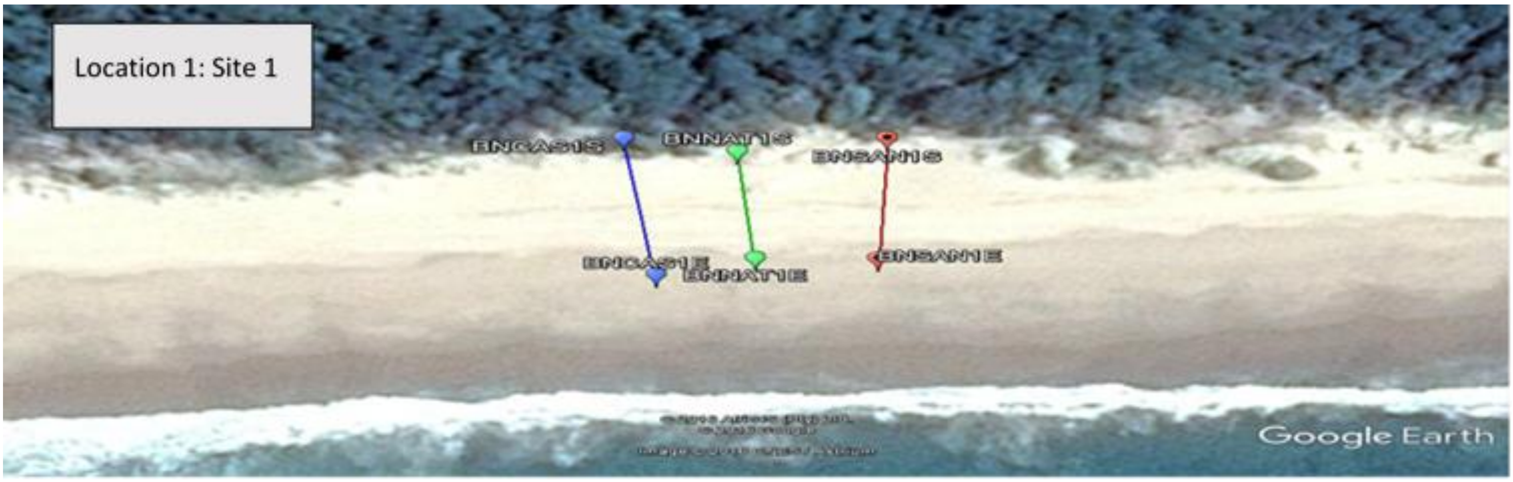
Index	Geographical application	Variables considered	Reference
Coastal Vulnerability Index (CVI)	USA	Elevation, local subsidence, tropical storm probability, hurricane probability, hurricane frequency-intensity, tropical cyclone forward velocity, extratropical cyclones, hurricane storm surge, tide range, geology, landform, shoreline erosion, wave height	Gornitz et al. (1994)
Coastal Vulnerability Index (CVI)	USA	Geomorphology, shoreline, erosion and accretion, coastal slope, relative sea-level change, mean wave height and mean tidal range	Thieler and Hammer- Klose (2000) and numerous other USGS reports
Coastal social vulnerability score (CSoVI)	USA	SoCVI: Poverty, age, development density, immigrants, rural/urban dichotomy, race and gender, population decline, ethnicity (Indian) and farming, infrastructure, employment reliance, income CVI: Mean tidal range, coastal slope, rate of relative sea level rise, shoreline erosion and accretion rates, mean wave height, geomorphology	Boruff et al. (2005)
Sensitivity index (SI)	Canada	Relief, rock type, landform, sea-level change, shoreline displacement, tidal range and maximum wave height	Shaw et al. (1998)

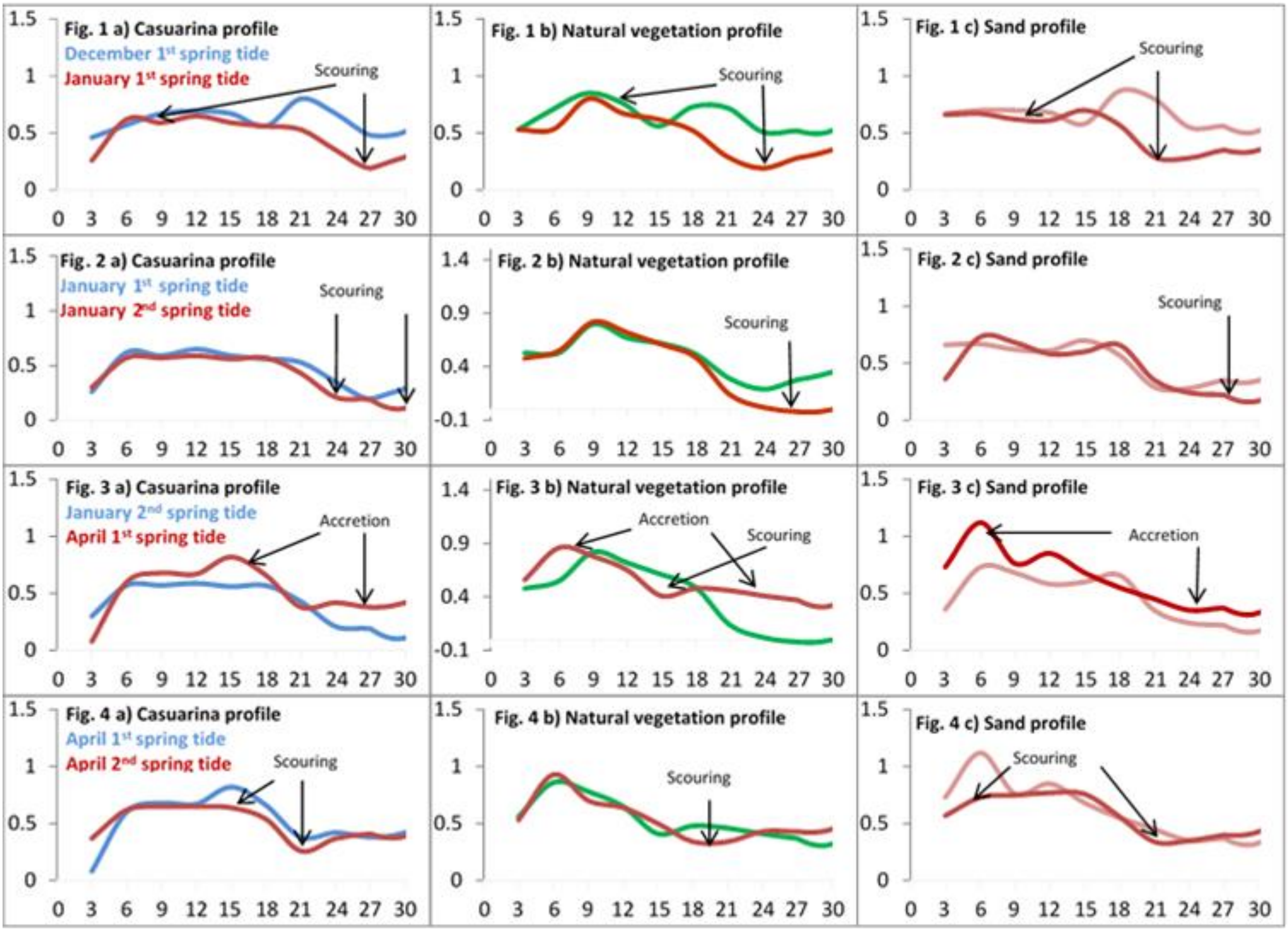
Erosion hazard index	Canada	As SI, plus exposure, storm surge water level, slope	Forbes et al. (2003)
Risk matrix	South Africa	Location, infrastructure (economic value), hazard	Hughes & Brundrit (1992)
Sustainable capacity index (SCI)	South Pacific	Vulnerability and resilience of natural, cultural, institutional, infrastructural, economic and human factors	Yamada et al. (1995)
Sensitivity index	Ireland	Shoreface slope, coastal features, coastal structures, access, land use	Carter (1990)
Vulnerability index	UK	Disturbance event frequency, relaxation (recovery) time	Pethick & Crooks (2000)
Coastal vulnerability index (CVI)	India	Geomorphology, coastal slope, erosion and accretion rates, and population	Hegde and Reju (2007)
Coastal vulnerability index relative to sea level rise (CVI-SLR)	Turkey	Physical parameters: Rate of sea level rise, geomorphology, coastal slope, significant wave height, sediment budget, tidal range, proximity to coast, type aquifer, hydraulic conductivity, depth to groundwater level above sea, river discharge, water depth at down stream Human parameters: reduction of sediment supply, river flow regulation, engineered frontage, groundwater consumption, land use	Özyurt & Ergin (2010)

		pattern, natural protection degradation, coastal protection structures	
Coastal vulnerability index (CVI)	USA	Geomorphology, shoreline change, regional coastal slope, relative sea- or lake level change, mean wave height, mean tide range, mean annual ice cover	Pendleton et al. (2010)
Coastal vulnerability index (CVI)	India	Shoreline change rate, sea-level change rate, coastal slope, significant wave height, tidal range, regional elevation, geomorphology, tsunami arrival height	Kumar et al. (2010)
Coastal erosion susceptibility Index (CESI)	Spain	Morphological Beach Sub-Index: Foreshore slope, grain size, backshore width, number of bars Dune Morphological Index: Mean dune height, mean dune width, vegetation succession continuity Shoreline Evolution Index: Short term evolution, medium term evolution, long term evolution	Rizzo et al. (2017)
Coastal vulnerability Index	Australia	Dune height, barrier type, beach type, relative sea level change, shoreline erosion and accretion, mean tidal range, mean wave height	Abuodha & Woodroffe (2006)
Coastal vulnerability Index	Ireland	Coastal characteristic sub-index: Solid geology, drift geology, shoreline type,	Mclaughlin & Cooper (2010)

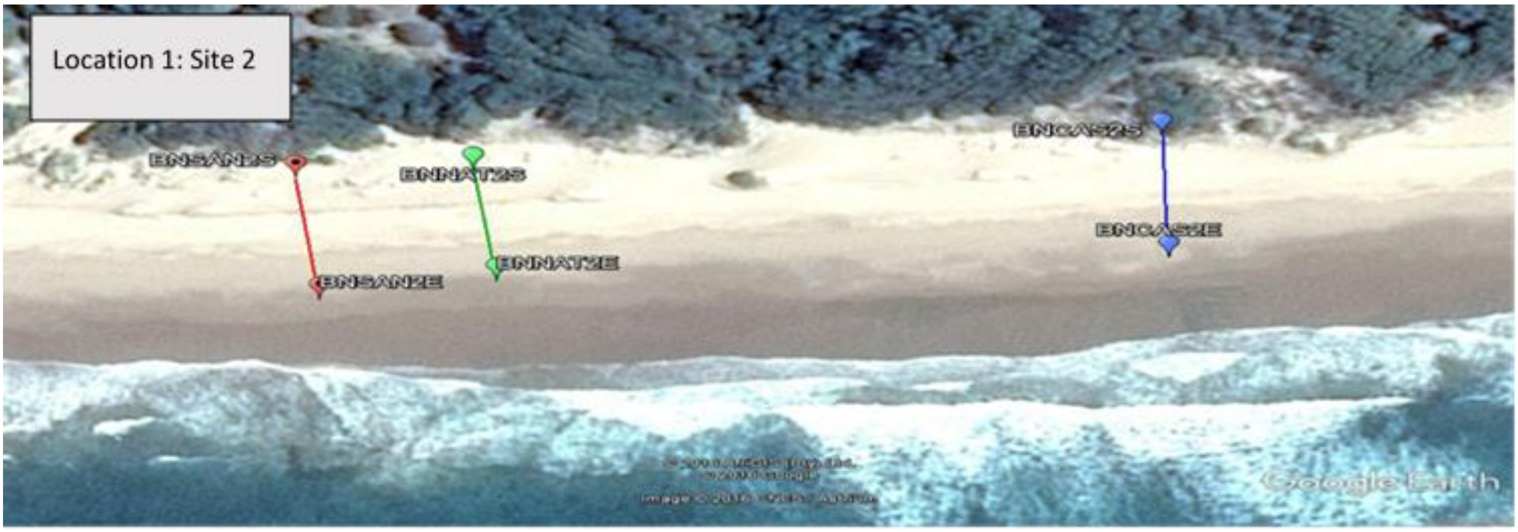
		elevation, river mouths, orientation, inland buffer Coastal forcing sub-index: Significant wave height, tidal range, difference in storm modal wave height, storm frequency Socio-economic sub-index: Population, cultural heritage, roads, railways, land-use, conservation status	
Coastal Sensitivity Index	New Zealand	Exposure, hinterland, sediment type and landform type	Goodhue et al. (2012)

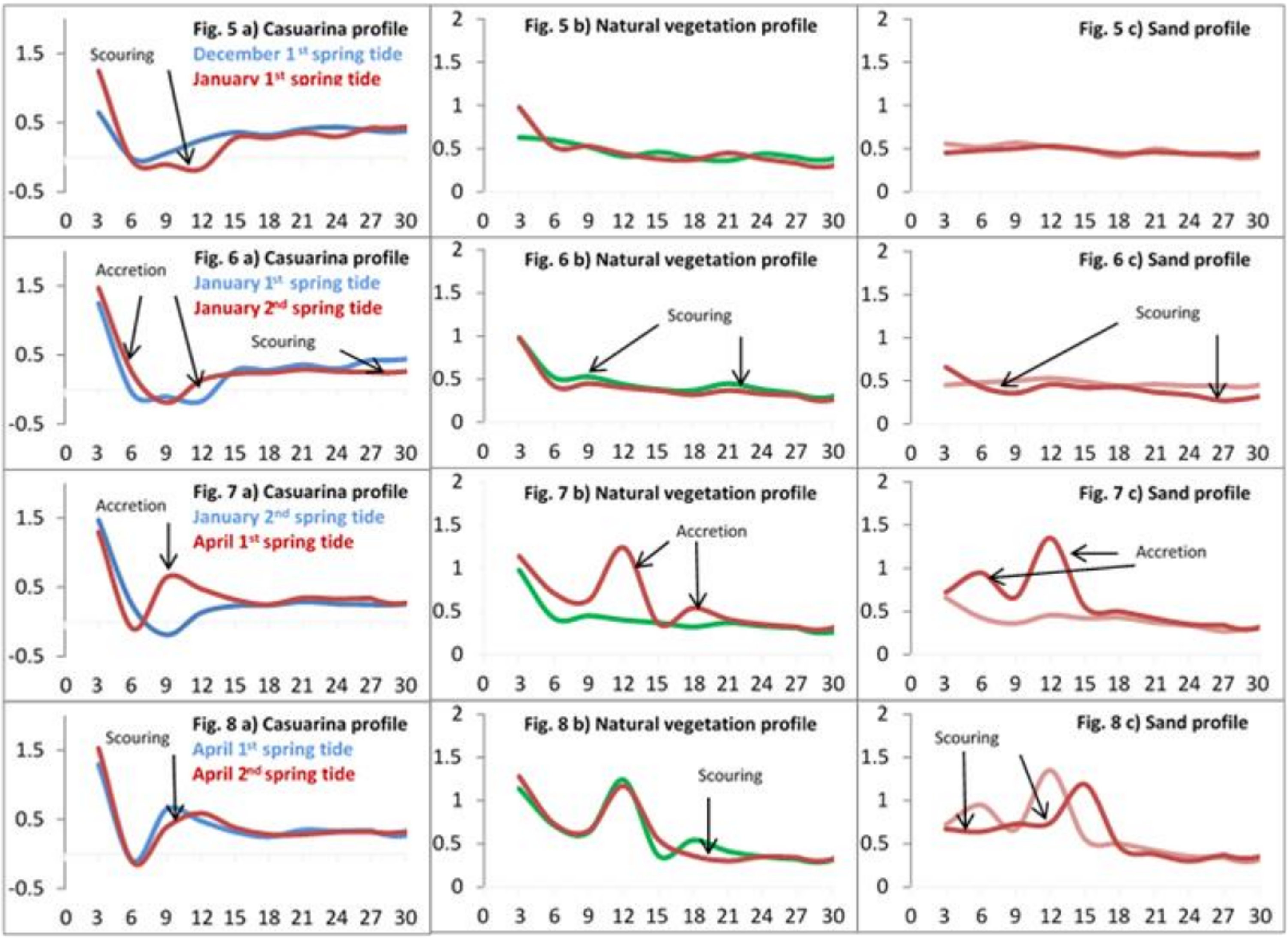
APPENDIX 2.1: Vegetation effect profiles



