

BEETLES ON THE BEACH
POPULATION SURVEY AND INDICATOR POTENTIAL OF A SPECIES OF
CONSERVATION CONCERN, *HABROSCELIMORPHA DORSALIS MEDIA*, IN THE
GEORGIA BARRIER ISLANDS

by

ELIZABETH ANNE STUDER

(Under the Direction of Joseph McHugh)

ABSTRACT

Tourism, sea trade, and real estate development on coastal beaches have numerous impacts on the environment, including pollution, trampling, and habitat loss or fragmentation. This study assesses the current population status of a potential bioindicator species, *Habroscelimorpha dorsalis media* LeConte (Coleoptera: Carabidae), along urban and non-urban beaches of the barrier islands in Georgia, USA. Beetle abundances were shown to be negatively impacted by human presence, and near potential extirpation in Tybee and St. Simons Islands. They were also shown to have superior indicator potential, supported by the predictive value of beach index variables. This subspecies has the potential to be an easy to use habitat monitoring tool for beach managers and scientists.

INDEX WORDS: *Habroscelimorpha dorsalis media*, Southeastern White Beach Tiger Beetle, beach conservation, population status, ecological indicators

BEETLES ON THE BEACH
POPULATION SURVEY AND INDICATOR POTENTIAL OF A SPECIES OF
CONSERVATION CONCERN, *HABROSCELIMORPHA DORSALIS MEDIA*, IN THE
GEORGIA BARRIER ISLANDS

by

ELIZABETH ANNE STUDER

B.A., The University of Colorado, 2010

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial

Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2016

© 2016

Elizabeth Anne Studer

All Rights Reserved

BEETLES ON THE BEACH
POPULATION SURVEY AND INDICATOR POTENTIAL OF A SPECIES OF
CONSERVATION CONCERN, *HABROSCELIMORPHA DORSALIS MEDIA*, IN THE
GEORGIA BARRIER ISLANDS

by

ELIZABETH ANNE STUDER

Major Professor: Joseph McHugh
Committee: Darold Batzer
Sally Walker

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
August 2016

DEDICATION

This thesis is dedicated to my father, Harry Studer. You thought we were just catching crawfish in the creek behind our house for fun, but it ended up making me a scientist. Thank you for supporting me and believing in me.

ACKNOWLEDGEMENTS

I am so fortunate to have found my way to the UGA Entomology Department and am thankful for the help, support, and friendship of many people here. First, I want to express my most sincere appreciation and gratitude to my advisor, Dr. Joe McHugh, whose kindness, supportiveness, and dedication is even greater than the diversity of beetles on earth. His trust in my potential gave me the courage to become an independent scientist, with the ability to design, ask, and implement on my own. Through freedom, I found confidence, and that confidence gave me the strength to reach higher than I ever thought I could.

I want to thank my lab brothers, Brad Hounkpati and Tommy McElrath, for teaching me everything about beetles. Tommy, your passion for your work is infectious and you spread that joy to everyone you teach, especially me! Brad – the way you can keep a smile through the darkest times is an inspiration. You bring a light to this world through your kindness and generosity, and I'm a better person after knowing you.

I want to thank Dr. Kris Miller and Dr. Trish Moore for convincing me that I can make difference through teaching. My path is forever altered for the better after seeing the impact I can make by connecting to students with empathy and honesty.

I am deeply grateful for the financial assistance provided by the H. H. Ross Fund for Taxonomic Research that allowed my ideas to become reality.

I would like to thank my committee members, Dr. Sally Walker and Dr. Darold Batzer, for committing their valuable time to my education and giving their insightful comments on my research.

Finally, I would like to thank my great friends, Gabriel Boily-Roy, Tiffany Nguyen, Matt Zawodniak, and Nancy Miorelli, for reading my drafts, getting coffee with me, and making my grad school experience very fun. Most importantly, I want to thank my eternally supportive and loving parents, Nancy and Harry Studer, for teaching me to believe in myself and follow my dreams.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	v
LIST OF TABLES	ix
LIST OF FIGURES	x
CHAPTER	
1 INTRODUCTION AND LITERATURE REVIEW	1
1. Tiger Beetles	1
2. Beach Ecosystems.....	8
3. Current Study and Goals.....	12
2 POPULATION STATUS OF THE POTENTIALLY THREATENED SOUTHEASTERN WHITE BEACH TIGER BEETLE, <i>HABROSCELIMORPHA DORSALIS MEDIA</i> LECONTE (COLEOPTERA: CARABIDAE), IN GEORGIA, USA.....	14
1. Introduction.....	14
2. Methods.....	17
3. Results.....	23
4. Discussion.....	27
3 EVALUATING <i>HABROSCELIMORPHA DORSALIS MEDIA</i> LECONTE (COLEOPTERA: CARABIDAE) AS A POTENTIAL BIOINDICATOR OF SOUTHEASTERN BEACH ECOSYSTEMS.....	36

1. Introduction.....	36
2. Methods.....	40
3. Results.....	44
4. Discussion.....	49
REFERENCES	54
APPENDICES	
A Count method with time search along wrack transect	63
B McLachlan et al. (2013) Conservation Index Criteria	64
C McLachlan et al. (2013) Recreation Index Criteria	64
D González et al. (2014) Urbanization Index Criteria.....	65

LIST OF TABLES

	Page
Table 1: Location description and GPS coordinates for each site	22
Table 2: Total counts of other beach tiger beetle species observed.....	33
Table 3: Legend of body character measurements taken.....	43
Table 4: CI, RI, UI values, average human abundance, and island area measurements....	46
Table 5: AIC model values	47
Table 6: Relative importance of model variables	47

LIST OF FIGURES

	Page
Figure 1: Drawing of tiger beetle larvae in burrow	3
Figure 2: Size comparison of <i>H. d. dorsalis</i> to <i>H. d. media</i>	5
Figure 3: Georgia Barrier Islands	19
Figure 4: Boxplots showing population densities	25
Figure 5: Generalized linear Poisson regression.....	26
Figure 6: Average abundance of humans and <i>H. d. media</i>	27
Figure 7: Map of locations in study	41
Figure 8: nMDS ordination plots using index values for all sites	46
Figure 9: Smoothers curve graphs for all variables	48
Figure 10: Boxplots showing the distribution of morphometric measurements.....	49

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1. Tiger Beetles

1.1 Taxonomy and Natural History

Tiger beetles are a group of predacious, fast running ground beetles that have long been popular with scientists and amateur collectors alike for their charisma and attractive appearance. Some have gone so far as to criticize their popularity as inconsistent with their ecological and economic importance relative to other beetle groups (MacRae, 2009). However, regardless of their popularity or appearance, they are indisputably important to ecosystems and are commonly the focus of conservation and biodiversity studies (Carroll and Pearson, 1998; Cassola and Pearson, 2000; Desender and Turin, 1989; Kitching, 1996; Pearson and Cassola, 1992). Their stable taxonomy, sensitivity to disturbances, and occurrence in many diverse habitats make them ideal bioindicators of ecological health (Rodríguez et al., 1998; Rolett and Diamond, 2004).

Over 250 years ago, Carolus Linnaeus first described nine species of tiger beetles he found on a student field trip (Pearson and Vogler, 2001). Since then, tiger beetles have become a topic of debate in modern taxonomy with classification falling into two fields of thought. They were initially described as their own family, Cicindelidae, but a divide began when Erwin (1985) argued its place as a supertribe (Cicindelitae) within the family Carabidae. The original family level designation continued to be supported for several

years (Cassola and Miskell, 2001; Pearson and Vogler, 2001), but additional phylogenetic and morphological analyses have solidified their place within Carabidae as a subfamily (Cicindelinae) (Bousquet, 2012; Erwin and Pearson, 2008; Erwin, 2007; Maddison et al., 1999).

Cicindelinae are considered predatory fluid feeders because, while they do use their large mandibles to macerate prey, they also secrete digestive enzymes externally to further break down tissues resulting in food being ingested in a liquid form (Evans and Forsythe, 1985). This makes traditional microscopic studies of the gut contents to identify prey morphologically post-digestion impossible. Tiger beetles are considered generalist predators, preying on a variety of smaller arthropods, but this lack of specificity may at times be the result of the difficulty of the task rather than reality of their feeding group. Observations in the field have suggested a more omnivorous diet than expected, including scavenging of dead insects and even vertebrates (Pearson and Mury, 1979).

Reproduction in tiger beetles begins when a male initiates copulation by leaping onto the back of a female and clasping her thorax with his mandibles and pro- and mesothoracic legs. Males have textured pads on the prothoracic tarsi that are used to adhere to the female (Pearson, 1988). Females often attempt to dislodge males by rolling and running erratically, which may act as a control over mate selection, as only the strongest males would be able to endure this until copulation (Orians, 1969). Males exhibit mate guarding by continuing to ride on a female's back after copulation has taken place (Willis, 1967).

As larvae, tiger beetles are passive “sit and wait” predators that remain in a burrow until small prey items come near the opening and can be snatched inside (Figure 1).

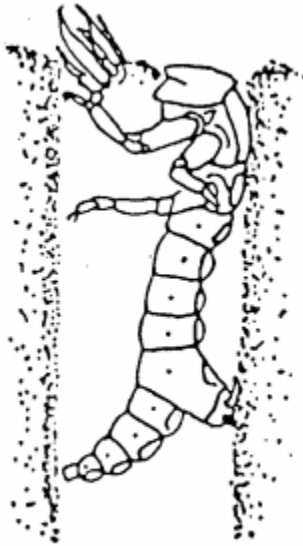


Figure 1. Drawing of tiger beetle larvae in burrow. From Hill and Knisley (1994).

1.2 *Habroscelimorpha dorsalis* (Say 1817), the North American White Beach Tiger Beetle

Habroscelimorpha dorsalis is a coastal dwelling species that formerly had a continuous distribution from New England, along the span of the Atlantic Coast, and throughout the Gulf of Mexico to south Texas (Boyd and Rust, 1982). It was first described as *Cicindela dorsalis* by Say (1817), as a member of the family Cicindelidae. It is a striking species with white to tan elytra often with dark lines and a bronze-green head and thorax.

Cazier (1954) reclassified four separate tiger beetle species as four subspecies of a single species, *C. dorsalis*. The four subspecies inhabit distinct regions of the coastal range and can be easily distinguished (Boyd and Rust, 1982). Erwin & Pearson (2008) elevated a

subgenus of *Cicindela*, *Habroscelimorpha*, to the generic level, thereby changing the name of the species to *Habroscelimorpha dorsalis*.