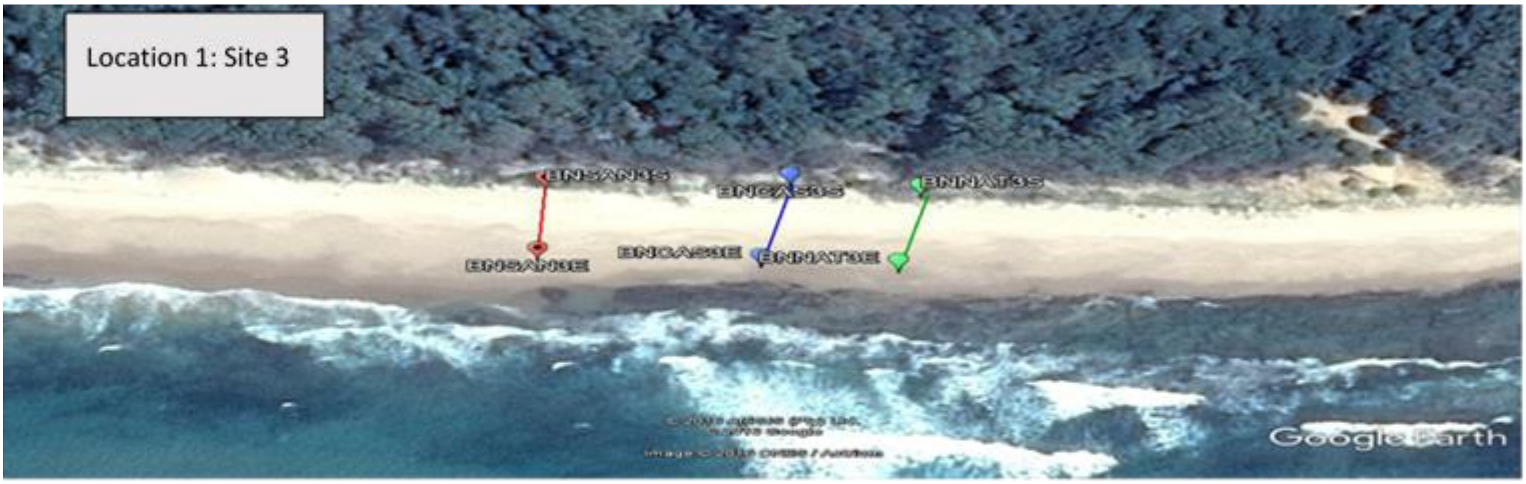


Figures A2.1: 1-4: Beach profiles at location1, Site 1. (1 a, b, c) For the December sampling event all the vegetation type beach profiles showed accretion/sand build-up on the back-beach. For the January, first spring tide sampling all the profiles demonstrated scouring of the back-beach accretion/sand build-up. The sand moved forward into *the intertidal zone to horizontal measurements of 24-30 m. (1a) had a vertical height change of 0.38 and to 21-30 m. (1bandc) showed a vertical height change of 0.35 m. (2 a, b, c) For the January second spring tide sampling event the profiles exhibit further erosion with extreme scouring of the intertidal zone for all the profiles. (2a) demonstrated scouring between the 24-42 m horizontal measurements with a vertical height change of 0.28 m; (2b) exhibited scouring between the 18-30 m horizontal measurements with a vertical height difference of 0.30 m and the (2c) showed scouring between 18-30 m horizontal measurements with a vertical change of 0.18 m. (3 a, b, c) For the April 1st spring sampling event the scouring of the intertidal zone filled-up (accretion) in all the profiles. For (3a) a vertical height increase of 0.31 m was demonstrated, (3b) had a 0.39 m increase and (3c) increased by 0.16. All the profiles also showed dune build-up/accretion of 0.25 for (3a); 0.31 m for (3b) and 0.39 m for (3c). (4 a, b, c) For the April 2nd spring tide sampling event all the profiles exhibited scouring between the 15-21 m horizontal measurements with a vertical change of 0.12 m for (4a); 0.14 m for (4b) and 0.11 m for (4c). (4a) and (4c) demonstrated dune scouring, with a vertical height change of 0.11 m and 0.16, respectively, while (4b) demonstrated dune build-up of 0.02 m.*





Figures A2.1: 5-8: Beach profiles at location 1, site 2. (5 a, b, c) For the December sampling event the beach profiles were relatively flat with some sand build-up in the intertidal zone at the 21m mark. (5a) showed a vertical decrease of 0.67 m on the back-beach with extreme scouring in front of the foredune.. (5 a, b, c) For the January, first spring tide sampling event the profiles did not exhibit much change and stayed relatively similar to the December beach profiles. The only changes were evident on the back-beach with dune scouring in front of (5a) *with a vertical height decrease of 1.31 m and dune build-up in front of (5b) with a vertical increase of 0.35 m. (6 a, b, c) For the January, second spring tide event all the vegetation type profiles exhibited scouring of the intertidal zone. (6a) exhibited scouring at 24-30 m with a vertical height decrease of 0.18 m, (6b) at 15-21 m with a vertical decrease of 0.08 m and (6c) at 15-45 m with a decrease of 0.13 m. (7 a, b, c) For the April, first spring tide sampling event, all the vegetation type profiles had demonstrated accretion on the back-beach in front of the foredune. (6a) exhibited build-up of 0.75 m, (6b) had a vertical increase of 1.2 m and (6c) had a vertical increase of 0.89 m. (8 a, b, c) The April, 2nd spring tide profiles were very similar to the April 1 spring tide profiles. There was slight scouring of the foredune for all the vegetation-cover types, but no big feature changes were evident.*



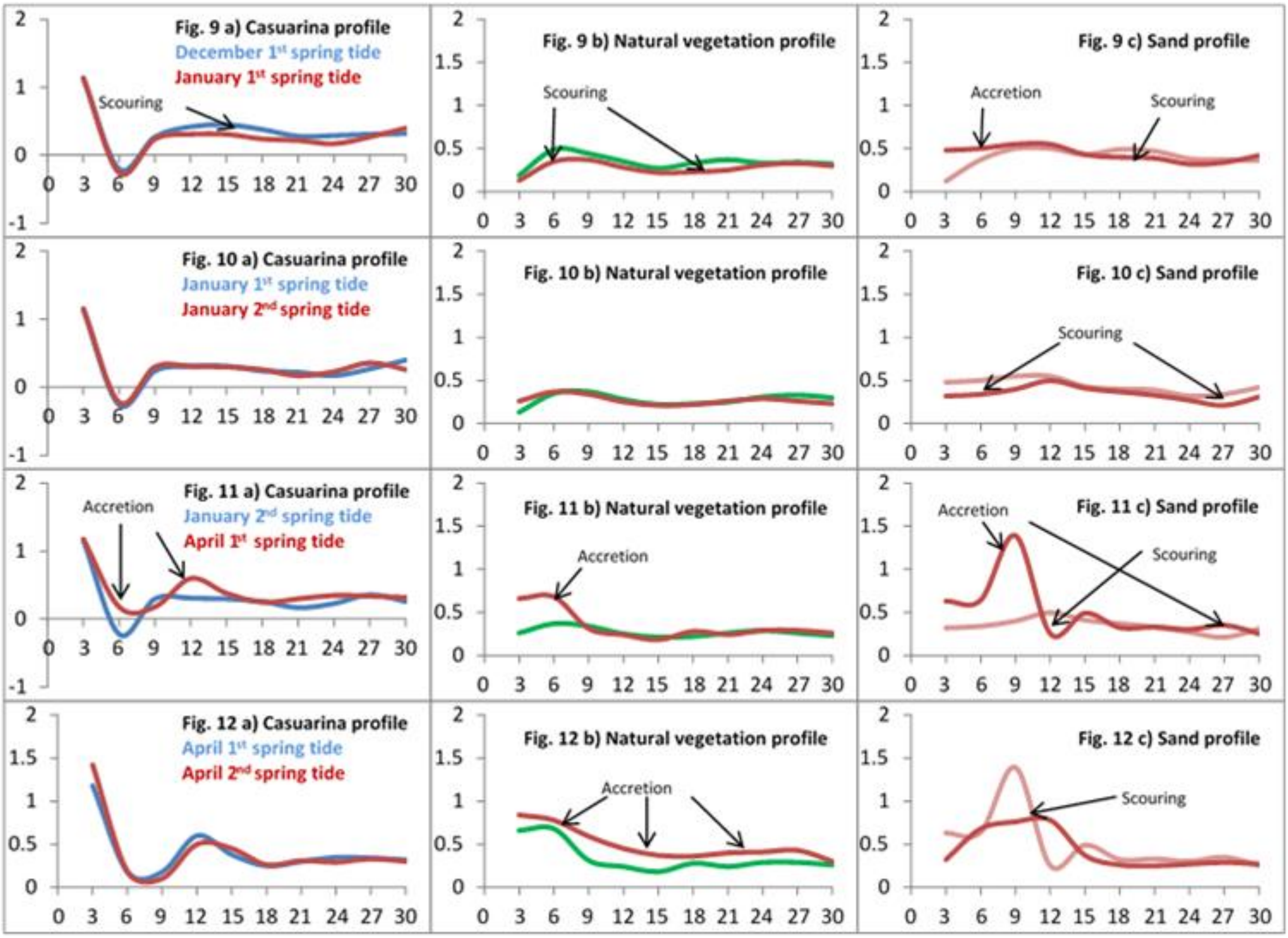
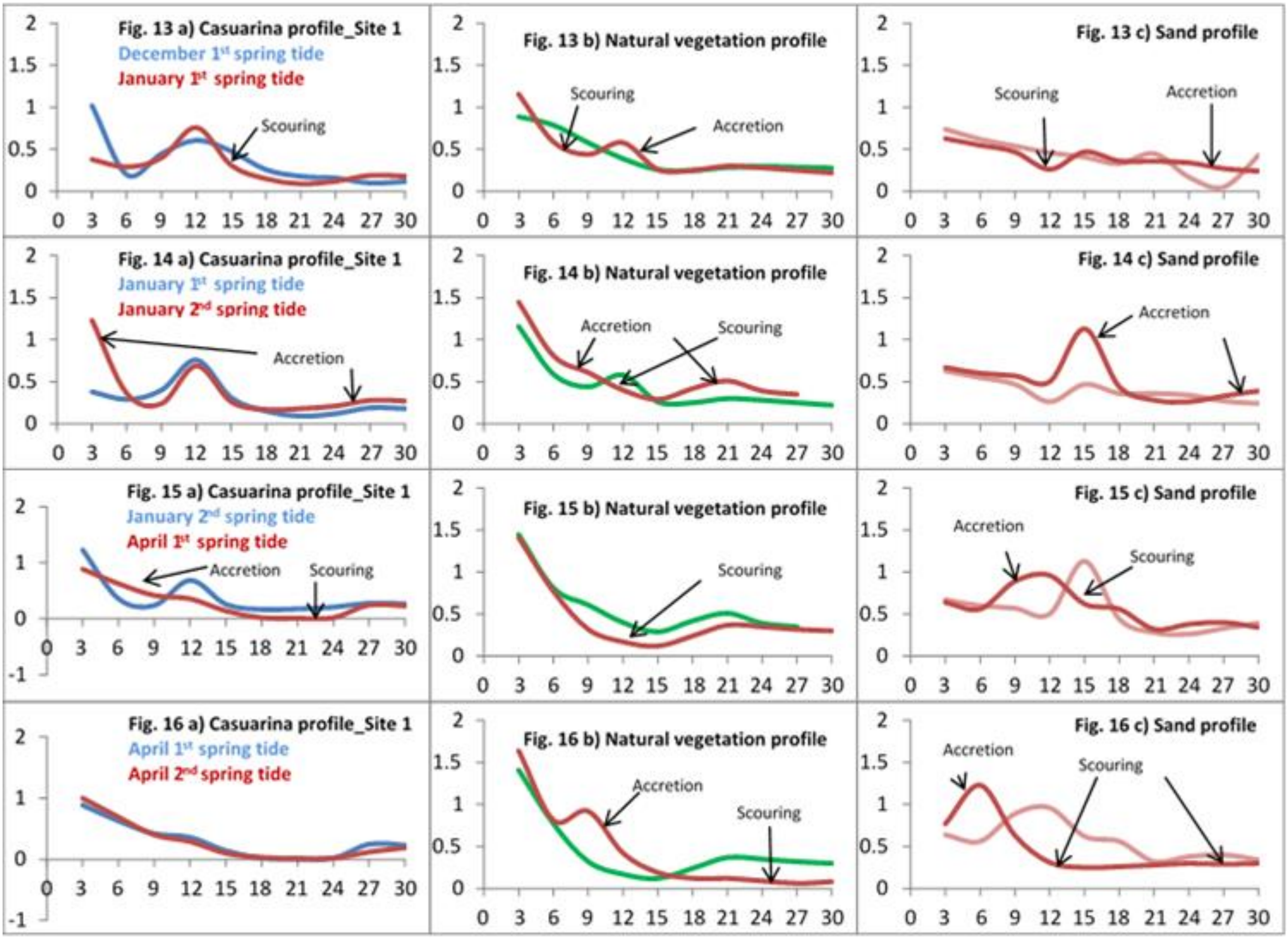
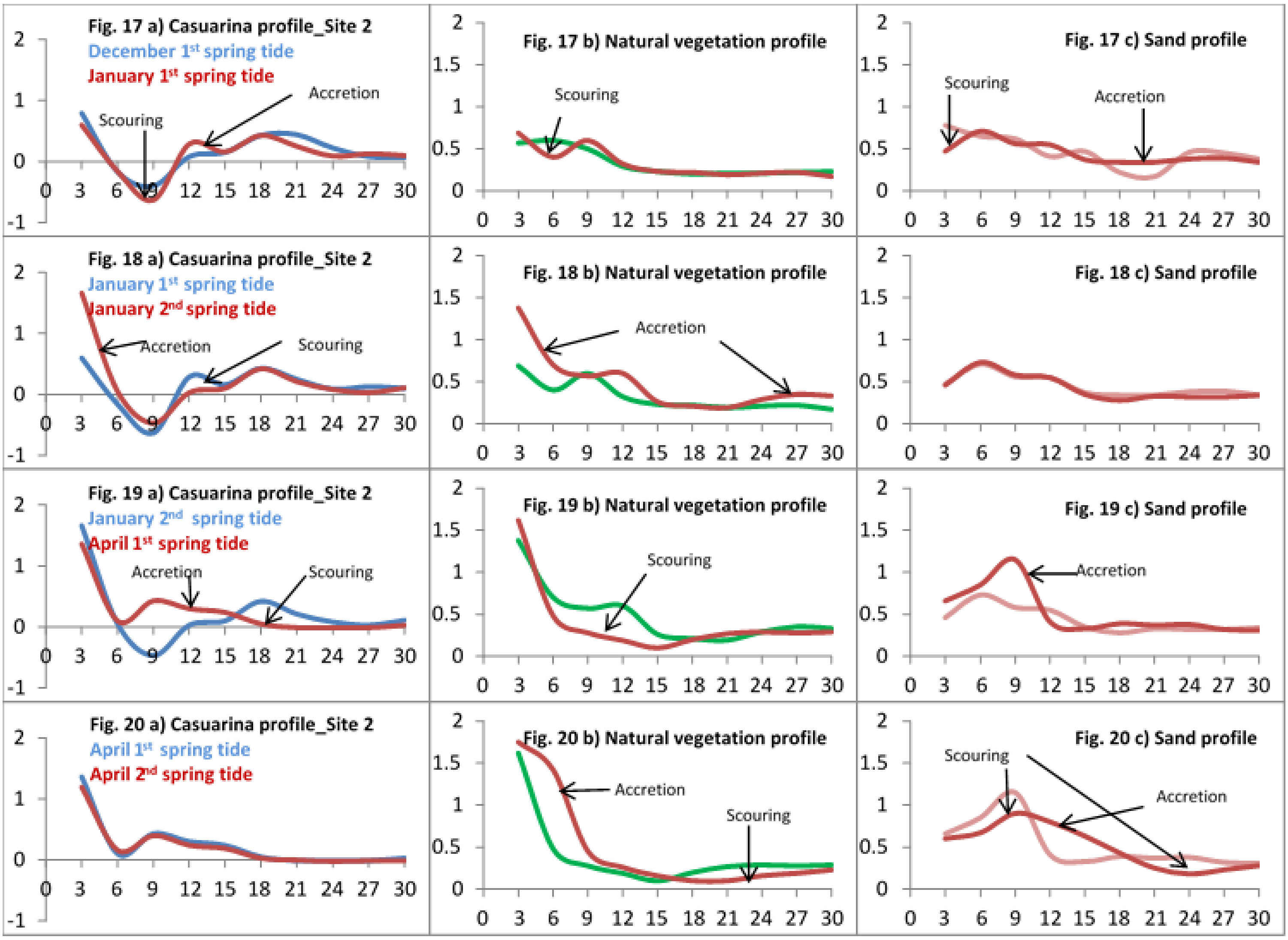