Habroscelimorpha dorsalis dorsalis lives in the most northern range, from Massachusetts to Virginia. *Habroscelimorpha dorsalis media* inhabits a more southern range, from New Jersey south to the tip of Florida, with some overlap in the northern area of its range with the northeastern subspecies. *Habroscelimorpha dorsalis saulyci* inhabits the gulf coast of Florida from the south tip, west into Mississippi. Finally, *Habroscelimorpha dorsalis venusta* ranges from Louisiana to the southern coast of Texas. Despite the reclassification as four subspecies, more recent studies have provided evidence supporting species-level differentiation between the northeastern subspecies (*Habroscelimorpha dorsalis dorsalis*) and southeastern subspecies (*Habroscelimorpha dorsalis media*). The two differ noticeably in size and elytral patterning (Figure 2). Additionally, crossbreeding experiments have shown some reproductive barriers but this has been questioned because pairs exhibit behavioral size-selective mating (Hill and Knisley, 1994). In areas of range overlap these two subspecies exhibit a closer overlap in size, suggesting the occurrence of a hybrid zone, but the elytral markings remain diagnostic (Hill and Knisley, 1994).

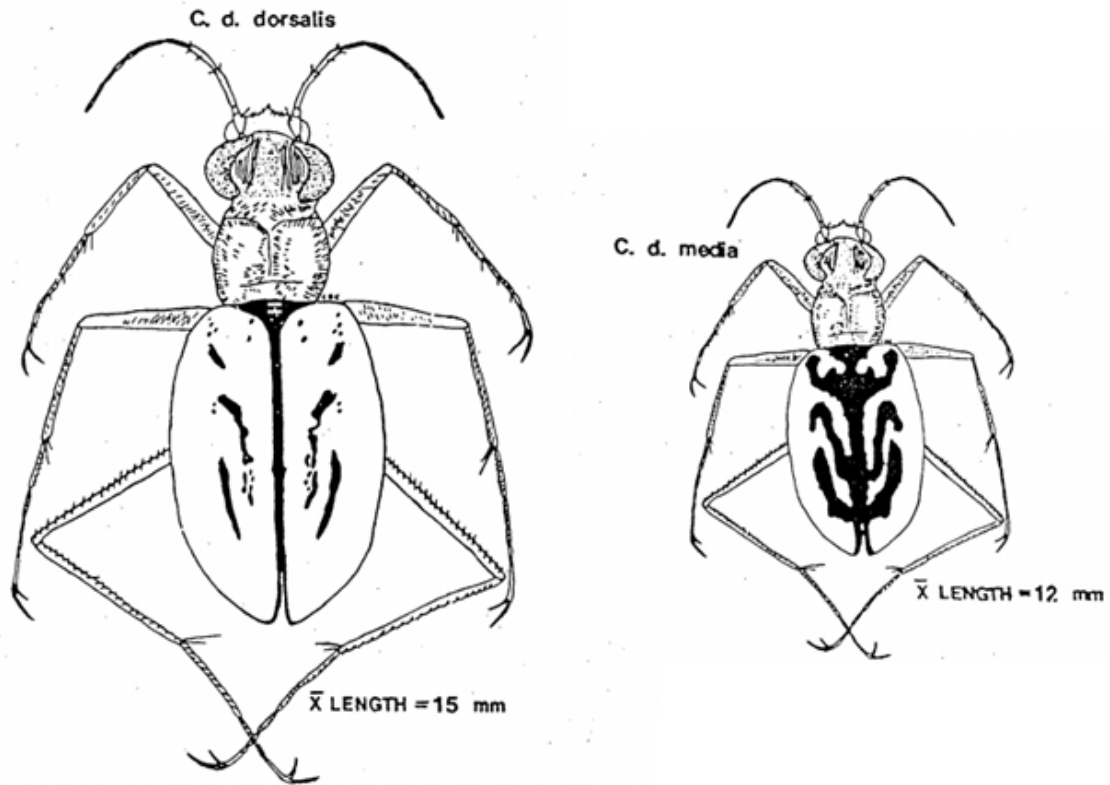


Figure 2. Size comparison of *Habroscelimorpha dorsalis dorsalis* to *Habroscelimorpha dorsalis media* from Drummond (2009).

This species was well documented by naturalists in the 1800s and early 1900s.

Habroscelimorpha dorsalis was once described as occurring in “great swarms” by Leng (1902) and “very abundant on open, sandy beaches of the Atlantic coast” by LeConte (1857). However, by the 1950s many populations had declined or disappeared (Knisley, 1987). Declines were experienced by all four subspecies, but the Northeastern subspecies, *H. d. dorsalis*, was most dramatically affected. Listed as federally threatened in 1990, its former range from Massachusetts to Virginia was greatly reduced by shoreline development, beach stabilization structures, and high recreational use by humans. These

disturbances extirpated the populations in New York, Rhode Island, and Connecticut. Their populations are in decline in Virginia, New Jersey, and Maryland with only one known population remaining in Massachusetts (Drummond, 2009). Reintroduction efforts were attempted starting in 1994, but increasing anthropogenic pressures instead further reduced the subspecies to only six suitably large populations on protected sites that fit the criteria for the recovery plan. Drummond (2009) recommended in his report to the U.S. Fish and Wildlife Service that the subspecies be reclassified as endangered in 2009 due to the high degree of threats from development, stochastic events, continued habitat loss, and its low recovery potential.

Habitat preferences for the *Habroscelimorpha dorsalis dorsalis* include large beaches, with a width greater than 5-8 meters (Drummond, 2009; Drummond, 2002). Sites at least 100 meters in length and 2 meters in width supporting a population of at least 30 adults have been found to be “suitable for breeding” (Knisley and Hill 1998, 1999; Knisley 2001, 2002). The beetles are typically found on beaches with dense back beach vegetation, fine sand particle size, and low human activity (Knisley et al. 1987). Fine sand density and size was found to be a more important criterion for population success because it increases larval burrow stability and increases the abundance and diversity of microarthropods that serve as prey (Blair et al., 1994; Drummond, 2002).

Microarthropods are the assumed prey for this species, but a detailed diet analysis has not been done (Drummond, 2009). In fact, adults have been observed eating unexpected prey, including dead fish and crab carcasses, but it was not confirmed whether the beetles were

eating the carrion, or the larvae of insect scavengers that were within the carcasses (Fenster et al. 2006).

A lack of knowledge about basic natural history information remains, complicating the study of this species. Information for the three non-listed subspecies is especially sparse and there has been considerably less research done on them. To illustrate the point, very recently, an unusual and unique behavior of the southeastern subspecies, *H. d. media*, was discovered by Harvey and Zukoff in 2011. Larvae of *Habroscelimorpha dorsalis media* were found to use wind-mediated locomotion to find and re-colonize more favorable habitats or to escape predators and parasitoids (Harvey and Zukoff, 2011). It is highly surprising that such a distinctly different and noticeable behavior in a well-studied beetle group would go undetected for so long.

Furthermore, few population surveys have been done to examine the status of the other three subspecies, even though the factors explaining the decline of the northeastern subspecies are present, sometimes in even greater degree, along the range of the three other subspecies.

Two studies examined the population of the southeastern subspecies, *Habroscelimorpha dorsalis media*, in South Carolina in the 1990s (Yarbrough and Knisley 1994, Ciegler 1997). Both studies found a decline consistent with that of the northeastern subspecies, related to anthropogenic effects, especially beach stabilization structures and trampling.

To our knowledge, no studies have been done more recently or in other parts of the southeastern subspecies' range.

2. Beach Ecosystems

Despite the importance of sandy beach ecosystems, less research has been conducted on this habitat when compared to rocky beaches, marshlands, and intertidal zones (Brown and McLachlan, 2002). This is in part due to the incorrect belief, held even today by some scientists, that this is a habitat with little biodiversity. In comparison to other types of coastal zones and wetlands, far fewer taxa that could be considered members of a charismatic macrofauna exist openly, thus contributing to the reputation of sand beaches to be morphologically like desert dunes, barren of life. However, the fauna in this region is diverse and uniquely adapted to the constantly changing environment.

2.1 Physical Beach Environment

Sand beaches are dynamic, ever changing environments. The morphology of a beach is consistently being re-shaped by erosion, wave action, and accretion. However, the most important elements of the physical beach environment are the interaction between sand and waves. Sand is the result of eroded material originating from two sources. Quartz sands (also known as silica) are from terrestrial erosion of land masses or sea cliffs. Carbonate sands are of marine origin and have a higher density than carbonate sands. Carbonate sands are also characterized by more irregular grain shapes. Sand grain size is also an important component of sand morphology. Sand grains are characterized by the

Wentworth (1922) size scale for limiting or enhancing the ability of organisms to complete behaviors like burrowing, nesting, and foraging (Knox, 2001).

While sand provides the material, waves provide the energy for remodeling the beach habitat. Waves are primarily generated by gravitational forces, but prevailing winds and the beach slope affect the degree of energy input to a specific beach (Komar 1976).

2.3 The Georgia Barrier Islands

The Georgia Barrier Islands include eight major island clusters that are comprised of many smaller islands, including thirteen oceanfront barrier islands (Hoyt, 1968). Eight of the oceanfront islands have sand beaches composed of fine quartz sand (Greaves, 1966). Georgia experiences the lowest wave energy of any shoreline in the southeastern Atlantic coast due to the gentle sloping that allows waves to dissipate before reaching the beach, with the height of waves averaging only 9-12 inches (Tanner, 1960; Helle, 1958).

Sandy beaches occur on the geologically youngest easternmost ocean coastline of each of the eight clusters. While these were deposited during the mid-Holocene (c. 4000-5000 BP), the majority of larger islands were part of mainland Georgia during the last glacial maximum (c. 18,000 BP) and became isolated following the post-glacial sea level rise (Walker and Coleman, 1987). These outer islands are Tybee, Wassaw, Ossabaw, St. Catherines, Sapelo, St. Simons/Little St. Simons, Jekyll, and Cumberland.

The islands experience a range of human impact, from highly visited tourist beaches, to undisturbed state or federally protected beaches. Tybee and St. Simons Islands are

accessible by car and are popular tourist destinations with extensive human development in place of all previous secondary dunes and few primary dunes remain fully intact. Walking bridges were built over the dunes that remain and tourists are not allowed to walk through them. Jekyll Island is also accessible by car via a bridge and has a few hotels and moderate tourist activity, but is also largely a state-owned park and the location of many nature conservation and outreach efforts. On Jekyll, the secondary dunes are intact across the majority of the north and south of the island, but absent near the middle where many of the hotels are located. The primary dunes are protected along the entire island and use of walking bridges is required to reach the beach. Sapelo Island is a majority state protected park with a small amount of private ownership by the residents of a Gullah/Geechee community of around 50-70 people (Sullivan, 2013). Cumberland Island is a National Seashore managed and protected by the National Park Service. Both Cumberland and Sapelo are not accessible by car but a small amount of tourists can visit as part of organized tours by taking a ferry from the mainland that leaves two-three times daily. On both islands, all of the primary and secondary dunes are intact and the beach can only be reached by two bridge access points that go over the dunes on each island.

2.4 Bioindicators of Beach Ecosystems

Beaches are currently among the most threatened habitats by climate change and human impact (Defeo et al., 2009; Doney et al., 2012). These threats are only expected to increase as humans continue to interact with and alter beach ecosystems as sea level contributes both to erosion and habitat loss (Brown and McLachlan, 2002; Brown, 2008;

Defeo et al., 2009; Doney et al., 2012; Nordstrom, 2000). These changes not only affect the taxa present in this ecosystem, but also its recreation value to humans, which holds a place of importance in preservation funding and support.

With such impending dangers, it is essential to actively monitor and continually assess these ecosystems from a conservation and recreation standpoint (Dale and Beyeler, 2001; Niemeijer and de Groot, 2008; Williams and Micallef, 2009). However, balancing these competing interests is a complex endeavor (McLachlan et al., 2013; Schlacher et al., 2014; Schlacher and Thompson, 2012).

Several metrics have been proposed to assess various aspects of beach habitat value and the extent of negative impacts (Boevers, 2008; Cervantes and Espejel, 2008; González et al., 2014; Leatherman, 1997; McLachlan et al., 2013). For example, González et al. (2014) developed a metric to estimate the level of coastal urbanization, including the effects of tourism, on sand beaches. This index was based on variables such as a beach's proximity to urban centers and the extent of development in the primary dunes. Similarly, McLachlan et al. (2013) created two metrics, one for conservation and another for recreation. Additionally, an emphasis was placed on making these indices easy to implement by managers to increase compliance and decrease time spent surveying (Cardoso et al., 2016).

In addition to beach indices, certain taxa are often chosen as ecological indicators of beach health. Like indices, they are chosen with the goal of increasing ease of use by

managers, who rarely have time to complete comprehensive diversity surveys. However, if a single taxon's abundance can represent that biodiversity with relative accuracy, it is feasible to use. Invertebrates are commonly used as indicators in beach ecosystems because they are sensitive to a range of human interactions (Comor et al., 2008; Schlacher et al., 2008).

Crustaceans, mollusks, and polychaete worms have been considered suitable indicators for a range of environmental conditions on beaches around the world (Bessa et al., 2014; Cardoso et al., 2016; Colombini et al., 2003; Dauvin et al., 2016; Fanini et al., 2009; Gonçalves et al., 2013; Noriega et al., 2012; Nourisson et al., 2014; Peterson et al., 2000; Schlacher and Thompson, 2012; Wenner, 1988). Less attention has been paid to the use of insect indicators in this habitat, despite their diversity and wide use for this purpose in terrestrial habitats (Avgin and Luff, 2010; Fattorini et al., 2015; Gerlach et al., 2013; Golfieri et al., 2016; McGeoch, 1998; Nasirian et al., 2014; Spake et al., 2016). González et al. (2014) showed that abundance of a Chilean beach tenebrionid beetle (*Phaleria maculata*) was highly correlated to coastal urbanization indices, demonstrating its potential use as an indicator on Chilean beaches.

3. Current Study and Goals

A review of the literature reveals two problems. First, the current population status of the Southeastern White Beach Tiger Beetle (*Habroscelimorpha dorsalis media*) is unknown in its Georgia range. Due to the decline and extirpation of its northeastern subspecies, and the decline in North Carolina, it is expected to be affected by anthropogenic stress and is

possibly in need of intervention or a recovery plan. For this reason, a population assessment of *H. d. media* in Georgia is critical.

Secondly, the Georgia Barrier Islands are experiencing more human impact than ever before, and for this reason ecosystem monitoring is essential to preserve the natural beauty that attracts tourists, and maintain the ecosystem diversity and stability of this unique habitat. Evaluating “easy-to-use” bioindicators for this system is important for managers to determine if a beach in question should be managed to support the health and safety of human activities, preservation of the natural system, or a balance between them. Using these indicators, decisive action can be taken by managers to allow for more appropriate and prudent division of resources, rather than attempting to over-extend without benefiting.

Thus, the goal of this study was to investigate the population status and indicator potential of a beetle of conservation concern that has a history of anthropogenic dissonance, *Habroscelimorpha dorsalis media*, as an ecological indicator in the Georgia Barrier Islands, a region experiencing high urbanization and disturbance from human habitation and tourism as well as very low urbanization in its multiple federally and state protected areas.

CHAPTER 2
POPULATION STATUS OF THE POTENTIALLY THREATENED
SOUTHEASTERN BEACH TIGER BEETLE, *HABROSCELIMORPHA DORSALIS*
MEDIA LeCONTE (COLEOPTERA: CARABIDAE), IN GEORGIA USA

1. Introduction

Coastal ecosystems are facing a trifold threat – from human alteration, pollution, and climate change. The compounding pressures of sea level change, tourism, commerce, and real estate development cause these ecosystems to experience highly disproportionate negative impacts from human disturbance (Brown et al., 2006; Kirwan et al., 2010; Whitman, 2013). Coastal Georgia is no exception and although 76% of the current coastline is protected, future increases in tourism and habitation will undoubtedly put even more pressure on the current system. With the recent announcement that the North American Coastal Plain is considered the world’s 36th biodiversity hotspot (Noss et al., 2015), biomonitoring of beach species in this region is now more critical than ever.

Unsurprisingly, many species inhabiting coastal ecosystems are in decline. Animals such as migrating shorebirds and sea turtles are well known terrestrial examples, but many insects inhabiting coastal wetlands and dunes are also highly imperiled. For example, the Miami Blue (*Cyclargus thomasi bethunebakeri* Comstock & Huntington) was once a common butterfly species in Florida coastal areas but urbanization in its coastal range

during the last 20 years has limited its current distribution to two small populations in the Florida Keys (Daniels, 2009). Similarly, Australia's endangered Illidge's Ant Blue Butterfly (*Acrodipsas illidgei* Waterhouse & Lyell) is highly imperiled due to destruction of its intertidal mangrove habitat (Breitfuss and Dale, 2004).

Historically, butterflies have received the brunt of conservation attention but tiger beetles are considered the second most imperiled insect group, second only to stoneflies, because of their susceptibility to environmental change. An estimated 19% of all tiger beetles are vulnerable to extinction, endangered, or already extinct (Stein et al., 2000). This is especially true for species of coastal tiger beetles. In fact, researchers have been noting the disproportionate decline of beach dwelling tiger beetles due to human impacts since the 1970s (Boyd, 1978; Nagano, 1980; Stamatov, 1972; Wilson, 1970). Species such as the Salt Marsh Tiger Beetle (*Cicindela marginata* Fabricius) previously inhabited Atlantic beaches from Maine to Florida (Pearson et al. 2006) but are in decline across the majority of its New England range (Leonard and Bell, 1998) with the exception of Maine where populations appear stable (Ward and Mays, 2014).

Similarly, two subspecies of the Hairy-necked Tiger Beetle (*Cicindela hirticollis hirticollis* Say, *Cicindela hirticollis rhodensis* Calder) previously inhabited coastal beaches along the length of the Atlantic Coast (Pearson et al. 2006) but are now reportedly in decline across many states in its former range with complete extirpations in beaches of high human recreation in New York (Knisley and Schultz, 1997; Mawdsley et al., 2013; Schlesinger and Novak, 2011; Sikes, 1998).

Finally, despite reintroduction efforts made after being listed as federally threatened (Hill and Knisley, 1994), the Northeastern Beach Tiger Beetle (*Habroscelimorpha dorsalis dorsalis* Say) has been nearly completely extirpated from the majority of its former coastal range (Hill and Knisley, 1994; Pearson et al., 2006). *Habroscelimorpha dorsalis* was once described as occurring in “great swarms” by Leng (1902) and “very abundant on open, sandy beaches of the Atlantic coast” by LeConte (1857) but by the 1950s many populations had declined or disappeared (Knisley, 1987). Listed as federally threatened in 1990, this species was once distributed along the northeastern coast from Massachusetts south to Virginia, but shoreline development, beach stabilization structures, and high recreational use by humans has completely extirpated the populations in New York, Rhode Island, and Connecticut. Their populations are in decline in Virginia, New Jersey, and Maryland with only one known population remaining in Massachusetts (Drummond, 2009).

The factors affecting the decline of *Habroscelimorpha dorsalis dorsalis* in the northeast are also present in the southeastern Atlantic Coast where the southern subspecies occurs. The Southeastern Beach Tiger Beetle, *Habroscelimorpha dorsalis media* LeConte, has historically been known to inhabit the coastline ranging from southern New Jersey to Southern Florida (Knisley and Hill, 1992; Pearson et al., 2006). Predictably, *H. d. media* was reported to be declining or disappearing in many states including Maryland (Glaser, 1977; Knisley and Hill, 1992) and South Carolina (Yarbrough and Knisley, 1994) around the same time or prior to the official listing of the northeastern subspecies as being threatened. In 2006, Pearson et al. estimated that it had disappeared from about 20-30%

of its former habitat due to anthropogenic impacts, mainly beach recreational activities and vehicle use. However, population surveys for this subspecies have not been published for any state in its range since 1994 and were never done for Georgia. Therefore, the aim of this study was to survey *H. d. media* populations in the Georgia Barrier Islands across sites representing a range of human disturbance.

2. Methods

2.1 Site Selection

The Georgia Barrier Islands are comprised of many small islands in eight major clusters that are separated from mainland Georgia by saltwater estuaries, tidal creeks, and wetland marshes. Sandy beaches occur on the geologically youngest easternmost ocean coastline of each of the eight clusters. While these islands were deposited during the mid-Holocene (c. 4000-5000 BP), most of the larger ones were part of mainland Georgia during the last glacial maximum (c. 18,000 BP) and became isolated following the post-glacial sea level rise (Graf, 1987). These outer islands are Tybee Island, Wassaw Island, Ossabaw Island, St. Catherines Island, Sapelo Island, St. Simons/Little St. Simons Island, Jekyll Island, and Cumberland Island. Historical specimen locality records from the University of Georgia Collection of Arthropods indicate the presence of *H. d. media* along the eastern coastline of all of the eight major outer islands from 1890-1970.

Out of the thirteen major barrier islands with sandy beach habitats, 12 sites spanning five islands were chosen for survey representing suitable habitats, as well as a gradient of human occupation. The islands chosen were Tybee, Sapelo, St. Simons, Jekyll, and

Cumberland (Figure 3). Tybee and St. Simons Islands are accessible by car and are popular tourist destinations with extensive human development in place of all previous secondary dunes. On these islands few primary dunes remain fully intact. Walking bridges are built over the dunes that still exist and foot traffic through them is prohibited. Jekyll Island is also accessible by car via a bridge and has a few hotels and modest tourist activity, but is also largely a state park and the location of many conservation and outreach efforts. On Jekyll, the secondary dunes are intact across the majority of the north and south ends of the island, but absent near the middle where most hotels are located. The primary dunes are protected along the entire island, so people are required to use walking bridges to reach the beach. Most of Sapelo Island is state protected land, with only a small amount of private land ownership by the residents of the Gullah/Geechee people in an inland community of around 50-70 people (Sullivan, 2013). Cumberland Island is a National Seashore managed and protected by the National Park Service. Both Cumberland and Sapelo are inaccessible by car but a small number of tourists can visit as part of organized tours by taking a ferry from the mainland. On both islands, all of the primary and secondary dunes are intact and the beach can only be reached by two bridge access points that go over the dunes on each island.