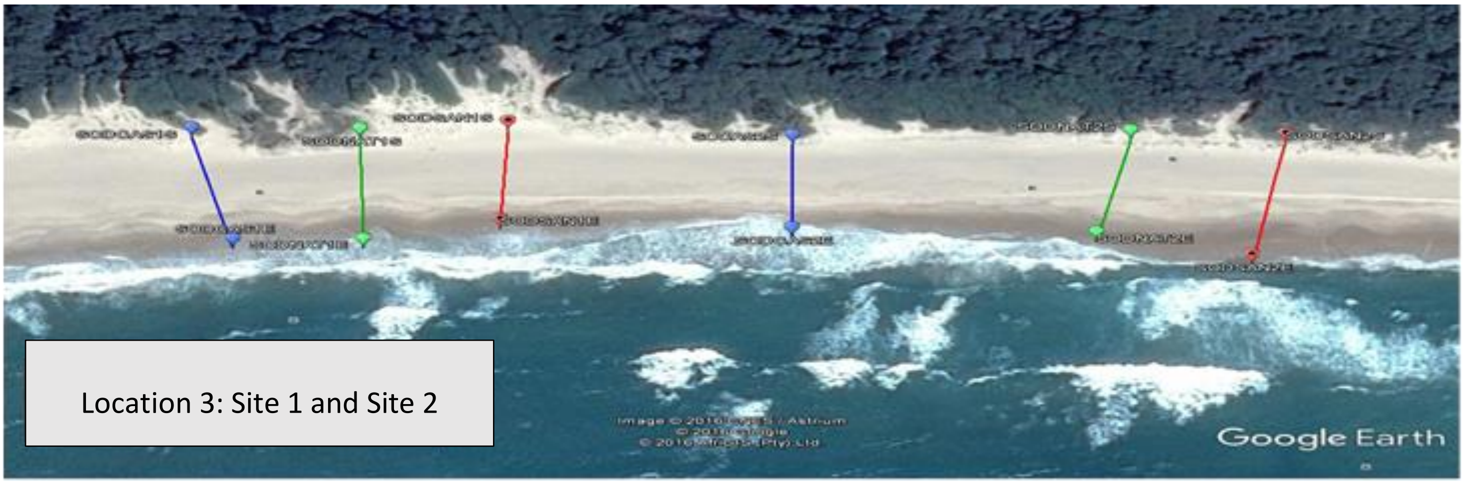
Figure A2.1: 9-12: Beach profiles at location 1, site 3. (9 a, b, c) For the December sampling event all the vegetation type profiles showed sand accretion just in front of the foredune. (9 a, b, c) For the January 1st spring sampling event there is not much change in the profiles, except for slight scouring of the upper intertidal for (9a) and (9b). (9c) showed accretion of sand in front of the foredune. (10 a, b, c) For the January 2nd spring tide event is very similar to the January 1st spring tide sampling event, with slight scouring of the general profile. (10c) exhibited scouring in front of the foredune with a vertical height decrease of 0.16 m. (11 a, b, c) For the April first spring tide sampling event there was accretion on the back-beach in front of the foredune for all the vegetation *type profiles, but (11 c) showed the most prominent accretion with a vertical height increase of 0.99 m. (12 a, b, c) For the April 2nd spring tide sampling event there was almost no difference between the April 1st spring tide profile and April 2nd spring tide profile for (12a). There seemed to be accretion of sand all along the (12b) profile and (12 c) showed scouring of the massive build-up of sand on the back-beach with a vertical height change of 0.63 m.*

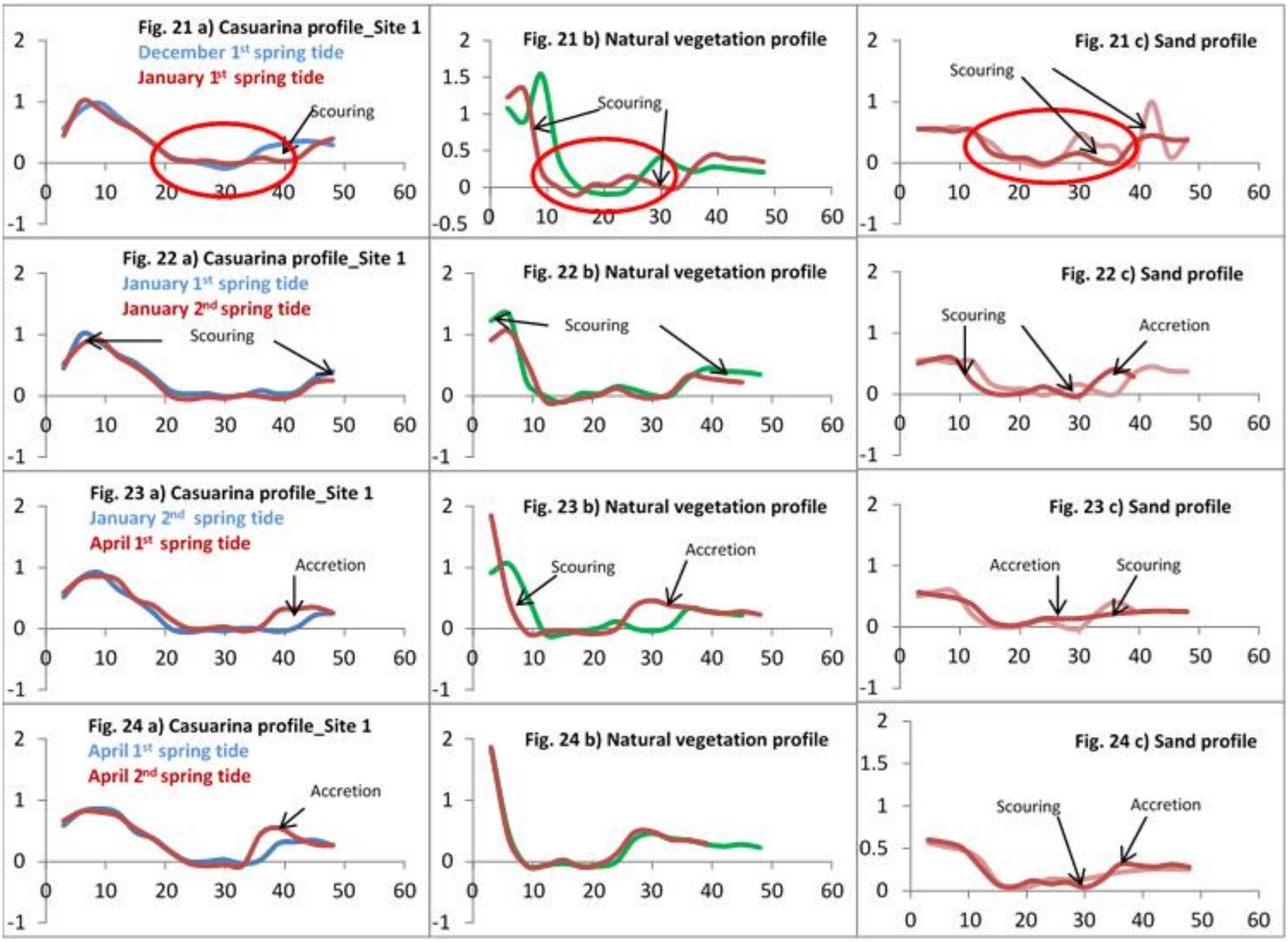


Figures A2.1: 13-16: Beach profiles at location 2, site 1. (13 a, b, c) For the December sampling event (13a) showed accretion on the back-beach, between horizontal measurements 3-18 m with a vertical height of 0.61 m. There was slight scouring from 24-30 m. (13b) had a smooth dune feature with no specific features. (13 c) demonstrated accretion on the back-beach between the 15-21 m horizontal measurements and on the lower intertidal between 27-30 m with a height of 0.45 m. There was scouring of the intertidal from 21-27 m with a vertical height decrease of 0.05m. (13 a, b, c) For the January first spring tide sampling event (13a) showed further accretion on the back-beach between horizontal measurements 13-18 m and a vertical increase of 0.15 m. The scouring of the intertidal *between 24-33 m was filled up with a vertical height increase of 0.09 m. (13 b) demonstrated scouring of the dune between the 3-6 m horizontal measurements with a vertical height decrease of 0.2 m. (13c) showed accretion between the 9-18 m horizontal measurements with a vertical height increase of 0.07 m and the scouring from the December sampling event filled up with a vertical height increase of 0.22 m. (14 a, b, c) For the January second spring tide sampling event all the vegetation type profiles demonstrated accretion on the back-beach. (14 a) exhibited accretion and build-up of the dune at the 0 m horizontal measurement with a vertical height increase of 0.85 m and slight accretion of the intertidal zone between 15-30 m horizontal measurements with a 0.09 m vertical increase. (14 b) demonstrated accretion and build-up of the dune between the horizontal measurements of 0-6 m with a vertical increase of 0.29 m and some scouring at the 9m horizontal measurement with a vertical change of 0.18 m. There was accretion in the intertidal zone between the 15-21 m horizontal measurements with a vertical increase of 0.21 m. (14c) demonstrated the greatest accretion on the back-beach between 9-15 horizontal measurements with a vertical increase of 0.66 m and some accretion in the intertidal zone at the 24-30 m horizontal measurements with a vertical change of 0.15. (15 a, b, c) For the April first spring sampling event all the vegetation type profiles exhibited accretion/build-up of the dune and scouring between the 9-21 m horizontal measurements. (15 a) showed a vertical increase of the dune between 3-6 m with a vertical increase of 0.27 m and scouring of the previous sand build-up between the 9-27 m horizontal measurements with a vertical change of 0.17 m. (15b) demonstrated scouring between 0-24 m horizontal measurements with a vertical decrease of 0.17 m. (15c) demonstrated the biggest accretion/build-up on the back-beach between 6-9 m horizontal measurements with a vertical increase of 0.46 m. There was scouring on the 12 m horizontal measurement with a vertical change of 0.51. (16 a, b, c) For the April second spring tide sampling event (16a) did not exhibit much change except for slight scouring in the intertidal zone. (16b) showed extreme accretion/build-up on the back-beach between 0-12 m horizontal measurements with a vertical increase of 0.6 m. There was scouring of the intertidal zone between the 15-30 m horizontal measurements with a vertical change of 0.26 m. (16c) also showed extreme accretion/build-up on the back-beach with a 0.56 m increase at the 3 m horizontal mark. There was also scouring of the intertidal zone between 6-30 m horizontal measurements with a 0.37 vertical change at the lowest point.*