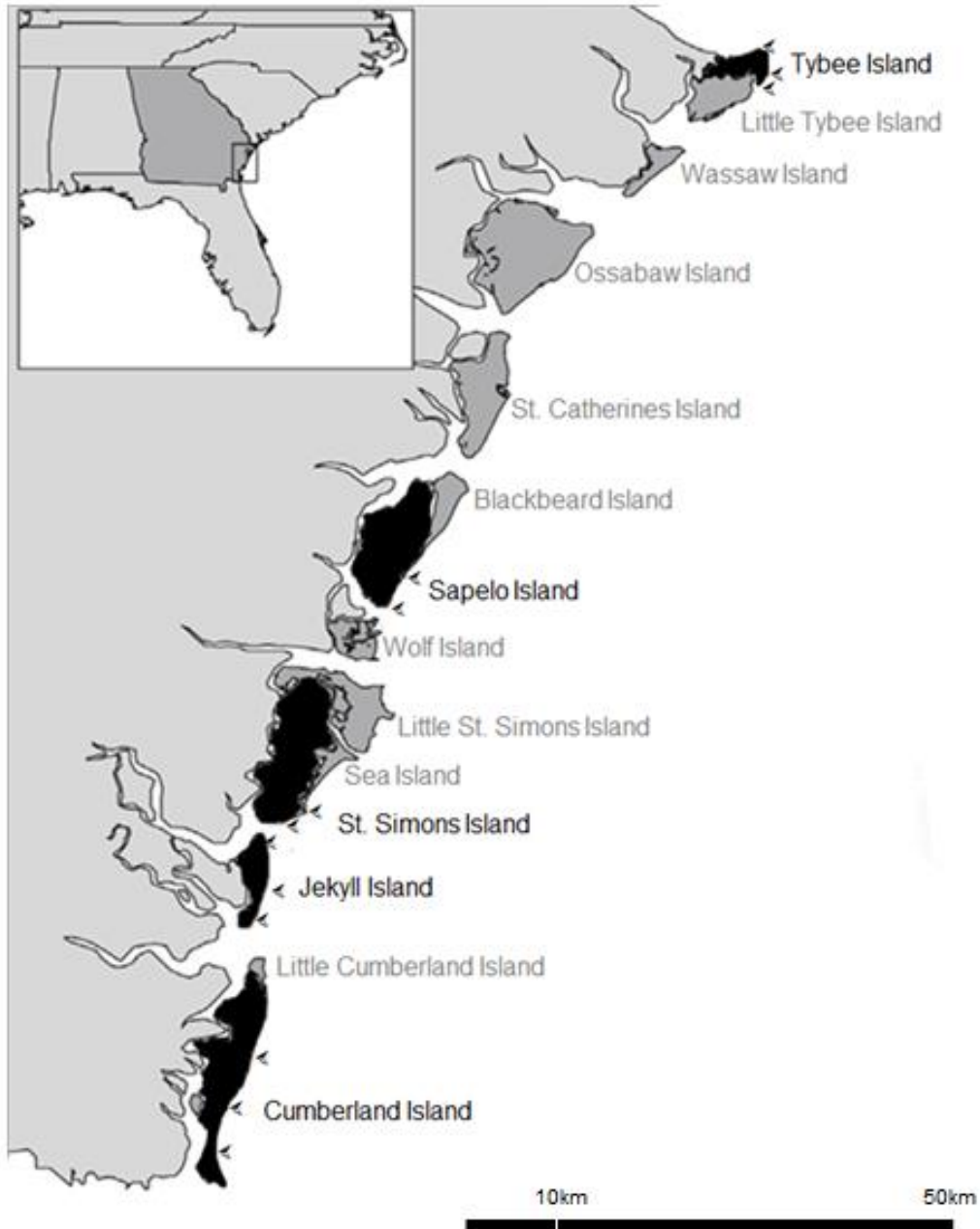


Figure 3. Georgia Barrier Islands. Islands surveyed indicated in black with markers identifying sites. Map modified from Ondich and Andrews (2013).

These islands were chosen to represent the range of human disturbance present across the Georgia Barrier Islands. Additionally, sites were selected to represent the minimum and maximum human occupation present on each island. This was determined by tourism records, discussions with local island management personnel, and the distance from beach access points (where present).

Potential sites were further screened to ascertain that they met minimal size requirements for the survey. Larval *H. dorsalis* typically require beaches of at least six meters in width to successfully develop and reach adulthood (Knisley and Schultz 1997). Therefore, each site chosen was a minimum of six meters wide from the coastal dune edge to the water at high tide. Sites had to be approximately one kilometer strips of shoreline running parallel to the dunes. We then followed the deviations of natural wrack line during our survey. The wrack line, or high tide line, is the area of the beach *H. d. media* adults primarily inhabit. Waves deposit rich organic matter in this area, attracting the arthropod scavengers (e.g., amphipods, Diptera larvae) upon which *H. d. media* adults are thought to prey. Sites were surveyed between 10am and 4pm throughout June and July of 2014, during the peak daily activity period and peak population months of adult *H. d. media* (Fenster et al., 2006). Counts were not done on stormy or rainy days to maintain the same visual conditions for each survey attempt.

2.2 Population Census

As with all other tiger beetle species, *H. d. media* are fast running, highly visual predators. Even so, in preliminary surveys we tested several traditional population census

methods commonly used for carabids including pitfall traps, malaise traps, and flight intercept traps. Unsurprisingly, these methods were not appropriate given the open beach habitat and behavior of *H. d. media*. These traps were easily detected by the beetles and avoided altogether. Furthermore, because the focal taxon was a potentially declining subspecies, preference was given to live census counts. Therefore to estimate abundance, a modified count method described in multiple tiger beetle abundance studies (Hori, 1982; Knisley and Hill, 1992; Knisley, 1984; Knisley, 1987; Mawdsley et al., 2013) was used to estimate counts along one transect spanning the length of each site. Similar linear time search methods or line transect methods have been used to survey other endangered insects including the Karner Blue Butterfly (Brown and Boyce, 1998).

In our study, one observer walked for a 30 minute period, counting all *H. d. media* within a visual distance of two meters on either side of the transect following the most recently deposited wrack line (Appendix A). The observer uses a fixed visual point during walking to avoid duplicate counts of individuals that are passed. This method has the potential to underestimate the actual abundance by 50-80% due to beetles being outside the designated area in other less populated areas of the beach (Knisley and Schultz 1997). To improve precision, each site was surveyed twice per visit, three times throughout the season, for a total of six censuses per site, to obtain averages. Timed counts were chosen over basic distance transects because the wrack line changes daily with the tides, so deviations were taken to follow it, thus pathing was slightly different for each survey visit. GPS coordinates recorded the starting and ending point and the path distance was approximated from there using Google Earth (Table 1).

Table 1. Location description and GPS coordinates for the survey starting point at each site.

Island	Location	Latitude	Longitude
Tybee Island	Northern tip, near Polk St. beach entrance	32° 1'33.90"N	80°51'16.75"W
	Mid island, near 12 th St. beach entrance	31°59'39.30"N	80°50'40.41"W
	Southern end, near Tybee Pier	31°59'36.21"N	80°50'41.66"W
Sapelo Island	Northern Nannygoat Beach	31°23'23.83"N	81°15'52.20"W
	Southern Nannygoat Beach	31°23'24.45"N	81°15'51.61"W
St. Simons Island	Northernmost tip, near 15 th St. beach entrance	31° 8'37.40"N	81°22'10.07"W
	East Beach, off of Maritime Center Public Parking	31° 8'37.44"N	81°22'10.78"W
Jekyll Island	Northern tip, Driftwood Beach, off Driftwood Beach Trail	31° 7'10.73"N	81°24'52.42"W
	Middle beach, Great Dunes Park, off Jekyll Island Convention Center	31° 4'14.24"N	81°24'9.81"W
	South beach, off Glory Beach Boardwalk	31° 1'2.84"N	81°25'14.84"W
Cumberland Island	Northern beach area	30°50'30.22"N	81°25'40.52"W
	Stafford Public Beach	30°47'9.88"N	81°27'19.84"W
	Southern beach, off Goats Way	30°44'50.38"N	81°27'30.22"W

Island population density estimates were approximated using the formula:

$$Density = Z/XY$$

Where Z is average number of beetles counted per transect, X is transect distance, and Y is transect width (Fisher 1939). To get an idea of island wide patterns, densities were calculated by island using site averages.

2.3 Quantifying Human Impact and Environmental Effects

All human presence and recreation on the beach causes a disturbance in the ecosystem. For this reason, human impact was estimated by taking a count along the kilometer transects at the same time as beetle counts. However, human counts were not limited to just a two meter width along the wrack line. Instead, all humans on the beach within visual distance were counted.

2.4 Data Analysis

A generalized linear Poisson regression model was used to analyze the interaction between human and beetle populations. All analyses were done in the statistical program R (R Core Team 2013).

3. Results

3.1 Population Census

Habroscelimorpha dorsalis media counts were highest at Jekyll Island's northern beach, with average counts exceeding 6000 beetles/hectare of wrack habitat. Such high populations were in sharp contrast with its other sites across the island, which were

sparsely populated with only 125-625 beetles/hectare. All Cumberland beaches exhibited similar abundance to the north Jekyll site, with ranges of between 1250-5000 beetles/hectare of wrack habitat. Sapelo Island surveys were inconsistent across the season. On two occasions during early July, beetle abundance at the northern site was over 2500 per hectare but throughout the rest of the season averaged around 1000 per hectare. St. Simons Island had moderate counts in its northern site at around 500 per hectare of wrack habitat but the southern site showed nearly complete extirpation of *H. d. media*. Only one beetle was observed at this site throughout the entire study. Similarly, Tybee Island had very low numbers of beetles across all sites. The northern site had around 375 beetles per hectare in early June, but throughout the rest of the season had less than 25 per hectare. The middle site was not observed to have beetles during the study. The southern site was consistently observed to have 75 per hectare during the study. Beetle densities reflected the variability in populations across sites (Figure 4).

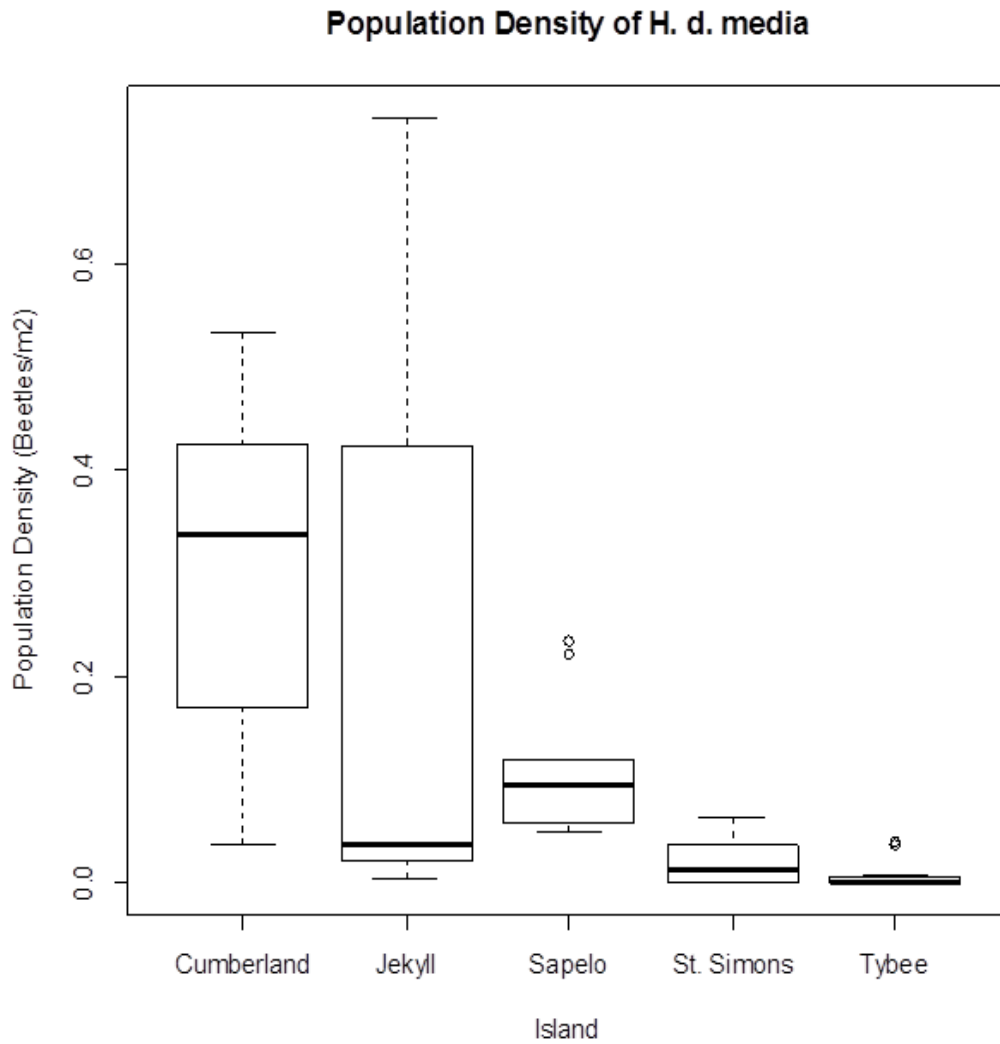


Figure 4. Boxplots showing population densities of *H. d. media* calculated per island in m^2 .

3.2 Quantifying Human Impact and Environmental Effects

Habroscelimorpha dorsalis media abundance trends across sites were highly inversely correlated with human pressure (Figures 4-5).

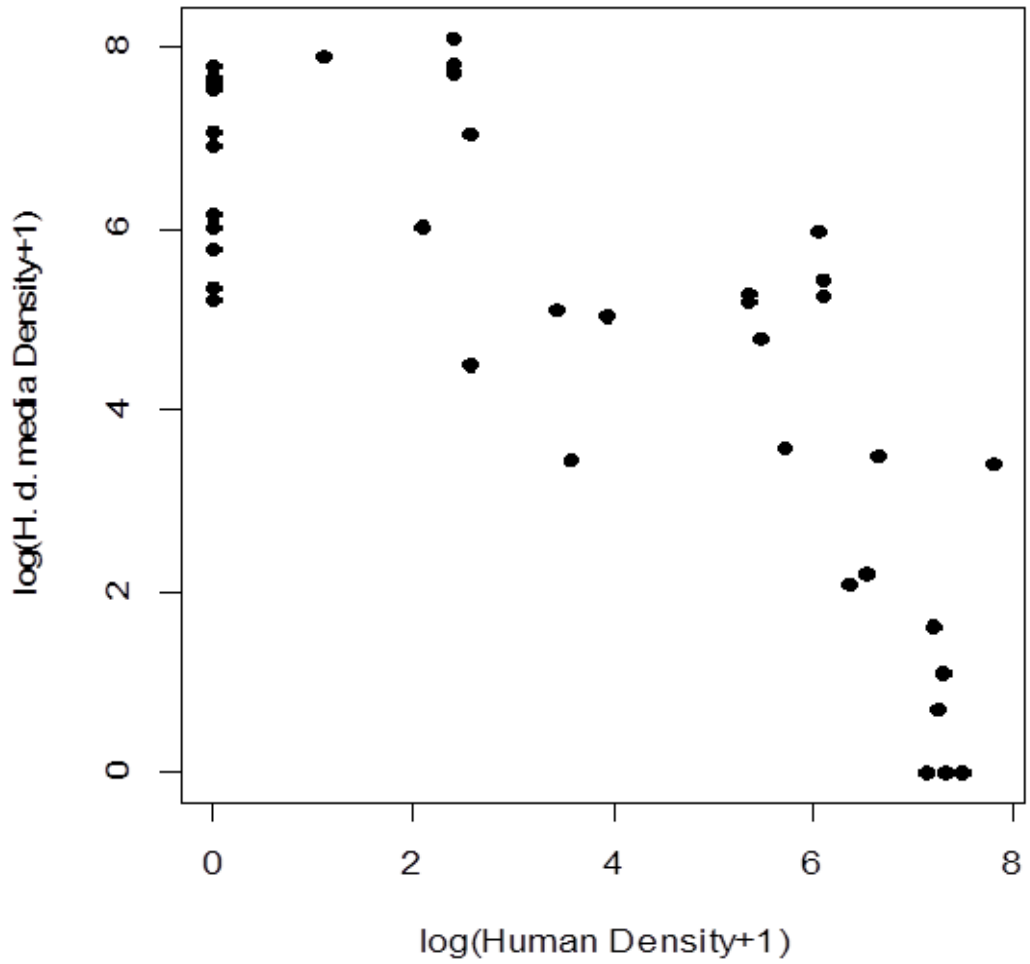


Figure 5. Generalized linear Poisson regression model analyzing the interaction between humans and beetles populations ($p < 0.005$).

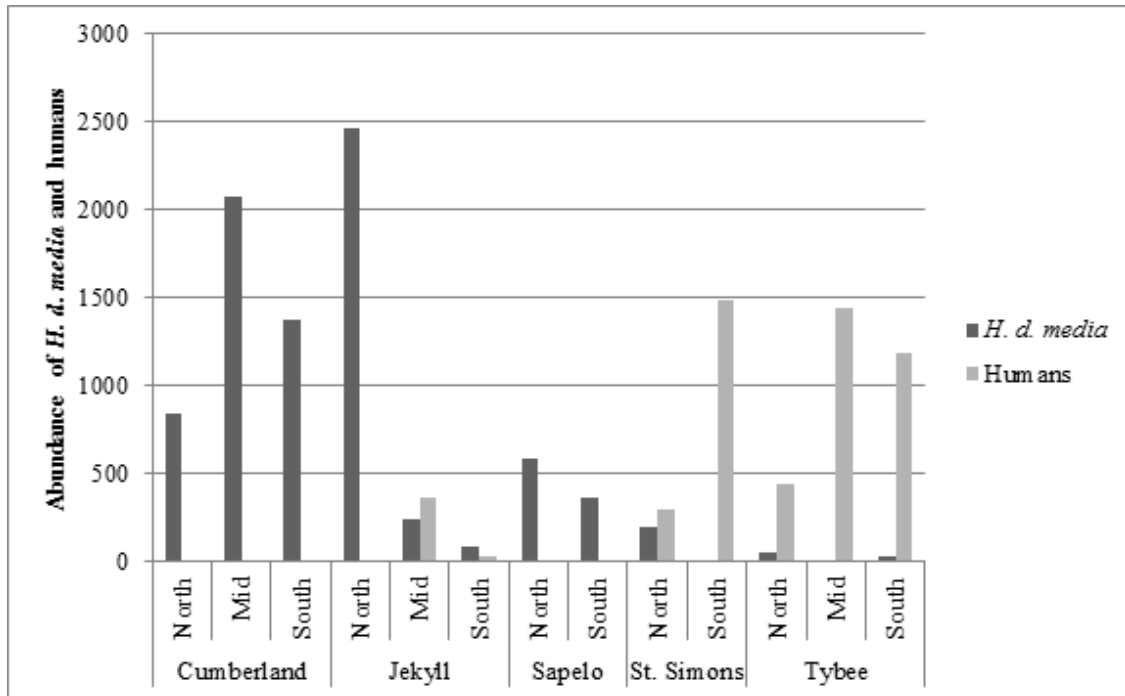


Figure 6. Average abundance of humans and *H. d. media* per transect at all sites.

4. Discussion

4.1 Population site analysis by island

Although the Georgia Barrier Islands are a continuous island chain with geographical and geological similarities, the anthropogenic pressures experienced by each island differ drastically, resulting in highly variable *H. d. media* population densities.

While Jekyll Island's northern beach had the highest beetle abundance overall, populations at other sites on the island were far sparser. Jekyll's middle beach is near a large conference center and hotel that results in sporadically heavy beach traffic. The southern beach, while not heavily populated by humans or beetles, experiences a great deal of vehicular traffic on the beach by researchers monitoring loggerhead sea turtle

nesting sites. So while that area of the beach is monitored for conservation purposes, strategies used to aid one species may be hindering the survival of others.

Cumberland had an expectedly high beetle abundance, as this island is the site of long term ecological management and conservation by the National Park Service and has very low human impact compared to other Georgia islands. Vehicles are also used on the Cumberland beaches to assist in sea turtle monitoring, but only one to two vehicles routinely drive between turtle nest sites, apparently not affecting the *H. d. media* population there.

Sapelo, while also a pristine, state-protected island, had lower beetle abundance. This was especially true for the southern site. This may be due in part because the southern site is located very near the only paved beach access point on the island. So while Sapelo receives little tourism and disturbance compared to other barrier islands, all tourism, local beachgoers, research traffic, and maintenance vehicles access the beach at the same point, focusing all disturbances there. Higher beetle densities were observed farther from the beach access point at the northern site. Between those sites there is continuous beach with no barriers to connectivity between them, suggesting that the low abundance at the southern site merely reflects the disturbances near the beach access point, and not a greater island-wide pattern of low abundance. For this reason, Sapelo populations do not appear to be in danger of decline.