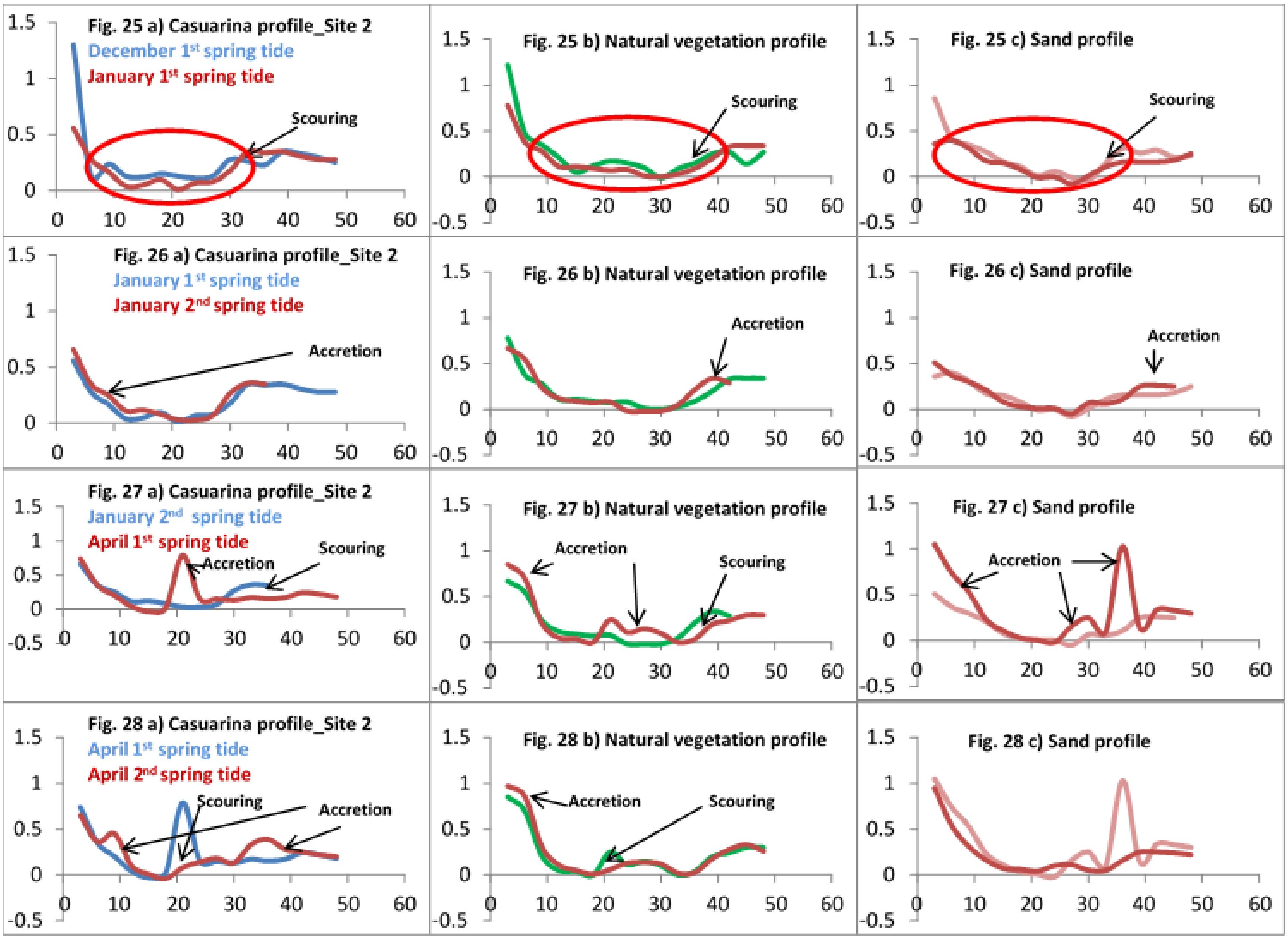


Figures A2.1: 17-20: Beach profiles at location 2, site 2. (17 a, b, c) For the December sampling event (17a) showed accretion in the intertidal zone between the 12-21 m mark with a vertical height of 0.44 m. There is extreme scouring in front of the foredune with a vertical height of -0.17 m. (17b) demonstrated accretion on the back-beach between the horizontal measurements of 0-12 m with a vertical height of 0.57. (17c) showed some accretion on the back-beach, but showed extreme scouring in the intertidal zone between the horizontal measurements of 12-21 m with a vertical height of 0.17. (17 a, b, c) For the January 1st spring tide sampling event (17a) demonstrated further scouring in front of the foredune with a vertical height change of 0.19 m. (17 b) also demonstrated scouring on the back-beach at the 3 m horizontal measurement with a vertical change of 0.2 m. (17c) The scoured zone between the 12-21 m horizontal measurements had filled up with a vertical height increase of 0.17 m. (18 a, b, c) For the January second spring tide sampling event there was accretion on the back dune for (18 a) and (18b), with a 1.06 m and 0.69 m vertical increase, respectively. (18 a) showed slight scouring at the 9 m horizontal measurement with a vertical change of 0.26 m. (18b) demonstrated accretion in the intertidal zone between the 21-36 m horizontal measurements with a vertical increase of 0.13 m. (19 a, b, c) For the April first spring tide sampling event (19a) and (19c) exhibited accretion on the back-beach. (19a) demonstrated accretion between the 3-12 m horizontal measurements with a vertical increase of 0.90 m and (19c) accreted between the 0-6 m horizontal measurements with a vertical increase of 0.57 m. (19b) demonstrated scouring of the back- beach between the 3-12 m horizontal measurements with a vertical decrease of 0.41 m. (20 a, b, c) For the April second spring tide sampling event all the vegetation type profiles showed scouring of the intertidal zone. (20 a) demonstrated scouring between the 27-30 m horizontal measurements with a vertical decrease of 0.29 m. (20b) exhibited scouring between the 15-33 m horizontal measurements with *a vertical decrease of 0.16 m. (20c) demonstrated scouring between the 0-6 m horizontal measurements with a vertical decrease of 0.25m and between the 18-30 m horizontal measurements with a vertical decrease of 0.2 m. There was some accretion the 9-15 m horizontal measurements with a vertical increase of 0.39 m.*





Figures A2.1: 21-24: Beach profiles at location 3, site 1. ***ALL of the profiles at location 3 site 1 exhibited a scoured intertidal zone.*** *(21 a, b, c) For the December sampling event (21a) showed accretion on the back-beach 0-12 m with a vertical height of 0.76 m. (21b) showed accretion on the back-beach between 0-9 m with a vertical height of 1.54 m. All the vegetation type profiles showed accretion in the intertidal zone. (21a) demonstrated accretion between 30-42 m with a vertical height of 0.35, (21b) between 24-33 m with a vertical height of 0.42 and (21c) between 24-33 m and 39-51 m with a vertical height of 0.47 m and 0.4 m, respectively. (21 a, b, c) For the January first spring sampling event all the vegetation type profiles demonstrated scouring of the intertidal zone. (21a)* *had scouring at 30-42 m with a vertical height decrease of 0.28 m. (21b) demonstrated scouring on the back-beach between 6-12 m with a vertical height decrease 1.32 m and in the intertidal zone between 24-33 m with a vertical height decrease of 0.41 m. (21c) demonstrated scouring between 24-33 m with a vertical height decrease of 0.31 m and 39-51 m with a vertical height decrease of 0.15 m. (22 a, b, c) For the January second spring tide sampling event all the vegetation type profiles demonstrated slight scouring of the back-beach and intertidal zone. (22c) demonstrated scouring at the 3 m horizontal measurement with a vertical height change of 014 m and at the 33-42 m horizontal measurement with a vertical height change of 0.07m. (22b) shows scouring between 0-3 m with a vertical height change of 0.27 m and between 36-45 m with a vertical decrease of 0.16m. (22c) exhibited scouring between 12-18 m with a vertical height change of 0.16 m and 24-27 m with a vertical height decrease of 0.19m. (22c) also demonstrated accretion between 30-33m with a vertical height increase of 0.41 m. (23 a, b, c) For the April first spring tide sampling event all the vegetation type profiles showed accretion in the intertidal zone. (23a) demonstrated accretion between 33-51 m with a vertical height increase of 0.30m. (23b) showed accretion between 24-33 m with a vertical height change of 0.5 m and scouring of the back-beach between 3 -12 m with a vertical height decrease of 0.5 m. (23c) showed accretion at 9-27 m with a vertical height increase of 0.17 m. There is also scouring of the back-beach between 3-6 m with a vertical height 0.10 m and of the intertidal at 30-36 m with a vertical height decrease of 0.19 m. (24 a, b, c) For the April second spring tide sampling event (24a) shows accretion of the intertidal zone between 33-39 m with a vertical height increase of 0.25 m. (24b) shows slight accretion along the profile. (24c) demonstrated scouring of the intertidal between 21-30 m with a vertical height decrease of 0.10 m and accretion between 33-45 m with a vertical height increase of 0.09 m.*



Figures A2.1: 25-28: Beach profiles at location 3, site 2. ***ALL of the profiles at location 3 site 2 exhibited a scoured intertidal zone.*** *(25 a, b, c) For the December sampling event, the profiles showed scouring of the mid- intertidal zone and accretion by the dunes as well as the lower intertidal zone. (25 a, b, c) For the January first spring tide sampling event (25a) and (25b) exhibited accretion. (25a) between 27-33 m with a vertical increase of 0.09 m and (25b) between 39-51 m with a vertical change of 0.20 m. (25c) showed further scouring of the intertidal zone between 30-42 with a vertical decrease of 0.15 m. (26 a, b, c) For the January second spring tide sampling event there is slight accretion along all the profiles. (26 a, b, c) exhibited accretion on the back-beach with a vertical increase of 0.10-0.20 m. (26b) demonstrated accretion in the lower intertidal between 30-36 m with a vertical increase of 0.13 m. (26c) demonstrated accretion in the lower intertidal between 36-42 m with a vertical increase of 0.10 m. (27 a, b, c) For the April first spring tide sampling event (27a) and (27c) showed great accretion in the intertidal zone. (27a) demonstrated accretion between 15-25 m with a vertical increase of 0.076 m. (27c) showed accretion in the intertidal between 30-36 m with a vertical increase of 0.92 m and between 21-27 m with a vertical increase of 0.18 m. (27b) also showed accretion in the intertidal zone, but not to the same as the other two vegetation type profiles. There was a vertical increase of 0.17 m between 15-30m. (27b) and (27c) also showed accretion on the back-beach. (27b) exhibited accretion between 0-3 m with a vertical increase of 0.18 m and (27c) demonstrated a vertical increase of 0.54 m between 0-12 m. (28 a, b, c) For the April second spring tide sampling event all the profiles showed scouring of the intertidal zone. (28a) demonstrated accretion on the back-beach between 3-12 m with a vertical increase of 0.43 m and accretion on the lower-intertidal between 30-36 m with a vertical increase of 0.24. There was scouring between 15-21 m with a vertical decrease of 0.71 m. (28b) showed accretion on the back-beach between 0-15 m with a vertical increase of 0.12 m and scouring of the intertidal zone at 18 m with a vertical decrease of 0.19 m. (28c) demonstrated scouring on the back-beach between 0-12 m with a vertical decrease of 0.2 m and of the intertidal zone between 20-30 m, vertical height difference of 0.2 m and at 33m, vertical height decrease of 0.87 m.*

APPENDIX 2.2: Temperature profiles for vegetation-cover types

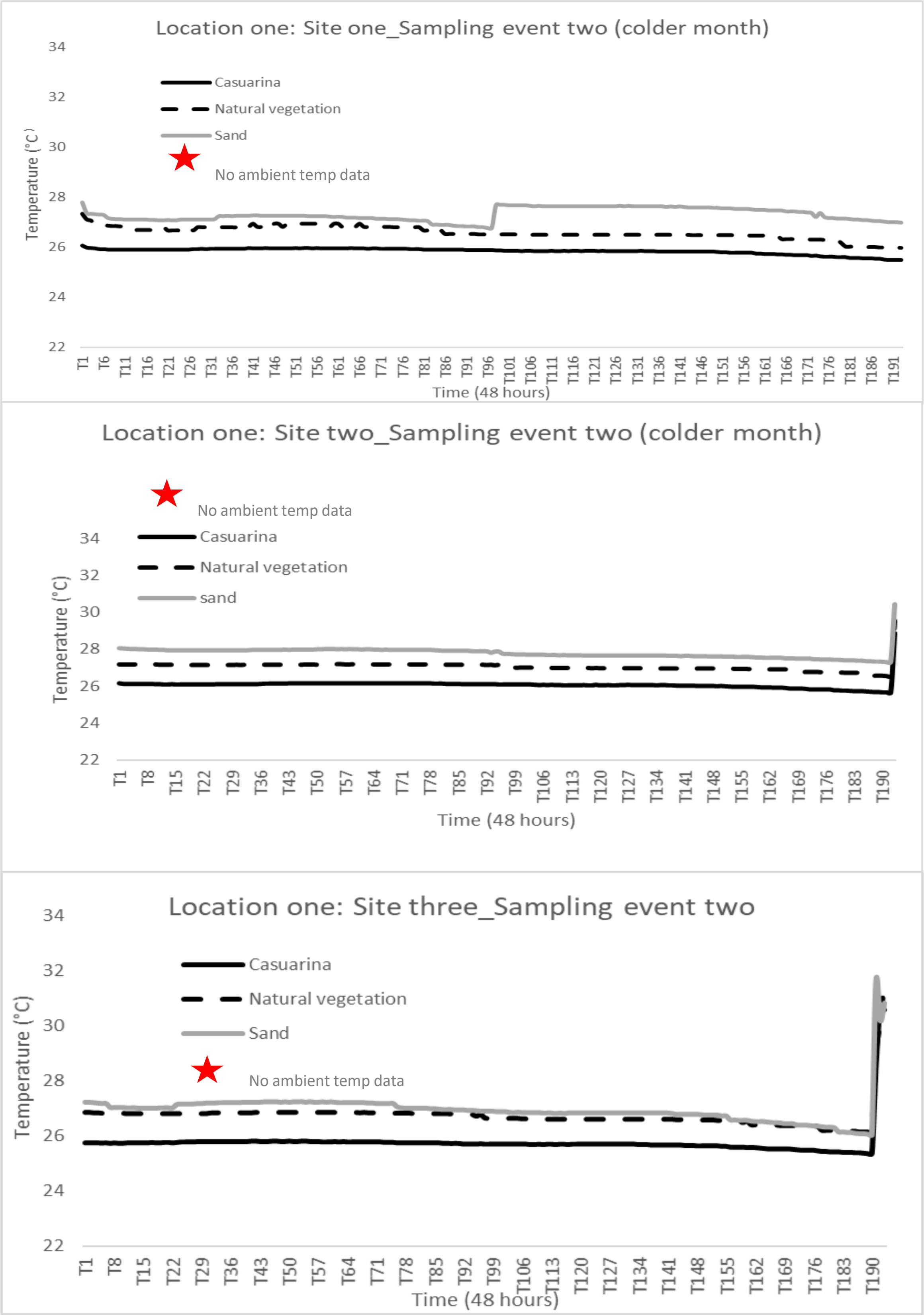


Figure A2.2: 0.1: Sand temperature profiles for vegetation-cover types at location one, across all three sites for one sampling event (colder month, April 2015). The y-axis represents temperature (°C) and the x-axis represents readings every 15 minutes over a 48 hour cycle (T1 = reading one) with a total of 192 readings (T192). Sand temperature indicated daily temperature cycles/fluctuations. Casuarina *temperature was consistently lower across all sites.*