The remaining islands, Tybee and St. Simons, both had average beetle counts below 50 for all but one site (Tybee North) which had averages below 100. Both are among the most populated Georgia islands with year round residents and an abundance of visiting tourists. In 2014, Tybee Island had 1,044,000 visitors who averaged 3 to 5 hours on the beach. The impact of this visitation rate is clear even to tourists, as one of the top five complaints that Tybee visitors had in 2014 was that there was too much trash on the beach. Tourism accounts for significant revenue generation for Chatham County (1.64 billion dollars in 2014 (Barber et al., 2015)), and thereby definitively shapes the economic and ecological activity on the island. Similarly, St. Simons, one of the “Golden Isles” of Georgia receives a great deal of tourism. In an expanse of less than three miles of St. Simons’ beach, there are 41 public beach access points and additional private access points belonging to homeowners. For more than half of the entire beach length there are no intact dunes, leaving no shelter for beach invertebrates to take refuge during storms and eliminating essential habitat for the majority of dune invertebrates. The extensive human disturbance on both St. Simons and Tybee Islands undoubtedly impacts *H. d. media* abundance.

The U.S. Fish and Wildlife recovery plan for the northeastern subspecies characterized “large” populations as exceeding 500 adults using the same counting protocol described in our study (Hill and Knisley, 1994). This was based on estimates by several studies that defined the minimum viable population as between 500-1000 adults (Hill and Knisley, 1994; Lacy, 1987; Mettler and Gregg, 1969; Thomas, 1990). Therefore, the recovery plan considered a population stable if it exceeded 500 individuals, and populations with 50-

500 were considered unstable and in need of further monitoring, regardless of the size of the habitable area. All sites on Tybee and St. Simons fell well below a 500 individual threshold. The southern Sapelo Island site population also fell marginally below 500, although the other site on Sapelo exceeded that threshold. Based on the USFWS criterion of population health, all Tybee and St. Simons sites, and possibly the southern Sapelo site, would be considered in need of further monitoring and intervention to attempt to stabilize the populations if they were under the directive of the northeastern subspecies recovery plan (Drummond, 2009).

Recovery efforts for the northeastern subspecies have been focused in the Chesapeake Bay area which has different beach geography than the southeastern subspecies. Most notably, the Chesapeake Bay area has discontinuous sand dunes that are intersected by tidal inlets, rocky masses, and truncated landforms, in contrast to the Georgia barrier islands which have longer, more continuous beaches and sand dunes. Therefore, the 500 individual threshold may not be appropriate for assessing the southern subspecies. The result of a continuous habitat across each island surveyed suggests that there is no break in connectivity between sites within islands. For this reason, the southern Sapelo Island site that is below 500 individuals is likely not imperiled, as it is connected to other stable populations and may instead be a reflection of concentrated human traffic.

We attempted to improve the precision of the abundance count method used by adding replicates. Clearly, the actual populations could not be recorded here because some beetles were always present outside the count area. Therefore, the numbers obtained

should be regarded as estimated abundances by site to be compared across sites in order to identify population patterns for the subspecies in Georgia.

The populations on Tybee and St. Simons were consistently low across all sites within the islands. Regardless, of whether 500 individuals is an appropriate cutoff point for this subspecies or if the populations were somewhat underestimated by our survey method, the low numbers observed at Tybee and St. Simons are in stark contrast to populations on other islands.

4.2 Potential causes of decline

While it is clear that *Habroscelimorpha dorsalis media* is experiencing population declines in Georgia and in other areas of its range, the direct causes for that decline are not well understood. In addition to habitat loss caused by land development, trampling may be a main contributor of decline in *H. d. media* populations. Ghost crabs (*Ocypode* spp.), another burrowing beach invertebrate, have been shown to decrease in heavily trampled areas and areas with vehicular use (Lucrezi et al., 2009). Vehicular use and trampling are already recognized for causing severe negative impacts on two other declining tiger beetles, *Cicindela hirticollis* and *Habroscelimorpha dorsalis dorsalis* (Knisley et al. 1987, Mawdsley et al. 2013). Vehicular use can crush sand invertebrates and, in fact, on Jekyll and Cumberland Islands adult beetles crushed by sea turtle research vehicles were observed during this study. It is unlikely, however, that human foot trampling is killing adult beetles, as they can easily fly or run to evade humans. Foot trampling and vehicular traffic are more likely to affect burrowing larvae which cannot

evade a footfall or car (Hill and Knisley 1993). Additionally, Lucrezi et al. (2009) noted that sand surface temperature increased slightly in human impacted areas, which may be the result of trampling more heat into the soil. Even slight sand temperature changes may affect the survival of burrowing tiger beetle larvae and the soil invertebrates on which they prey as larvae and adults, driving larger trophic shifts.

4.3 Other tiger beetle species of note

In Georgia, two other tiger beetle species are known to inhabit oceanfront beaches, the Margined Tiger Beetle (*Ellipsoptera marginata* Fabricius) and the Hairy-necked Tiger Beetle (*Cicindela hirticollis* Say). These species were not the target of the current study but their presence was documented during the surveys. While these counts cannot be considered a comprehensive record of their populations, it should be noted that their presence and general abundance matched the patterns observed for *Habroscelimorpha dorsalis media*. The Tybee Island mid beach and St. Simons East beach were lacking all three tiger beetle species.

Table 2. Total counts of other beach inhabiting tiger beetle species observed for the entire season.

Island	Location	<i>Cicindela hirticollis</i>	<i>Ellipsoptera marginata</i>
Tybee Island	Northern tip	2	4
	Mid island	0	0
	Southern end	0	43
Sapelo Island	Northern Nannygoat Beach	0	173
	Southern Nannygoat Beach	0	112
St. Simons Island	Northernmost tip	1	21
	East Beach	0	0
Jekyll Island	Northern tip, Driftwood Beach	8	18
	Mid beach, Great Dunes Park	6	8
	South beach	27	66
Cumberland Island	Northern beach area	3	0
	Stafford Public Beach	19	1
	Southern beach	0	0

4.4 Year to year variation

The beach ecosystem is a highly volatile and ever changing environment. The size, width, and shape of a shoreline can change year to year due to coastal storms and natural geologic erosion and accretion which can affect population dynamics of coastal

organisms (Beatley et al., 2002; Yang et al., 2012). It has been noted that *H. d. dorsalis* populations are highly variable from year to year with two- to three-fold differences observed in some areas (Knisley and Hill 1990, Hill and Knisley 1991). It is possible that this magnitude of variation exists in the southeastern subspecies as well, and while it was not in the scope of this study to investigate this temporal variation, it is worth noting that long term studies are necessary to determine the viability of the southeastern populations. Furthermore, since the completion of this study, there have been dramatic increases in economic development of the Georgia coastal region that will greatly impact the future of coastal ecology in the state. Reports from 2016 indicate a 12% increase in coastal tourism from 2014 to 2015 and another 16% increase from 2015 to 2016. A 51% growth in the lodging industry since 2014 has motivated several large hotel construction and infrastructure projects on the islands (Sadler, 2016). These new developments, all recorded one to two years post-study, emphasize trends that raise concerns about these already threatened populations.

4.5 Conclusions

Although the northern subspecies of *Habroscelimorpha dorsalis* was known to be sensitive to human disturbance, this study is the first to find that the southern subspecies also is impacted. There has been near extirpation of *H. d. media* in heavily disturbed tourist beaches in Georgia. Thanks to exceptional conservation practices and state or federal protection of the majority of Georgia's coast, many populations in the state still reach numbers fitting Leng's historic description of this species existing in "great swarms."

Tiger beetles are particularly relevant to conservation biology because they can be used as indicator species to gauge the health or structure of potentially imperiled ecosystems (Pearson and Cassola, 2006). Therefore, this species can be monitored and serve as an early warning signal for ecosystem instability throughout the Georgia coast.

CHAPTER 3

EVALUATING *HABROSCELIMORPHA DORSALIS MEDIA* LeCONTE (COLEOPTERA: CARABIDAE) AS A POTENTIAL BIOINDICATOR OF SOUTHEASTERN BEACH ECOSYSTEMS

1. Introduction

Beaches are currently among the most threatened habitats by climate change and direct human impact (Defeo et al., 2009; Doney et al., 2012). These threats are only expected to increase as humans continue to interact with and alter beach ecosystems and as sea level shifts contribute to erosion and habitat loss (Brown and McLachlan, 2002; Brown, 2008; Defeo et al., 2009; Doney et al., 2012; Nordstrom, 2000). These changes not only affect the taxa present in this ecosystem, but also impact the recreation value to humans, which is an important consideration with respect to preservation funding and support. With such impending dangers, it is essential to actively monitor and continually assess these ecosystems from both a conservation and recreation standpoint (Dale and Beyeler, 2001; Niemeijer and de Groot, 2008; Williams and Micallef, 2009). However, balancing these competing interests is a complex endeavor (McLachlan et al., 2013; Schlacher et al., 2014; Schlacher and Thompson, 2012).

Several metrics have been proposed to assess various aspects of beach habitat value and the extent of negative impacts (Boevers, 2008; Cervantes and Espejel, 2008; González et al., 2014; Leatherman, 1997; McLachlan et al., 2013). For example, González et al.

(2014) developed a metric to estimate the level of coastal urbanization, including the effects of tourism, on sand beaches. This index was based on variables such as a beach's proximity to urban centers and the extent of development in the primary dunes. Similarly, McLachlan et al. (2013) created two metrics, one for conservation and another for recreation. The Conservation Index (CI) included variables such as the intactness of the dunes, the presence of nesting rare species, and macrobenthic diversity, while the Recreation Index (RI) qualified the availability of infrastructure to tourists, safety measures to protect them, and the physical carrying capacity of the beach to accommodate them. These effectively compared competing variables important to the health and value of the ecosystem to help land managers determine if a beach in question should be managed to support human activities, preservation of the natural system, or a balanced combination of both priorities. Using these metrics, a more informed decision can be made by managers about the appropriate and prudent division of limited resources, rather than attempting to over-extend efforts toward some goal without maximizing benefits. An emphasis has been placed on making these indices easy for managers to implement in order to increase compliance and decrease time spent surveying (Cardoso et al., 2016).

In addition to beach indices, certain taxa are often chosen as ecological indicators of beach health. Like indices, they are chosen with the goal of facilitating use by managers, who rarely have time to complete comprehensive biodiversity surveys. However, if a single taxon's abundance represented a system's diversity accurately, monitoring it would be a feasible option. Invertebrates are commonly used as indicators in beach

ecosystems because they are sensitive to a range of human interactions (Comor et al., 2008; Schlacher et al., 2008).

Crustaceans, mollusks, and polychaete worms have been considered suitable indicators for a range of environmental conditions in many beaches around the world (Bessa et al., 2014; Cardoso et al., 2016; Colombini et al., 2003; Dauvin et al., 2016; Fanini et al., 2009; Gonçalves et al., 2013; Noriega et al., 2012; Nourisson et al., 2014; Peterson et al., 2000; Schlacher and Thompson, 2012; Wenner, 1988). Less attention has been paid to the use of insect indicators in this habitat, despite their diversity and wide use for this purpose in terrestrial habitats (Avgin and Luff, 2010; Fattorini et al., 2015; Gerlach et al., 2013; Golfieri et al., 2016; McGeoch, 1998; Nasirian et al., 2014; Spake et al., 2016). González et al. (2014) showed that abundance of a Chilean beach tenebrionid beetle (*Phaleria maculata*) was highly correlated to coastal urbanization indices, demonstrating its potential use as an indicator on Chilean beaches.

Additionally, insects, and particularly carabid beetles, have been frequently investigated for body size variation caused by anthropogenic stressors (Ikeda et al., 2006; Lagisz, 2008; Laparie et al., 2010; Nygren et al., 2008; Sukhodolskaya, 2013; Sukhodolskaya and Saveliev, 2014; Weller and Ganzhorn, 2004). For this reason, it also is important to investigate whether potential indicators on southeastern beaches experience body size variation in line with disturbance patterns along their range.

Tiger beetles (Carabidae) have been used as ecological indicators in numerous studies because their condition is thought to closely reflect that of other species and the environment (Rodríguez et al., 1998; Rolett and Diamond, 2004). They have a mature and stable taxonomy simplifying specimen identifications and providing some historic record of distributional ranges. In addition, tiger beetles occur in diverse habitats, making them useful bioindicators of ecological health in many ecosystems (Cassola and Pearson, 2000; Pearson and Cassola, 1992, 2006; Rodríguez et al., 1998; Rolett and Diamond, 2004). Beach dwelling tiger beetles have already been used successfully as indicators of human impact in Mediterranean beach habitats, suggesting that they might be useful bioindicators on North American beaches as well (Arndt et al., 2005).

One such tiger beetle of conservation interest in North American beaches is *Habroscelimorpha dorsalis* Say, the White Beach Tiger Beetle. Its northeastern subspecies, *Habroscelimorpha dorsalis dorsalis*, was listed as federally threatened in 1990 (Hill and Knisley, 1994). Its decline was attributed entirely to human encroachment which caused habitat destruction through installation of beach stabilization structures, vehicular use on beaches, and development in the dunes (David L. Pearson, 2006; Drummond, 2009; Hill and Knisley, 1994; Knisley et al., 2005). The southern subspecies, *Habroscelimorpha dorsalis media* LeConte, while not currently under state or federal protection, is undoubtedly affected by anthropogenic pressures from beach tourism and development as well.

The goal of this study was to investigate the potential use of a beetle of conservation concern that has a history of anthropogenic dissonance, *Habroscelimorpha dorsalis media*, as an ecological indicator in the Georgia Barrier Islands, a region experiencing high urbanization and disturbance from human habitation and tourism in some areas, as well as very low urbanization and impact in its multiple federally and state protected areas.

2. Methods

2.1 Site Selection

The Georgia Barrier Islands comprise 15 major islands and many smaller islands to form the 100 mile long ocean coastline of the state. The thirteen geologically youngest, easternmost islands all have sand beaches that range in urbanization and popularity with tourists, but the majority of the coastline is federally or state protected. Only five of the islands are accessible by car via bridges connecting to mainland Georgia. A daily ferry makes trips from the mainland to two other islands that are not accessible by road. Research vessels, chartered boats and private boats are the only way to access to the remaining islands.

We chose sites ranging from highly human impacted areas to very pristine, isolated natural beaches. This range included 12 sites across five islands (Figure 9). Each site was known to have an historical record of *H. d. media* populations. Current *H. d. media* abundance, and human abundance, was known for these sites from a companion study by the authors (Studer and McHugh, unpublished).

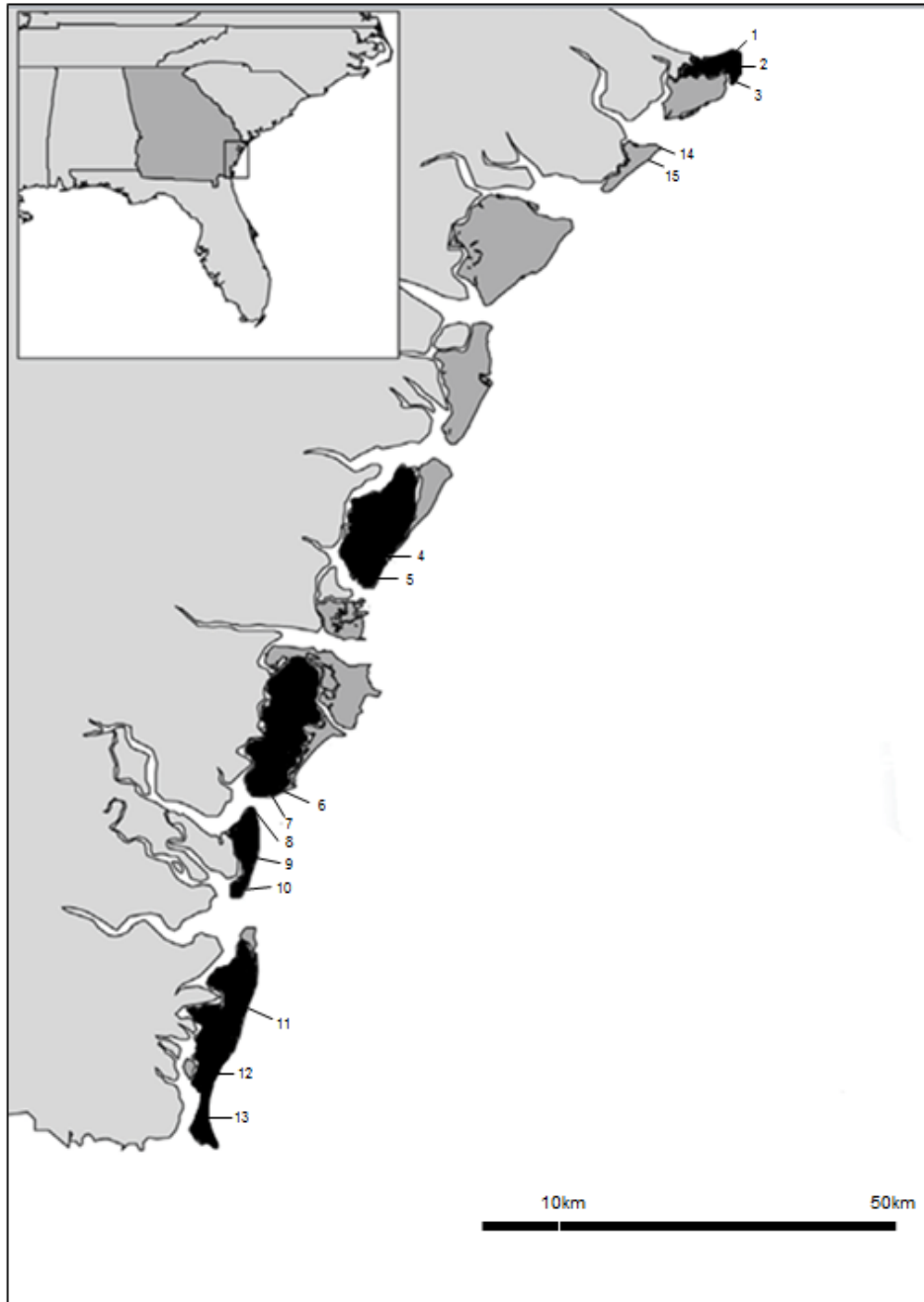


Figure 7. Map of locations used in study. Islands in black represent areas where the populations of *H. d. media* were investigated by Studer and McHugh (2016). These sites are: 1) Tybee (North), 2) Tybee (Mid), 3) Tybee (South), 4) Sapelo (North), 5) Sapelo (South), 6) St. Simons (North), 7) St. Simons (South), 8) Jekyll (North), 9) Jekyll (Mid) 10), Jekyll (South), 11) Cumberland (North), 12) Cumberland (Mid), 13) Cumberland (South). Additionally, Sites 14 and 15 from Wassaw Island were included in this paper, but abundances of *H. d. media* are not known or included in related analyses. Map modified from Ondich and Andrews (2013).

2.2 Beach Indices

Three beach indices were used to quantify different aspects of beach health and value. The Conservation Index (CI) and Recreation Index (RI) described by McLachlan et al. (2013) and the Urbanization Index (UI) from González et al. (2014) (Appendix B, C, D). We followed the protocol by McLachlan et al. (2013) to score CI and RI, and the protocol by González et al. (2014) to score UI.

In addition to calculating beach index values, we measured wind speed and air temperature at each site using a Kestrel 5500 Weather and Environmental Meter (kestrelmeters.com, Birmingham, MI). Soil temperature was measured at a depth of 6 inches using a handheld soil temperature probe (Carolina Biological Supply Co., carolina.com, Burlington, NC). Sand samples were collected and sized using the Sand Grain Sizing Folder (Forestry Suppliers Inc., Jackson, MS) as an initial measure of the morphodynamic state.

2.3 Analysis and Modelling

To determine the relationship between beetle abundance estimates and the three indices, generalized additive models (GAM) were used. nMDS ordination plots with average clustering analyses were used to determine the relationship between the sites and each beach index. Finally, model selection was completed using Akaike Information Criteria (AICc), logLikelihood scores, and Akaike weights (AICw) in the package MuMIn for R (Barton, 2014). All analyses were done in R (R Core Team, 2013).

2.4 Morphometric Analysis

We intended to collect 10-20 beetles per site to be photographed, measured, and used in morphometric analyses. However, for several beaches this was impossible due to very low abundances there. For this reason, beetles were grouped by island, rather than by site, because many beaches had too few beetles to collect to have a sufficient number for analysis. Furthermore, because no physical barriers existed between beach sites occurring on the same island, it was justifiable to group them together as they do not represent different populations. We also included samples from an additional island, Wassaw, where beetles were collected only for morphological analysis but because abundance was not measured, this island was not included in the other aspects of this study. Beetles with damage to the elytra were not included in the analysis. In total, 95 specimens from 6 islands were used. Photomicrographs were taken of each specimen using a Sony HD Super Steady Shot camera with a Leica Leitz DMR compound microscope. Measurements were made using Auto-Montage 3D imaging software (Synoptics Ltd., Frederick, MD). Four characters known to be variable in other impacted carabids were measured across all specimens (Table 3).

Table 3. Legend of body character measurements taken.