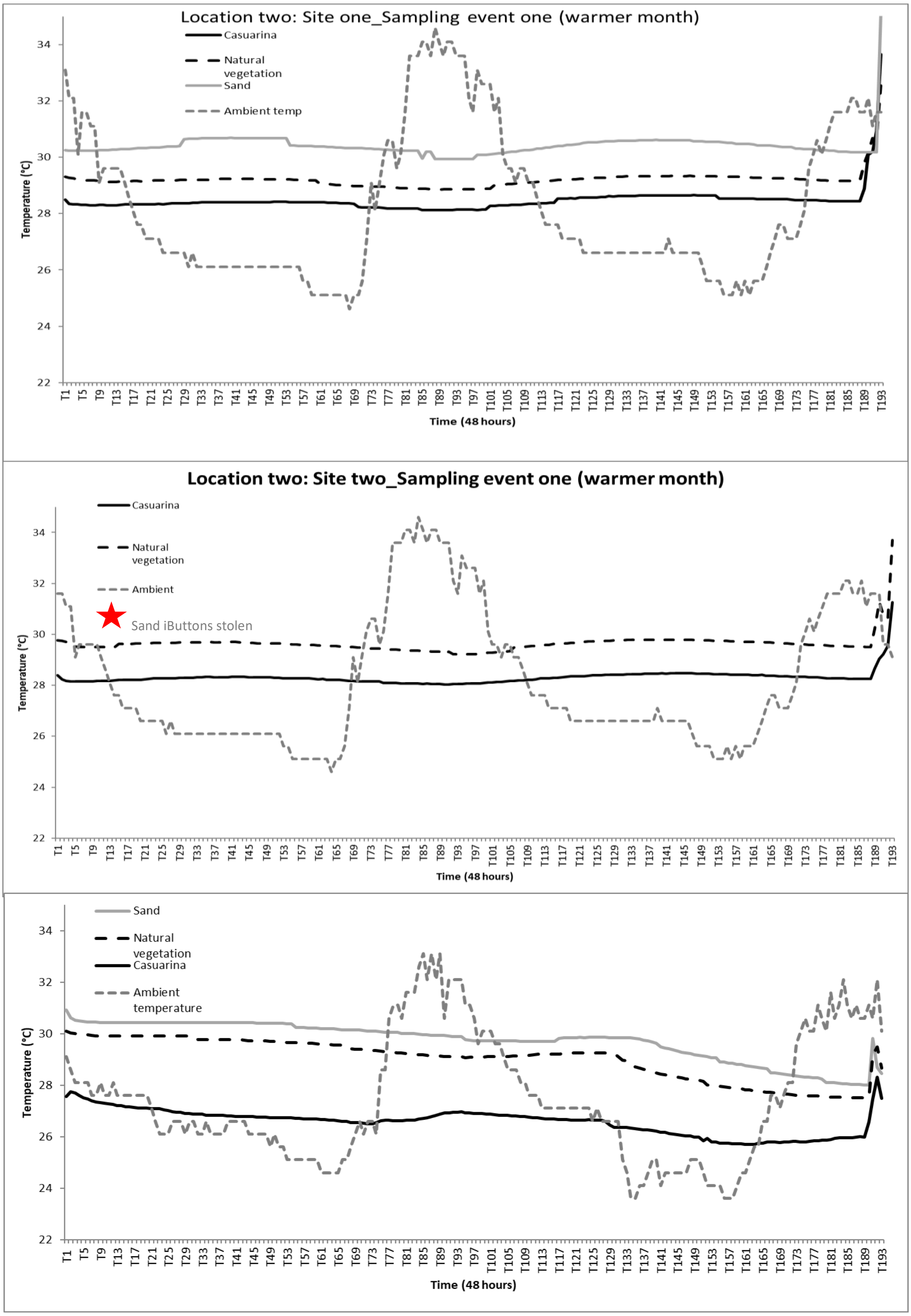


Figure A2.2: 0.2: Sand temperature profiles for vegetation-cover types at location two, across all three sites (1-3) for two sampling event (warmer month, January 2015). The y-axis represents temperature (°C) and the x-axis represents readings every 15 minutes over a 48 hour cycle (T1 = reading one) with a total of 192 readings (T192).

Sand temperature indicated daily temperature cycles/fluctuations. Casuarina *temperature was consistently lower across all sites.*

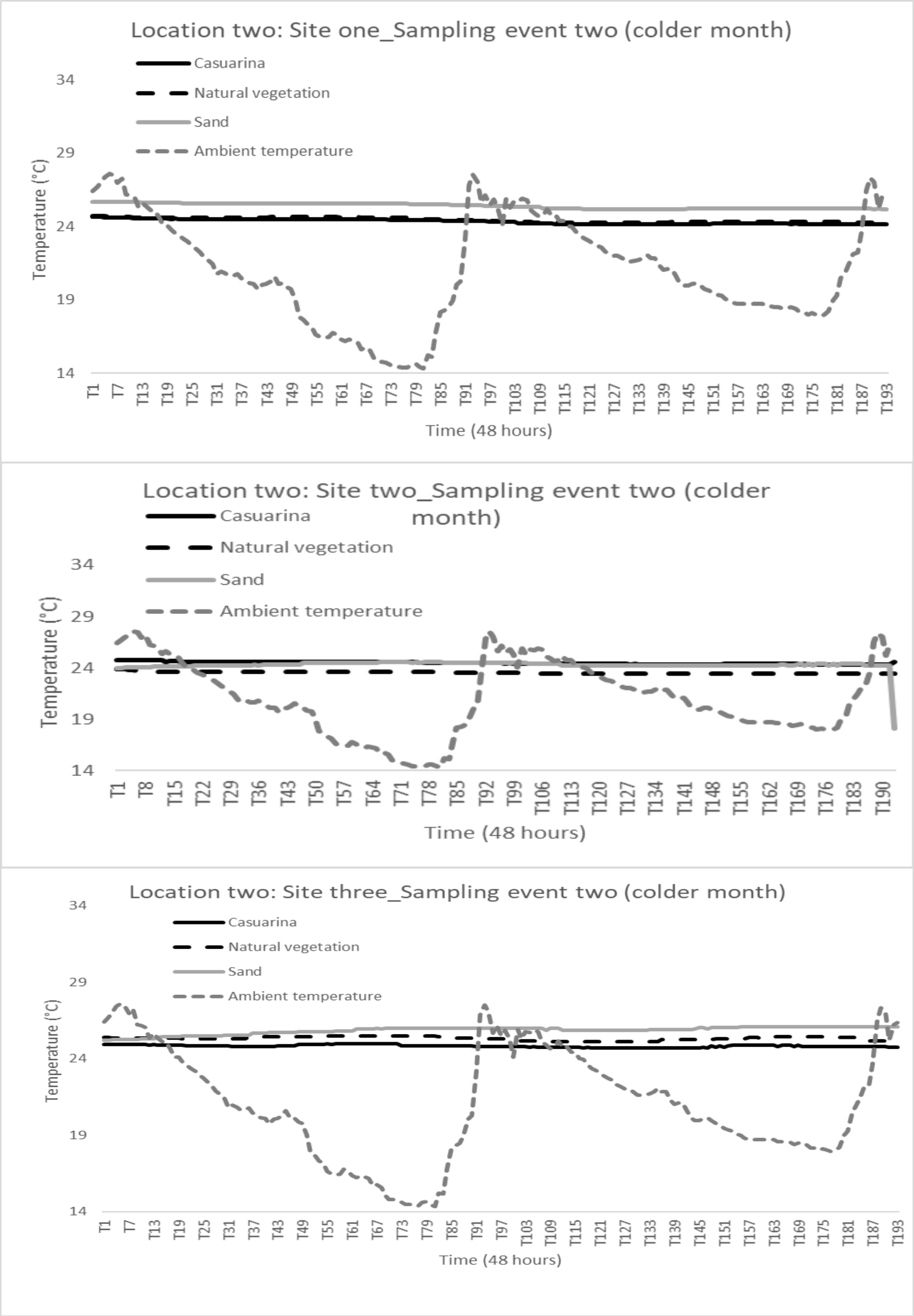


Figure A2.2: 0.3: Sand temperature profiles for vegetation-cover types at location two, across all three sites (1-3) for two sampling event (colder month, April 2015). The y-axis represents temperature (°C) and the x-axis represents readings every 15 minutes over a 48 hour cycle (T1 = reading one) with a total of 192 readings (T192).

Sand temperature indicated daily temperature cycles/fluctuations. Casuarina *temperature was consistently lower across all sites.*

APPENDIX 3.1: Beaches

STUDY SITES/SEA TURTLE NESTING BEACHES:

Site ID	Site name	X	Y	Species	Year	Reported	Reported1	Converted
AU08	Bungelup	113.8308	-22.28139	Caretta caretta	2006	659	#clutches exact	194 females
AU33	Woongarra coast including Mon Repos	152.4413	-24.79539	Caretta caretta	2005	320	#females exact	320 females
AU34	Wreck Island	151.9572	-23.33325	Caretta caretta	2005	62	#females exact	62 females
LK05	Rekawa	80.8235	6.042668	Caretta caretta	2000	800	#clutches exact	206 females
LK21	Kosgoda	80.01823	6.35326	Caretta caretta	1999	400	#clutches exact	103 females
MZ07	Malongane	32.89278	-26.77082	Caretta caretta	2009	326	#clutches exact	84 females
OM02	Masirah	58.70777	20.208721	Caretta caretta	2005	30000	#females exact	30000 females
YE01	Abalhan Protected Area/Socotra Man and Biosphere Reserve	53.9219	12.5967	Caretta caretta	2005	74	#females exact	74 females
AU300	Moulter Cay, north Great Barrier Reef	144.0203	-11.4099	Chelonia mydas	2001	2164	#females exact	2164 females
AU309	Raine Island, north Great Barrier Reef	144.0333	-11.59091	Chelonia mydas	2001	70122	#females exact	70122 females
ID27	Bilang-Bilangan	118.9472	1.5611	Chelonia mydas	2009	4775	#clutches exact	1194 females
MY02	Turtle Islands, Sabah	118.024	6.1115	Chelonia mydas	2000	8000	#clutches exact	2000 females
OM12	Ras al Had	59.826	22.421	Chelonia mydas	1985	44000	#clutches exact	14667 females
SC52	Farquhar Group	51.18627	-10.13623	Chelonia mydas	2002	4145	#females exact	4145 females
TF03	Europa	40.3628	-22.35793	Chelonia mydas	1984	10844	#females exact	10844 females
ID02	Jamursba Medi	132.4377	-0.34792	Dermochelys coriacea	2003	3601	#clutches exact	721 females
ID14	Warmon	132.8077	-0.421857	Dermochelys coriacea	2003	2881	#clutches exact	577 females
IN02	Beaches straddling the Alexandria and Dagmar Rivers	93.69367	7.017542	Dermochelys coriacea	2001	1228	#clutches exact	246 females
IN05	Galathea Beach, Great Nicobar Island	93.85243	6.81737	Dermochelys coriacea	2003	574	#clutches exact	115 females
LK02	Bentota	79.98471	6.446412	Dermochelys coriacea	2004	25-100	#females binned	62 females
PG02	Busama (Buli)	146.9459	-6.92241	Dermochelys coriacea	2010	284	#clutches exact	57 females
PG04	Kamiali Wildlife Management Area	147.1245	-7.285559	Dermochelys coriacea	2003	71	#females exact	71 females
ZA01	Mabibi to Kosi Lake	32.805	-27.165	Dermochelys coriacea	2005	49	#females exact	49 females
AU10	Dayman Island	142.373	-10.7628	Eretmochelys imbricata	1997	500-1000	#clutches binned	250 females
AU11	Hawkesbury (Warral) Island	142.126	-10.3812	Eretmochelys imbricata	1997	500-1000	#clutches binned	250 females
AU15	Long Island	142.847	-10.0459	Eretmochelys imbricata	1997	500-1000	#clutches binned	250 females
AU27	Rosemary Island	116.5854	-20.47246	Eretmochelys imbricata	2006	423	#females exact	423 females
ER01	Aucan Island	40.80259	15.510841	Eretmochelys imbricata	2007	500-1000	#females binned	750 females
ER02	Mojeidi Island	40.86491	15.502738	Eretmochelys imbricata	2007	500-1000	#females binned	750 females
OM11	Dalmaniyat	58.06778	23.853392	Eretmochelys imbricata	1986	1225	#clutches exact	341 females
SC08	Cousin Island Special Reserve	55.66227	-4.330824	Eretmochelys imbricata	2007	793	#females exact	793 females
SC10	D’Arros Island and St. Joseph Atoll	53.29899	-5.415606	Eretmochelys imbricata	2005	250-500	#females binned	375 females
AU284	Cape Van Diemen	130.381	-11.1727	Lepidochelys olivacea	2004	3300	#clutches exact	1500 females
BNX	Brunei	114.4741	4.679503	Lepidochelys olivacea	2001	301	#clutches exact	137 females
IN04	Cuthbert Bay	92.96796	12.708577	Lepidochelys olivacea	2003	711	#clutches exact	324 females
IN102	Kalingapatnam/Vamsadhara	84.12767	18.327816	Lepidochelys olivacea	2001	570	#clutches exact	260 females
IN126	Mamallapuram - Pondi	80.19759	12.613229	Lepidochelys olivacea	2000	600	#clutches exact	273 females
IN137	Nagapattinam	79.85265	10.712352	Lepidochelys olivacea	2000	1080	#clutches exact	491 females
IN180	Srikurmam	84.02962	18.25152	Lepidochelys olivacea	2001	264	#clutches exact	120 females
IN200	Srikakulam	83.95686	18.220438	Lepidochelys olivacea	2001	283	#clutches exact	129 females
IN76	Devi River mouth, Orissa; includes Rushikulya, Gahirmatha Rivers	86.40603	19.98021	Lepidochelys olivacea	2003	150000-20	#females binned	175000 females
Murali_01	Gahirmatha	87.043	20.699747	Lepidochelys olivacea	DD	DD	DD	DD
Murali_02	Rushikulya	85.08534	19.386358	Lepidochelys olivacea	DD	DD	DD	DD
AU119	Cemetery Beach	118.608	-20.30764	Natator depressus	2007	1128	#clutches exact	403 females
AU39	Cape Domett	128.4091	-14.80117	Natator depressus	2006	3250	#females exact	3250 females
AU70	Crab Island	142.1024	-10.99022	Natator depressus	2008	1000-5000	#females binned	3000 females
AU71	Flinders Beach	141.7358	-12.21896	Natator depressus	2008	250-500	#females binned	375 females
AU80	Wild Duck	149.8604	F16-22.001	Natator depressus	2008	100-250	#females binned	175 females
AU81	Barrow Island	115.4589	-20.79204	Natator depressus	2007	1607	#females exact	1607 females
AU82	Mundabullangana Beach	118.0377	-20.4449	Natator depressus	2008	1700	#females exact	1700 females

TRAINING DATA SET

Site number	Beach	Country	Latitude	Longitude
1	90 Mile	N. Zealand	-34.90889	173.08333
2	Achiras	Uruguay	-33.93333	-53.50000
3	Aguada	Uruguay	-34.63333	-54.15000
4	Ahui	Chile	-41.81667	-73.85000
5	Al-Ashkarah	Oman	21.66667	59.50000
6	Alepue I	Chile	-39.48333	-73.25000
7	Alepue R	Chile	-39.50000	-73.25000
8	Ambinanibe	Madagascar	-25.06666	46.95550
9	Ambudi	Madagascar	-15.25000	50.48333
10	America	Spain	42.13295	-8.81866
11	Ampanavoana	Madagascar	-15.68050	50.34983
12	Ampanavoana Coral	Madagascar	-15.75000	50.38000
13	Andrín	Spain	43.41146	-4.70814
14	Arachania	Uruguay	-34.61612	-54.15156
15	Area Longa	Spain	43.16667	-9.18333
16	Armstrongs	Australia	-21.52372	149.21778
17	Arrawarra	Australia	-30.06015	153.19386
18	Atami	Brazil	-25.63755	-48.41507
19	Baie de Singe	Madagascar	-25.05000	46.98333
20	Bakio	Spain	43.43031	-2.80839
21	Baldaio	Spain	43.29657	-8.68568
22	Ball Bay	Australia	-21.14636	149.18511
23	Ballenita	Ecuador	-2.20482	-80.87454
24	Bares	Spain	43.76995	-7.67578
25	Barra Chuy	Uruguay	-33.75556	-53.38889
26	Barrañan	Spain	43.31139	-8.55431
27	Barrancos	Brazil	-25.61667	-48.40000
28	Bashams	Australia	-35.51067	138.70532
29	Baylys	N. Zealand	-35.95972	173.74944
30	Berria	Spain	43.46601	-3.46914
31	Blacks	Australia	-21.07275	149.18395
32	Bloubergstrand	South Africa	-33.79720	18.46200
33	Blythdale	South Africa	-29.26667	31.26667
34	Boambee	Australia	-30.33987	153.06901
35	Boqueiraa	Brazil	-22.93333	-42.48333
36	Brejatuba	Brazil	-25.88341	-48.57621
37	Briceño	Ecuador	-0.31881	-80.41886
38	Britannia Bay	South Africa	-32.72079	17.93689
39	Bucasia	Australia	-21.03674	149.15811
40	Campwin	Australia	-21.38147	149.30915
41	Cap Est High Energy	Madagascar	-15.26667	50.48333
42	Cap Est Low Energy	Madagascar	-15.26667	50.48333
43	Carapebus	Brazil	-22.18643	-41.46667
44	Carnota	Spain	42.82261	-9.10528
45	Cassino	Brazil	-32.17881	-52.16204
46	Cassino 1	Brazil	-32.24068	-52.20703
47	Cassino 2	Brazil	-32.28249	-52.24823
48	Cassuarina	Australia	-21.07145	149.22168
49	Centro	Brazil	-25.57889	-48.35766
50	Chan - Chan	Chile	-39.51389	-73.25694

Site number	Beach	Country	Latitude	Longitude
51	Cheuque	Chile	-39.40833	-73.22500
52	Chiton Rocks	Australia	-35.53770	138.65473
53	Codihue	Chile	-39.85000	-73.38000
54	Concheiros	Brazil	-32.51903	-52.38281
55	Coorong	Australia	-35.94977	139.46694
56	Corrubedo	Spain	42.54503	-9.03058
57	Costa Azul	Brazil	-22.51667	-41.91667
58	Costa Azul	Uruguay	-34.76944	-55.65944
59	Cumuruxatiba	Brazil	-17.10000	-39.18333
60	Curinanco	Chile	-39.72564	-73.38723
61	De Panne	Belgium	51.09837	2.58789
62	Deserta	Brazil	-25.43333	-48.18333
63	Doniños	Spain	43.49400	-8.31989
64	Dwarkesboos	South Africa	-32.70266	18.18257
65	Evans Cave	Australia	-37.17622	139.75618
66	Fampotabe	Madagascar	-15.93635	50.14044
67	Farnborough (S)	Australia	-23.09162	150.74379
68	Fonteintjies	Belgium	51.33333	3.16667
69	Fora	Brazil	-22.95000	-43.18333
70	Formosa	Brazil	-22.80000	-41.91667
71	Fotobato	Madagascar	-15.16667	50.45000
72	Frouxeira	Spain	43.61149	-8.16528
73	Gaviotas	Chile	-41.85000	-73.75000
74	Goolwa	Australia	-35.50198	138.78310
75	Grande	Brazil	-25.45335	-48.41878
76	Grande I.d.Mel	Brazil	-25.56667	-48.30000
77	Granites	Australia	-36.44770	139.58354
78	Grass Tree	Australia	-21.14636	149.18511
79	Groenrivier	South Africa	-30.77746	17.76806
80	Grumari	Brazil	-23.05000	-43.50000
81	Guabun	Chile	-41.80000	-74.01667
82	Harmonia	Brazil	-29.92389	-50.09500
83	Havaizinho	Brazil	-17.96667	-39.46667
84	Hearns Lake	Australia	-30.13688	153.19714
85	Heist	Belgium	51.34036	3.24004
86	Hendaya	Spain	43.37922	-1.79022
87	Huicha	Chile	-41.83333	-73.73333
88	Iemanjá	Brazil	-17.71356	-39.15000
89	Ilha do Cardoso 1	Brazil	-25.13167	-47.96639
90	Itaipu	Brazil	-22.96895	-42.98203
91	Jaconé	Brazil	-22.91667	-42.63333
92	Jardim do Eden	Brazil	-30.08333	-50.17330
93	Jose Ignacio	Uruguay	-34.81667	-54.61667
94	Kelso	South Africa	-30.26667	30.66667
95	Khaluf	Oman	20.47195	58.06011
96	Korora	Australia	-30.24980	153.12830
97	La Baguala	Uruguay	-34.79694	-55.52528
98	La Espasa	Spain	43.47486	-5.21488
99	Laga	Spain	43.40917	-2.65733
100	Lammermoor	Australia	-23.16108	150.76317

Site number	Beach	Country	Latitude	Longitude
101	Langre	Spain	43.47587	-3.69228
102	Lanzada	Spain	42.45198	-8.87960
103	Laredo	Spain	43.41338	-3.42715
104	Lechagua	Chile	-41.86667	-73.85000
105	Liencres	Spain	43.44622	-3.97679
106	Llas	Spain	43.57964	-7.26186
107	Long beach	Australia	-37.16249	139.75489
108	Los Molinos2	Chile	-39.81233	-73.39707
109	LosMohinos1	Chile	-39.81233	-73.39707
110	Louro	Spain	42.75366	-9.09823
111	Lugar Comum	Brazil	-17.90000	-39.35000
112	Mackay	Australia	-21.14636	149.18511
113	Mackay Harbour	Australia	-21.10876	149.20978
114	Maiquillahue	Chile	-39.45177	-73.26972
115	Maiquillahue	Chile	-39.45000	-73.25000
116	Majis	Oman	24.44253	56.62943
117	Manantiales	Uruguay	-34.90556	-54.82500
118	Mar Brava	Chile	-41.90000	-73.98333
119	Marambaia	Brazil	-23.05000	-43.60000
120	Maroansetra	Madagascar	-15.43745	49.73877
121	Masirah	Oman	20.31734	58.69159
122	Massambaba	Brazil	-22.95022	-42.11475
123	Matias	Chile	-39.45000	-73.23333
124	Moolach	USA	44.66670	-124.08333
125	Moonee	Australia	-30.19334	153.16272
126	Mughsayl	Oman	16.50000	53.75000
127	N. Corindi	Australia	-30.03092	153.19867
128	Naseem	Oman	23.69426	58.04842
129	Navegantes	Brazil	-26.50000	-48.75000
130	Ocean	N. Zealand	-39.74167	177.03500
131	Ocean View	Australia	-30.06015	153.19386
132	Ohope	N. Zealand	-37.99528	177.12306
133	Olon	Ecuador	-1.75139	-80.77297
134	Otur	Spain	43.55374	-6.59675
135	Oyambre	Spain	43.39194	-4.33107
136	Pakiri	N. Zealand	-36.25306	174.74083
137	Parsons	Australia	-35.57466	138.48256
138	Pecado	Brazil	-22.80000	-41.93333
139	Pecas	Brazil	-25.48333	-48.25000
140	Peñarronda	Spain	43.55395	-6.99664
141	Pichicuyin	Chile	-39.42361	-73.21184
142	Ponta da Baleia	Brazil	-17.70000	-39.15000
143	Ponta do Bicho	Brazil	-25.45335	-48.41878
144	Pontal do Sul	Brazil	-17.75000	-39.18333
145	Portéte	Ecuador	-1.97042	-80.75264
146	Praia do Farol	Brazil	-17.48333	-39.20000
147	Prainha	Brazil	-23.03333	-43.48333
148	Prainha	Brazil	-26.24222	-48.50222
149	Punta de la Barra	Chile	-39.43118	-73.21184
150	Punta del Diablo	Uruguay	-34.04583	-53.53889

Site number	Beach	Country	Latitude	Longitude
151	Quinns	Australia	-31.33333	115.61667
152	Quriyat	Oman	23.26516	58.90344
153	Rarawa	N. Zealand	-34.71667	173.08333
154	Raversijde	Belgium	51.20651	2.86426
155	Riviera	Brazil	-25.75000	-48.50000
156	Ronca	Chile	-39.81959	-73.24521
157	Rostro	Spain	42.96512	-9.26659
158	Salvaje	Spain	43.38915	-2.99527
159	San Clemente	Ecuador	-0.75436	-80.51017
160	San Cosme	Spain	43.56498	-7.22396
161	San Pablo	Ecuador	-2.13997	-80.77691
162	San Pedro	Ecuador	-1.45400	-80.72903
163	San Pedro	Spain	43.55119	-6.47453
164	San Roman	Spain	43.71878	-7.62459
165	Santa Monica	Uruguay	-34.85000	-54.71667
166	Santiene	Brazil	-25.70000	-48.46667
167	Sarina	Australia	-21.42372	149.21778
168	Scarborough	Australia	-31.58333	115.58333
169	Schippadium	Belgium	51.13333	2.66667
170	Shoal Point	Australia	-21.00339	149.15354
171	Silwerstroomstrand	South Africa	-33.58333	18.35000
172	Sodwana	South Africa	-27.41667	32.73333
173	Solari	Uruguay	-34.65000	-54.16667
174	Spoegrivier	South Africa	-30.44184	17.43294
175	St Lucia	South Africa	-28.25000	32.41667
176	StLaureins	Belgium	51.16667	2.78333
177	Stompneus Bay	South Africa	-32.72303	17.96800
178	Strandfontien	South Africa	-31.75556	18.22722
179	Sur	Oman	22.56667	59.52889
180	Taquaras	Brazil	-27.46667	-48.16667
181	Threemile	USA	43.75000	-124.20000
182	Toranda	Spain	43.44049	-4.83865
183	Tororao	Brazil	-17.23333	-39.21667
184	Traba	Spain	43.18908	-9.04971
185	Tramandai	Brazil	-30.00611	-50.11667
186	Tucúns	Brazil	-22.63333	-42.00000
187	Ubatuba	Brazil	-26.20000	-48.51667
188	Unamar	Brazil	-22.64764	-42.00618
189	Urca	Brazil	-22.95000	-43.15000
190	Varingut	Madagascar	-15.48333	49.71660
191	Vega	Spain	43.48002	-5.13962
192	Velddrif	South Africa	-32.77920	18.16959
193	Viveiro	Spain	43.71109	-7.55993
194	Vosseslag	Belgium	51.25814	3.00832
195	Waihi	N. Zealand	-37.43250	175.96750
196	Wainui	N. Zealand	-38.67167	178.10944
197	Waitpinga	Australia	-35.57466	138.58393
198	Whirinaki	N. Zealand	-39.39611	176.89111
199	Whisky Run	USA	43.16667	-124.41667
200	Xagó	Spain	43.60193	-5.92365
201	Xivares	Spain	43.57032	-5.72002
202	Xuño	Spain	42.68333	-9.01667
203	Zarautz	Spain	43.28804	-2.17032
204	Zeloris	Brazil	-17.58333	-39.18333

APPENDIX 3.2: Criteria and category development

Back-beach width

Back-beach width measurements were obtained as stipulated in the Methods section of this chapter. The back-beach percentile values for the training data set was calculated as: 20th = 8.71 m, 40th = 11.67 m, 60th = 17.92 m, 80th = 26.31 m and 100th = 100.79 m. Values were rounded and score categories were developed, where more narrow beaches were allocated a higher risk score and wider beaches a lower risk score. See table below (**Table 0.1**).

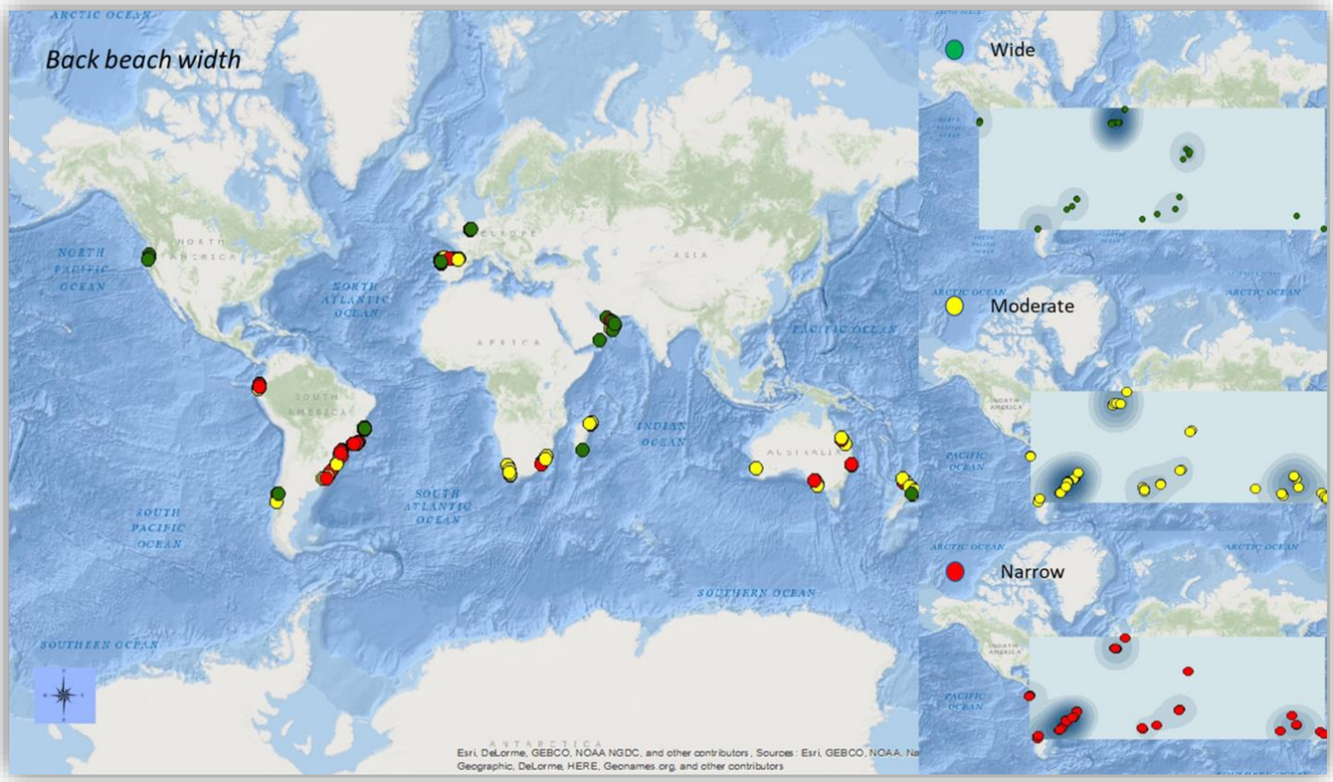
Table 0.1: Back-beach width rounded percentile value (m) categories and relevant risk scores, created from the Defeo and McLachlan (2013) training beach data set

Percentiles	Rounded BB width percentile values (m)	Score
0 - 20 %	0 -9	5
20 - 40%	9-12	4
40 - 60 %	12-18	3
60 - 80 %	18-26	2
80 - 100 %	> 26	1

Average back-beach width range for the training data set (average of three BBW measurements across beach) range of 0 – 100. 8 m. The widest average BBW (100.8 m) was recorded for Fonteintjies beach, Belgium and the narrowest BBW (0 m) recorded for Andrin beach, Spain. Mapping the relative density of these back-beach width categories (narrow, moderate and wide) in ArcMap 10.5.1 (Kernel density analysis) and beach frequency analyses within BBW categories for the training data set (**Figure A3.2: 0.1**), might suggest a *correlation* between *back-beach* width and *longitude*. However, no statistics has been conducted to establish the significance of this trend. Generally, beaches north of the equator had wider beaches, including the beaches of Belgium, Oman, Spain and the USA (**Table 0.2** and **Figure A3.2: 0.1)**. While beaches south of the equator have moderate to narrow beaches, including beaches of Australia, Brazil, Chile, Ecuador, Madagascar, New Zealand, South Africa and Uruguay. This trend may explain why the majority of the study sites/sea turtle nesting beaches had a narrow back-beach (< 10 m), because the Indian Ocean lies south of the equator.

Table 0.2: Percentage of beaches (%) within a BBW category (narrow, moderate and wide) per country, where red represents narrow BBW, orange represents moderate BBW and green represents wide BBW.

Back beach category	Percentage of beaches (%) within a BBW category (narrow, moderate and wide) per country											
	Australia	Belgium	Brazil	Chile	Ecuador	Madagascar	N. Zealand	Oman	South Africa	Spain	Uruguay	USA
Narrow BBW	30	17	37	42	57	36	22	13	23	16	45	0
Mod BBW	67	17	54	26	43	36	67	25	62	41	55	0
Wide BBW	3	67	9	32	0	27	11	63	15	43	0	100



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors, Sources: Esri, GEBCO, NOAA, Na
Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure A3.2: 0.1: a) Map depicting the score (low/wide, moderate or high/narrow) assigned to ***back-beach width measurements*** *for the Defeo and McLachlan (2013) beaches. To map back-beach width, the five score categories were simplified to narrow (< 10 m), moderate (10 – 25 m) and wide (> 25 m) back-beach categories. b) Map depicting the relative density (Kernel density) of beaches with a low back-beach width score. c) Map depicting the relative density (Kernel density) of beaches with a moderate back-beach width score. d) Map depicting the relative density (Kernel density) of beaches with a high back-beach width score. According to these analyses, sampled beaches north of the equator (Belgium, Oman, Spain and USA) have the lowest* ***overall*** *back-beach width scores, i.e. some of these beaches have the broadest back-beaches. While the sampled south of the equator beaches of South America (Brazil, Chile, Ecuador, Uruguay) has both the highest density of beaches that scored moderate and high, i.e. some of these beaches have a moderate to very short back-beach.*

Sea level rise

Sea level rise values were obtained as stipulated in the Methods section of this chapter. The sea level rise percentile values for the training data set was calculated as: 20th = 0.36 m, 40th = 0.38 m, 60th = 0.40 m, 80th = 0.48 m and 100th = 0.60 m. See table below (Table 0.3). These scores were then allocated to the sea level rise values of the study sites/sea turtle nesting beaches.

Table 0.3: Sea level rise categories and relevant threat score, created from the Defeo and McLachlan (2013) training beach data set

Percentiles	Sea level rise values	Score
0 - 20 %	0.33 - 0.36	1
20 - 40 %	0.36 - 0.38	2
40 - 60 %	0.38 - 0.40	3
60 - 80 %	0.40 - 0.48	4
80 - 100 %	> 0.48	5

To get a global picture for the threat of sea level rise to certain regions, the beaches of the training data set was initially scored on a threat range of 1 to 3 by using quartile range values. The quartile range values of the sea level rise values were calculated: Q1 = 0.30 m and Q 3 = 0.38 m. According to the quartile ranges, score categories were developed as follows; beaches with a sea level rise value > 0.38 m = 3 (high risk), beaches with a sea level rise value between 0.30 – 0.38 m = 2 (moderate risk) and beaches with a sea level rise value < 0.30 m = 1 (low risk). Using these preliminary score categories, a map was created in ArcMap 10.5.1, where each of the beaches were depicted according to their sea level rise score (1-3) score. A kernel density analysis was conducted to show where threat of sea level rise is most relevant (**Figure A3.2: 0.2**).

The beaches of the global training data set had a range of sea level rise values from 0.33 to 0.48 m by 2100 with the highest density of threatened beaches (SLR > 0.48) occurring on the European Coastline (North Atlantic Ocean) (**Figure A3.2: 0.2**), *but most of the beaches of the Indian ocean and South-East Asia had moderate to low sea level rise values* (SLR = 0.36 – 0.40 m) and were therefore allocated low to moderate scores (scores = 1 – 3).

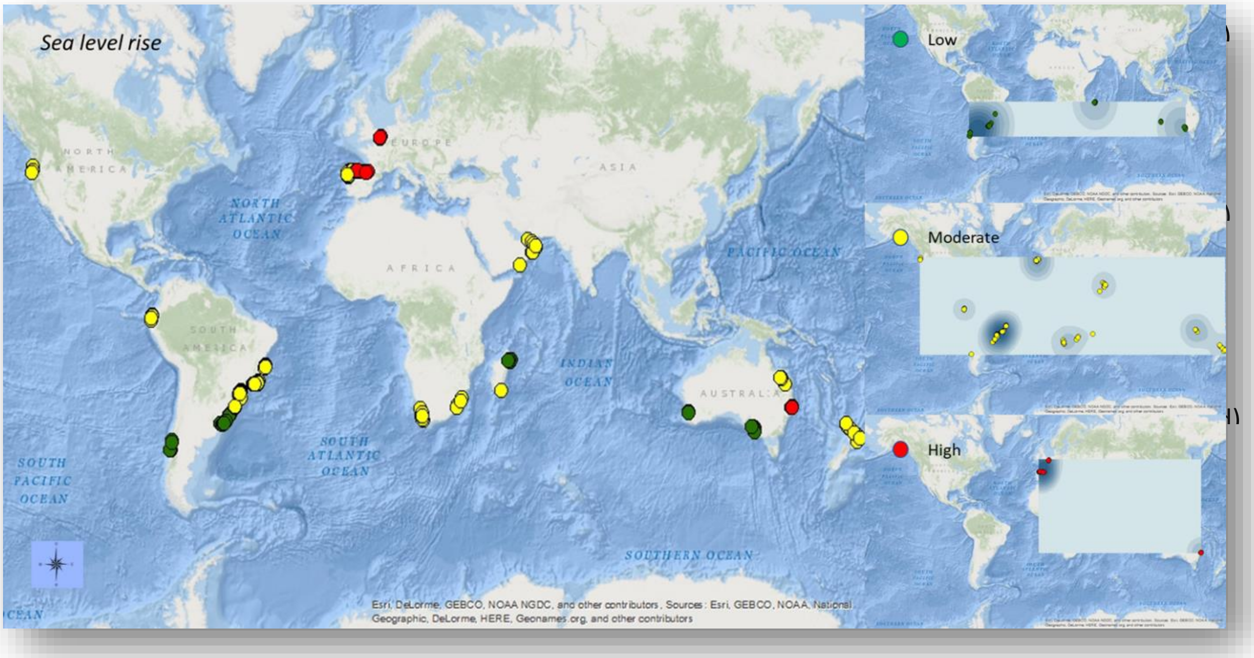


Figure A3.2: 0.2: a) Map depicting the score (low, moderate or high) assigned to ***SLR*** *(average increase 2020s-2090s) for the Defeo and McLachlan (2013) beaches. b) Map depicting the relative density (Kernel density) of beaches with a low SLR score. c) Map depicting the relative density (Kernel density) of beaches with a moderate SLR score. d) Map depicting the relative density (Kernel density) of beaches with a high SLR score. According to these analyses, the sampled beaches in South America (Brazil, Chile, Ecuador, Uruguay) have low and moderate* ***overall*** *SLR scores, i.e. these beaches are least threatened by SLR. The sampled beaches of Europe (Belgium and Spain) have the highest SLR scores, i.e. these beaches are most threatened by SLR.*

Storminess

Storm frequency

A storm frequency value was calculated as stipulated in the Methods section of this chapter. To score storm frequency the density categories from the line density output was used (**Figure A3.2: 0.3** and **Table 0.4**).

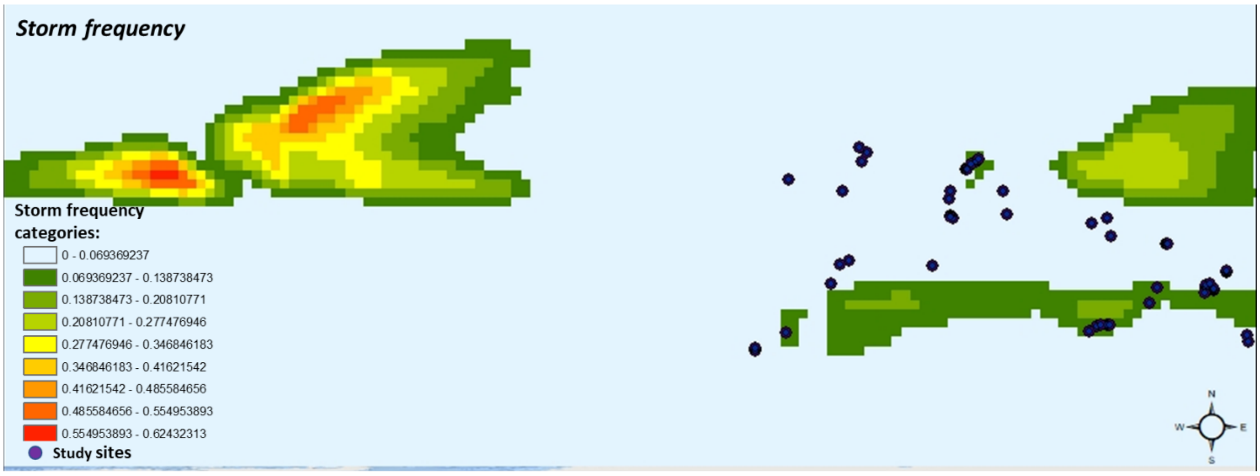


Figure A3.2: 0.3: Storm track density analysis with an output cell size of 250 km^2.

Table 0.4: Scores allocated to the storm track density (km^2) categories from the line density output

Value (magnitude per km2)	Score
0	0
0-0.069	1
0.069-0.139	2
0.139-0.208	3
0.208-0.277	4
0.277-0.347	5
0.347-0.416	6
0.416-0.486	7
0.486-0.554	8
0.554-0.624	9

Storm intensity

A storm intensity value was calculated as stipulated in the Methods section of this chapter. To score storm frequency the density categories from the feature to raster output based on maximum sustained winds (knots) was used (**Figure A3.2: 0.4** and **Table 0.5**).

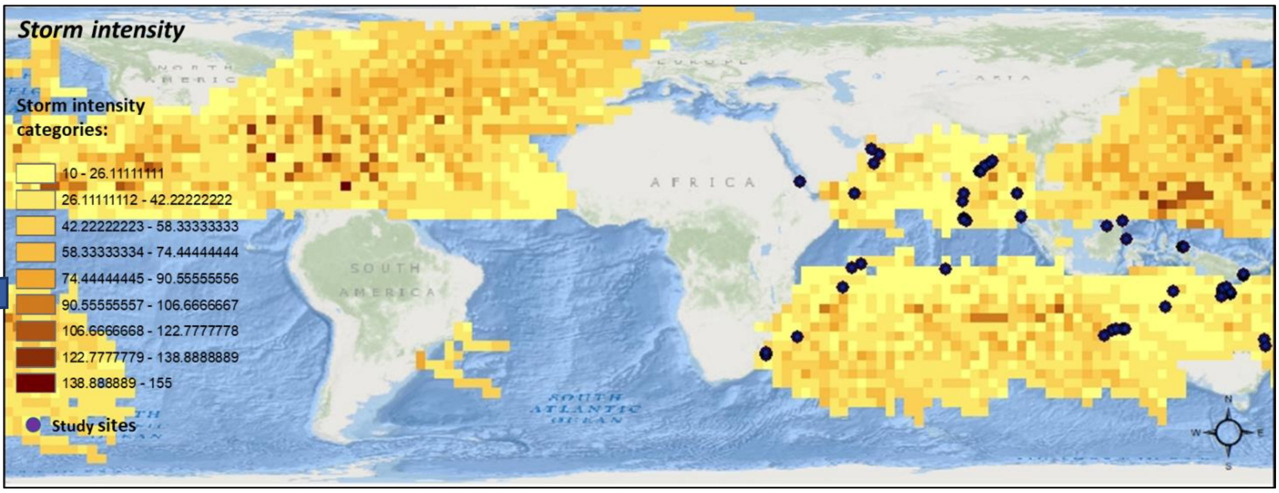


Figure A3.2: 0.4: Storm intensity analysis with an output cell size of 250 km^2.
Table 0.5: Scores allocated to the storm intensity (km^2) categories from feature (maximum sustained wind (knots)) to raster output

Value (magnitude per km2)	Score
0	0
10 - 26	1
26 - 42	2
42 - 58	3
58 - 74	4
74 - 91	5
91 - 107	6
107 - 123	7
123 - 139	8
139 - 155	9

APPENDIX 3.3: Additional datasets

Dataset 1: Beach orientation and protection

Site ID	Beach name	Exposure rating	Qualitative information
AU08	Bungelup	1.5	Curved beach No surfzone + low entropy Offshore reef system offers shelter Windy: Waves = SW and runs parallel with the beach, so no direct wave action
AU10	Dayman Island	1.5	Island with curved beaches Multiple beaches make up the sea turtle nesting habitat of the island, so I rated each sandy beach's exposure and got an average No surfzone and low entropy Windy: Waves = SE to E To the SE and E is protected by continent, distance 4 km. Sheltered to the N by other island. Exposed on the W.
AU11	Hawkesbury (Warral) Island	1	Island with curved beaches No surfzone and low entropy Multiple beaches make up the sea turtle nesting habitat of the island, so I rated each sandy beach's exposure and got an average Offshore sand deposits OR reef surrounds entire island and offers protection Windy: Waves = SE
AU119	Cemetery Beach	2	Straight beach No surfzone + low entropy Sheltered on the west side of the island by an artificial sand deposit/harbour and to the east it is sheltered by

			offshore reef. Windy: Waves approaching from the NE.
AU15	Long Island	1.5	Island with curved beaches Sea turtle habitat on the western beaches of the island, I rated each sandy beach's exposure and calculated an average Reef and sand deposits to the SE of island offers shelter Small surfzone + moderate entropy Windy: Waves = SE
AU27	Rosemary Island	1	Island No surfzone and low entropy Windy: Waves moves in a NE The NE portion of the island protected by other islands.
AU284	Cape Van Diemen	2	Curved beach + long straight beach N and Western facing beach. Windy: indicates that waves = NE direction, which means only the point of Cape van Diemen will be exposed to some direct wave action while the rest of the beach on the Western side will be fairly sheltered. I could not elicit surfzone width and image entropy from the image as it was of poor quality. Those two factors therefore do not contribute to the final exposure score of this beach, only wave direction and beach angle do.
AU300	Moulter Cay, north Great Barrier Reef	1	Coral Cay Island Entire island is nesting habitat No surfzone + Low entropy The planar reef underneath the island, surrounding the island, offers protection from the waves Windy: Waves = SE

AU309	Raine Island, north Great Barrier Reef	1	Coral Cay Island Entire island is nesting habitat No surfzone action + Low entropy The planar reef underneath the island, surrounding the island, offers protection from the waves Windy: Waves = SE
AU33	Woongarra coast including Mon Repos	2	Curved beach Small surfzone + low entropy Windy: Waves = N and it is a NE facing beach, so semi-exposed
AU34	Wreck Island	1	Island Entire island surrounded by offshore reef system and sand bank that offers shelter No surfzone + low entropy Windy: Waves = S
AU39	Cape Domett	3.5	Straight beach Moderate surfzone (2-3 waves), moderate entropy Straight north facing beach. Rocky outcrop on east side of the beach may offer some shelter, but Windy indicates that waves move in a southern direction and therefore hits the beach directly.
AU70	Crab Island	1	Island No surfzone + low entropy Entire island = nesting habitat. Island is situated ~ 1km off Australian coast. Island is in the shape of a C and completely sheltered on the east side by Australian continent. Therefore, only the west side of the island is exposed. West side is the back of the C. Windy indicates that waves move in a SE direction which means it will not directly hit exposed western side of the island.

AU71	Flinders Beach	2.5	Long straight beach Small surfzone + moderate entropy Slightly sheltered SW of the beach by sandy outcrop Windy: SW direction parallel to the beach
AU80	Wild Duck	0.5	Island with curved beaches Multiple beaches make up the sea turtle nesting habitat of the island, so I rated each sandy beach's exposure and calculated an average No surfzone + low entropy Windy: Waves + wind = Southern direction. There is only one North facing bay, but this bay is sheltered by sand island offshore. The other bays are sheltered by the island itself and rocky outcrops
AU81	Barrow Island	2	Island The island is very big and multiple beaches make up the sea turtle nesting habitat. To rate exposure I rated the exposure of each of the sandy beaches and calculated an average Windy: Waves = SE, so southern side of island is exposed and some parts of western side
AU82	Mundabullangana Beach	2.5	Curved beach Small surfzone + low entropy Windy: Waves move parallel to the beach (NE). Outer edge of the beach to the east shelters E portion of the beach
BNX	Brunei	3.5	Straight beach Moderate surfzone + low entropy NW facing beach Windy: Waves = N, therefore large portion of beach receives direct wave action
ER01	Aucan Island	1	Island No surfzone and low entropy Windy: Waves=NE to E

			The NE portion of the island slightly protected offshore reef system. To the N, E and SW the island is protected by other islands.
ER02	Mojeidi Island	1.5	Island No surfzone + low entropy Windy: Waves = NE to E The NE portion of the island slightly protected offshore reef system. To the W the island is protected by another island.
ID02	Jamursba Medi	3.5	Long straight beach Moderate to large surfzone + high entropy Windy: Waves = NE, perpendicular to the beach as this is a NE facing beach Therefore beach is fully exposed to oncoming waves
ID14	Warmon	4	Long straight beach Large surfzone + high entropy Windy: Waves = NE, perpendicular to the beach as this is a NE facing beach Therefore beach is fully exposed to oncoming waves
ID27	Bilang-Bilangan	1	Island Entire island is nesting habitat Island on top of sand that surrounds it, which should reduce wave action No surfzone + low entropy Windy: Waves approach from SE direction, but big land form offers some protection.
IN02	Beaches straddling the Alexandria and Dagmar Rivers	3	Curved beach Large surfzone + moderate entropy Windy: Waves = SW. Waves run perpendicular to the beach, therefore beach is exposed to direct on coming waves, but rocky outcrop to west might offer some shelter

IN04	Cuthbert Bay	2	Curved beach Moderate surfzone + moderate entropy SE facing beach with outcrop providing shelter on both the northern and southern sides of the island Windy: Waves = SW therefore moving parallel to the beach.
IN05	Galathea Beach, Great Nicobar Island	2	Curved beach (C-shaped) Large surfzone + moderate entropy Windy: Waves = SW. Therefore, rocky outcrop on W of island should offer some shelter
IN102	Kalingapatnam/Vamsadhara	2.5	Curved beach Large surfzone + moderate entropy SE facing beach Windy: Waves = S The curves of the bay provides shelter form the southern waves
IN126	Mamallapuram - Pondi	3.5	Straight beach Moderate surfzone + moderate entropy SE to E facing beach Windy: Waves = SE, therefore a large portion of the beach will have direct wave action
IN137	Nagapattinam	3.5	Straight beach Moderate surfzone + moderate image entropy No barriers or shelter Eastern facing beach Windy: Waves=SE, so some exposure to waves.
IN180	Srikurmam	4	Straight beach Large surfzone + high entropy No barriers SE facing beach Windy: Waves = S. Waves run almost perpendicular to the beach (direct wave action

IN200	Srikakulam	4	Straight beach Large surfzone + high entropy No barriers SE facing beach Windy: Waves = S. Waves run almost perpendicular to the beach (direct wave action
IN76	Devi River mouth, Orissa; includes Rushikulya, Gahirmatha Rivers	2	Beaches and islands Multiple beaches make up the sea turtle nesting habitat of the island, so I rated each sandy beach's exposure and got an average Beaches are facing SE. Windy: Waves = S, so some exposure to waves
LK02	Bentota	3.5	Slightly curved beach Large surfzone + moderate entropy Windy: Waves = SW and it is a south-western facing beach, therefore beach is exposed to direct oncoming waves. No barriers.
LK05	Rekawa	3	Curved beach Moderate surfzone + high entropy Windy: Waves=N and it is a south facing beach, therefore the waves impact directly.
LK21	Kosgoda	3	Straight beach Moderate surfzone + moderate entropy Windy: Waves = SW and it is SW to W facing beach, some direct wave action
Murali_01	Gahirmatha	3.5	Straight beach Moderate surfzone + moderate entropy SE facing beach Windy: Waves= S. Waves run almost perpendicular to the beach

Murali_02	Rushikulya	3	Straight beach Small surfzone + low entropy SE facing beach Windy: Waves= S. Waves run almost perpendicular to the beach (direct wave action)
MY02	Turtle Islands, Sabah	1.5	Island Entire island is nesting habitat Island on top of sand that surrounds it, which should reduce wave action No surfzone + low entropy Windy: Waves approach from SE direction, which means the largest portion of the island and the longest stretch of beach would be subjected to oncoming waves.
MZ07	Malongane	4	Curved beach Moderate surfzone + high entropy Windy: Waves = NE and it is a NE to E facing beach. No barriers.
OM02	Masirah	2	Island made up of curved beaches Multiple bays constitute sea turtle nesting habitat, therefore I rated the exposure for each beach and then calculated an average Windy: Waves = N. Most of the island is sheltered from the oncoming waves.
OM11	Dalmaniyat	1	Island with curved beaches Multiple beaches make up the sea turtle nesting habitat of the island, so I rated each sandy beach's exposure and got an average No surfzone and low entropy Windy: Waves = NE to E To the E the island is protected by other island.

OM12	Ras al Had	2	Log spiral bays More than one beach included in sea turtle nesting habitat for this region. I rated each bay's exposure, then calculated an average. Small surfzone + Low entropy Log spiral bay formations offers some shelter to the majority of these beaches. Windy: Waves = N to NE, run parallel to beach, some exposure on the more northern beaches
PG02	Busama (Buli)	3	Curved beach Small surfzone + low entropy Windy: Waves = SE and it is and E facing beach, therefore waves do not hit beach directly, but some portions are exposed
PG04	Kamiali Wildlife Management Area	2.5	Curved beach Small surfzone + moderate entropy Windy: Waves = SE and it is and E facing beach and rocky outcrop to the S should offer shelter
SC08	Cousin Island Special Reserve	3	Island Moderate surfzone with high entropy Windy: Waves moving SE
SC10	D’Arros Island and St. Joseph Atoll	1.5	Islands No surfzone and low entropy Both islands surrounded and therefore protected by offshore reef. Island elevated on sand banks. Slightly exposed on the SE side. Windy: Wave = SE
SC52	Farquhar Group	0.5	Island No surfzone + low entropy Entire island is nesting habitat Island is c-shaped. Outside of c is protected by coral reef. Inside is protected by outer edges Windy: Waves = SE.

TF03	Europa	1	Island No surfzone + low entropy Nesting habitat is only northern portion of island Sheltered by coral reef offshore Windy: Waves coming from the S, therefore the northern portion of the island is sheltered by the rest of island. Island is most exposed on the S.
YE01	Abalhan Protected Area/Socotra Man and Biosphere Reserve	3	Island with mainly straight beaches Moderate to large surfzone on southern side of island Moderate to high entropy on southern side Windy: Waves=S. Therefore, the entire southern side of the island (approximately half of the nesting habitat) is receiving direct wave action
ZA01	Mabibi to Kosi Lake	4	Curved beach Moderate surfzone + high entropy Windy: Waves = NE and it is a NE to E facing beach. No barriers.

Dataset 2: All risk scores

Site number	Site ID	Bbwidth Score_Normal	Exposure Score_Normal	Modal beach energyScore_Normal	DunesScore_Normal	Summed risk score
1	AU08	1	0.38	0.38	0.33	2.08
2	AU10	1	0.38	0.29	1.00	2.67
3	AU11	0.4	0.25	0.42	1.00	2.07
4	AU119	1	0.50	0.33	0.67	2.50
5	AU15	1	0.38	0.42	1.00	2.79
6	AU27	1	0.25	0.33	0.33	1.92
7	AU284	1	0.50	0.33	0.67	2.50
8	AU300	0.2	0.25	0.46	1.00	1.91
9	AU309	0.2	0.25	0.50	1.00	1.95
10	AU33	0.8	0.50	0.38	0.67	2.34
11	AU34	1	0.25	0.42	1.00	2.67
12	AU39	0.8	0.88	0.33	0.67	2.68
13	AU70	0.2	0.25	0.33	0.83	1.62
14	AU71	0.6	0.63	0.29	0.67	2.18
15	AU80	0.4	0.13	0.33	0.67	1.53
16	AU81	0.2	0.50	0.29	0.33	1.33
17	AU82	0.8	0.63	0.29	0.33	2.05
18	BNX	0.6	0.88	0.25	1.00	2.73
19	ER01	1	0.25	0.25	0.33	1.83
20	ER02	1	0.38	0.25	0.33	1.96
21	ID02	0.6	0.88	0.25	1.00	2.73
22	ID14	0.6	1.00	0.21	1.00	2.81
23	ID27	1	0.25	0.25	1.00	2.50
24	IN02	1	0.75	0.29	0.33	2.38
25	IN04	0.6	0.50	0.33	1.00	2.43
26	IN05	1	0.50	0.38	1.00	2.88
27	IN102	0.2	0.63	0.38	0.67	1.87
28	IN126	0.6	0.88	0.29	1.00	2.77
29	IN137	0.4	0.88	0.25	1.00	2.53
30	IN180	0.2	1.00	0.42	0.33	1.95
31	IN200	0.2	1.00	0.42	0.33	1.95
32	IN76	0.2	0.50	0.38	1.00	2.08
33	LK02	0.2	0.88	0.33	1.00	2.41
34	LK05	0.2	0.75	0.38	0.67	1.99
35	LK21	0.4	0.75	0.33	1.00	2.48
36	Murali_01	0.2	0.88	1.00	0.33	2.41
37	Murali_02	0.2	0.75	0.96	0.67	2.58
38	MY02	1	0.38	0.25	1.00	2.63
39	MZ07	0.2	1.00	0.38	0.50	2.08
40	OM02	0.2	0.50	0.42	0.33	1.45
41	OM11	1	0.25	0.25	0.33	1.83
42	OM12	0.2	0.50	0.29	0.33	1.33
43	PG02	1	0.75	0.21	1.00	2.96
44	PG04	1	0.63	0.21	1.00	2.83
45	SC08	0.8	0.75	0.38	1.00	2.93
46	SC10	1	0.38	0.42	1.00	2.79
47	SC52	0.8	0.13	0.46	1.00	2.38
48	TF03	0.8	0.25	0.40	0.67	2.11
49	YE01	0.6	0.75	0.25	0.33	1.93
50	ZA01	0.4	1.00	0.38	0.50	2.28

Dataset 3: All threat scores

Site number	Site ID	DevelopmentScore_Normal	Sea level rise Score_Normal	Storm frequency Score_Normal	Storm intensity Score_Normal	Summed threat score
1	AU08	0.00	0.20	0.11	0.33	0.64
2	AU10	0.33	0.20	0.11	0.11	0.76
3	AU11	0.00	0.20	0.11	0.11	0.42
4	AU119	0.89	0.20	0.11	0.33	1.53
5	AU15	0.00	0.20	0.00	0.11	0.31
6	AU27	0.00	0.20	0.11	0.22	0.53
7	AU284	0.00	0.20	0.22	0.11	0.53
8	AU300	0.00	0.40	0.22	0.11	0.73
9	AU309	0.00	0.40	0.11	0.11	0.62
10	AU33	0.00	0.60	0.11	0.22	0.93
11	AU34	0.00	0.60	0.22	0.22	1.04
12	AU39	0.00	0.20	0.22	0.11	0.53
13	AU70	0.00	0.20	0.22	0.11	0.53
14	AU71	0.00	0.20	0.11	0.22	0.53
15	AU80	0.22	0.60	0.11	0.00	0.93
16	AU81	0.78	0.20	0.00	0.22	1.20
17	AU82	0.00	0.20	0.00	0.33	0.53
18	BNX	0.67	0.20	0.22	0.00	1.09
19	ER01	0.00	0.20	0.11	0.00	0.31
20	ER02	0.00	0.20	0.11	0.00	0.31
21	ID02	0.00	0.20	0.00	0.00	0.20
22	ID14	0.22	0.20	0.11	0.00	0.53
23	ID27	0.22	0.20	0.22	0.00	0.64
24	IN02	0.00	0.20	0.11	0.00	0.31
25	IN04	0.00	0.20	0.22	0.22	0.64
26	IN05	0.00	0.20	0.11	0.00	0.31
27	IN102	0.67	0.20	0.22	0.22	1.31
28	IN126	0.56	0.20	0.22	0.33	1.31
29	IN137	0.56	0.20	0.22	0.22	1.20
30	IN180	0.00	0.20	0.11	0.22	0.53
31	IN200	0.00	0.20	0.11	0.22	0.53
32	IN76	0.00	0.20	0.22	0.33	0.76
33	LK02	0.89	0.20	0.11	0.22	1.42
34	LK05	0.78	0.20	0.11	0.11	1.20
35	LK21	0.67	0.20	0.11	0.11	1.09
36	Murali_01	0.00	0.20	0.11	0.22	0.53
37	Murali_02	0.00	0.20	0.11	0.22	0.53
38	MY02	0.44	0.20	0.22	0.00	0.87
39	MZ07	0.33	0.20	0.11	0.22	0.87
40	OM02	0.67	0.20	0.22	0.11	1.20
41	OM11	0.22	0.20	0.11	0.56	1.09
42	OM12	0.44	0.20	0.11	0.56	1.31
43	PG02	0.00	0.20	0.11	0.00	0.31
44	PG04	0.33	0.20	0.11	0.11	0.76
45	SC08	0.33	0.20	0.11	0.22	0.87
46	SC10	0.44	0.20	0.11	0.11	0.87
47	SC52	0.33	0.20	0.11	0.11	0.76
48	TF03	0.00	0.20	0.22	0.22	0.64
49	YE01	0.67	0.40	0.11	0.22	1.40
50	ZA01	0.44	0.20	0.11	0.22	0.98