Character	Description
Elytra Length	Elytra sutural length, scutellum base to tip of elytra suture
Elytra Width	Widest point of single elytron in dorsal view from suture to lateral margin
Pronotum Length	Total length of pronotum at midline
Interocular Width	Dorsal interocular width at the widest point

3. Results

3.1 Beach Indices

We investigated how three indices performed on Georgia Island beaches independently. When using a two group split in the nMDS analysis, identical groupings occurred when categorizing all sites except for one using each index. The nMDS analysis on the Urbanization Index (González et al. 2014) values grouped eight sites together, including all sites of Sapelo, Cumberland, and Wassaw, and the northern site of Jekyll. The other group comprised the remaining seven sites, including the other two Jekyll sites, and all sites on Tybee and St. Simons. Similar groupings resulted from analyses of the remaining indices. The recreation and conservation indices (McLachlan et al. 2013) separated sites into the exact same groupings with all Tybee, St. Simons, and Site 9 of Jekyll separate from all Sapelo, Cumberland, Wassaw, and Sites 8 and 10 of Jekyll. Therefore, all three indices separated the beaches into two distinct groups. Based on their placement within the groupings and their index values, we characterized the groupings as representative of “disturbed” and “undisturbed” sites (Figure 10). All sites on Cumberland, Sapelo, and Wassaw formed the undisturbed group for each index. Tybee Island and St. Simons Island sites formed the disturbed group for all indices. Jekyll island sites were the only sites split between undisturbed and disturbed groups, and with some variation between indices. The Urbanization Index grouped Jekyll’s Site 8 in undisturbed, 9 in disturbed, and 10 at the intersection of the two. The Recreation Index grouped only Site 9 with the high recreation potential sites (considered disturbed for comparison) with 8 and 10 grouped as low recreation potential. Finally, the Conservation Index grouped Jekyll’s Site 9 as having low conservation value, and 8 and 10 as of high conservation value.

3.2 Prediction models

All sand grains were measured to between 1/8-1/4 mm and characterized as fine, subangular in shape, and were not significantly different by site (ANOVA $p>0.05$). Because of this, sand size was excluded from the analyses.

CI, RI, human abundance, and habitable area were the best predictors of *H. d. media* abundance. The top four models included these parameters (Table 3) and the combined AIC weight of all models that included those variables was 0.78. The evidence ratio between the top model and the model including only those four (1234) was 1.27, meaning that the two have nearly the same likelihood of being the best model. Additionally, the package ranked the relative importance of the variables and statistical significance as listed in Table 4. The relationships of the top 5 variables (CI, RI, human abundance, habitable area, and UI) to the abundance of *H. d. media* are shown in Figure 9.

3.3 Morphometric Analysis

There were no significant differences in size for elytra length, width, pronotum length, and interocular width measured between developed and undeveloped areas as determined by our grouping analysis. However, boxplots of the measurements of each character show that samples from the non-urban beaches had a greater size range than those from urban beaches (Figure 10).

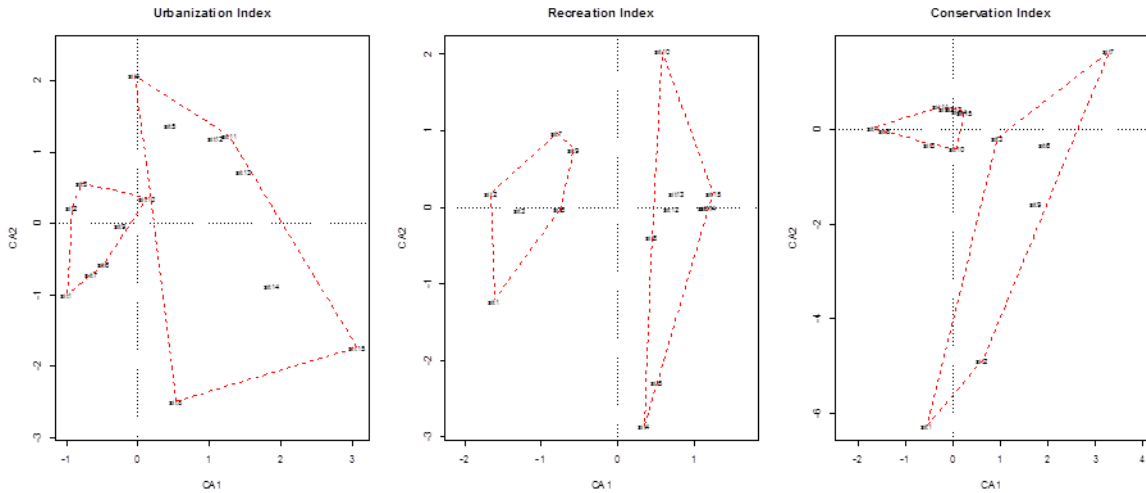


Figure 8. nMDS ordination plot using index values for all sites. Hierarchical clustering analysis done using the average linkage clustering method with 2 groupings (shown in red). Site IDs correspond to sites mapped in Figure 7.

Table 4. CI, RI, UI values, average observed human abundance per survey, and island habitable area measurements. UI: 1(highest urbanization) – 0 (lowest urbanization). CI: 1 (highest conservation value) – 0 (lowest conservation value). RI: 1 (highest recreation value to humans) – 0 (lowest recreation value to humans).

Site	UI	CI	RI	Average Human Abundance	Habitable Area km ² (Island)
1	0.53	0.1	0.9	439	6.13
2	0.83	0.1	0.9	1435.33	6.13
3	0.80	0.2	0.8	1180.33	6.13
4	0.27	0.9	0.4	2.67	5.26
5	0.17	0.9	0.4	0.5	5.26
6	0.57	0.2	0.9	299.33	13.4
7	0.87	0.1	0.9	1489.67	13.4
8	0.20	0.9	0.5	4.17	13.4
9	0.63	0.3	1	358.67	2.77
10	0.47	0.7	0.4	25.67	2.77
11	0.17	1	0.4	0	29.5
12	0.23	1	0.6	3.67	29.5
13	0.17	1	0.6	7.5	29.5
14	0.10	1	0.5	NA	NA
15	0.00	1	0.5	NA	NA

Table 5. Models arranged in order of lowest Akaike's Information Criterion (AICc). Variables included 1) Conservation Index (CI), 2) Human Abundance, 3) Habitat Area, 4) Recreation Index, (RI) 5) Soil Temperature, 6) Temperature, 7) Urbanization Index, and 8) Wind Speed.

Model	Df	logLik	AICc	dAIC	AICw
12347	7	-107.95	231.54	0	0.14
123457	8	-106.74	231.63	0.09	0.13
1234	6	-109.44	232.09	0.55	0.11
1234567	9	-105.96	232.64	1.1	0.08
1247	6	-110.02	233.25	1.71	0.06
12345	7	-108.95	233.55	2.01	0.05
123478	8	-107.7	233.56	2.02	0.05

Table 6. Relative importance of variables as ranked by the AIC selection package MuMIn for R. Statistically significant ($p < 0.05$) variables indicated with *.

CI	Human Abundance	RI	Habitat Area	UI	Soil Temperature	Temperature	Wind Speed
1.0*	1.0*	1.0*	0.8*	0.7	0.44	0.26	0.23

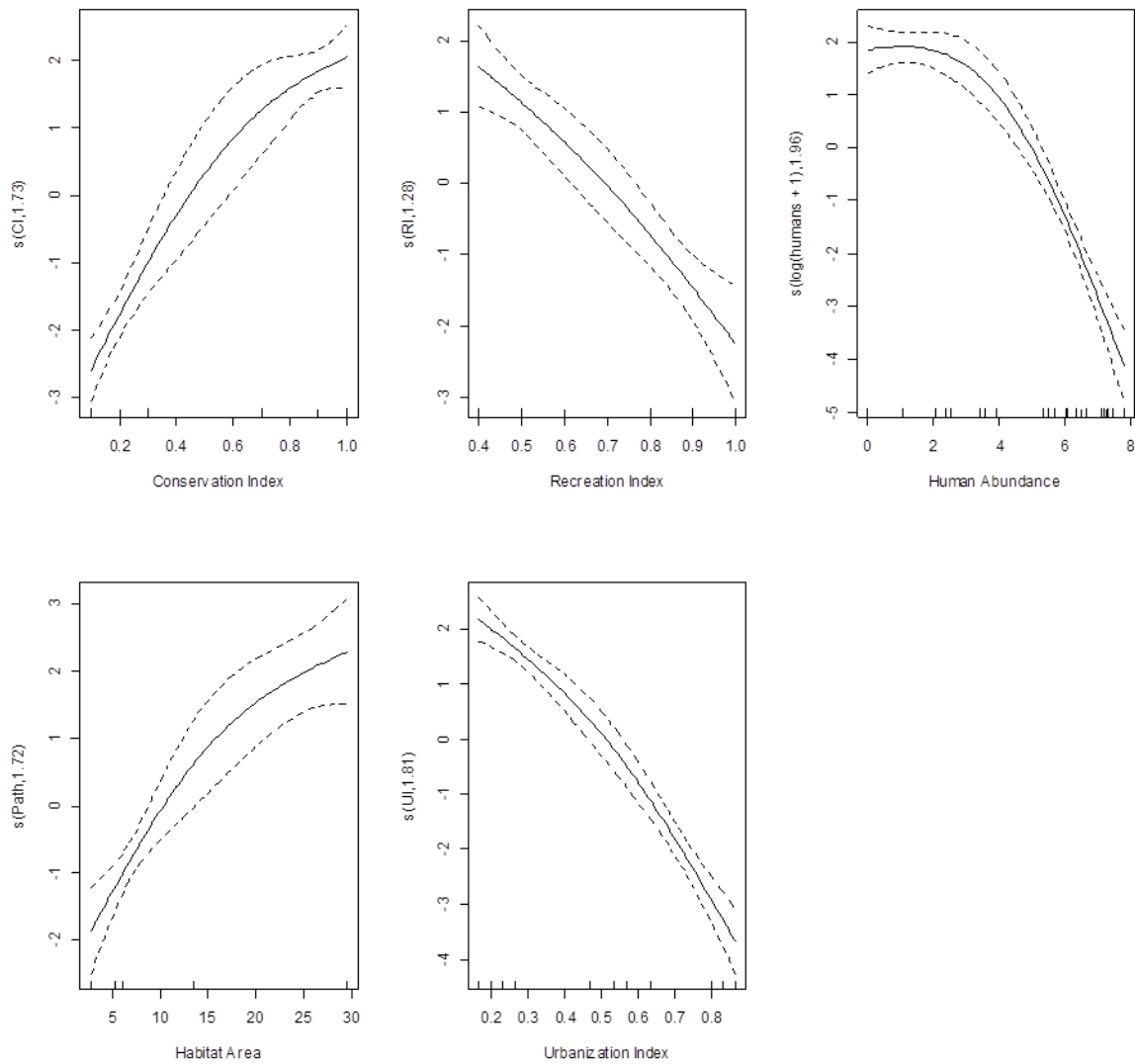


Figure 9. Smoothers curves showing the relationship between *H. d. media* abundance and the variables of interest. Standard error of smoother curves depicted by dotted lines. Estimated degrees of freedom depicted on y-axis.

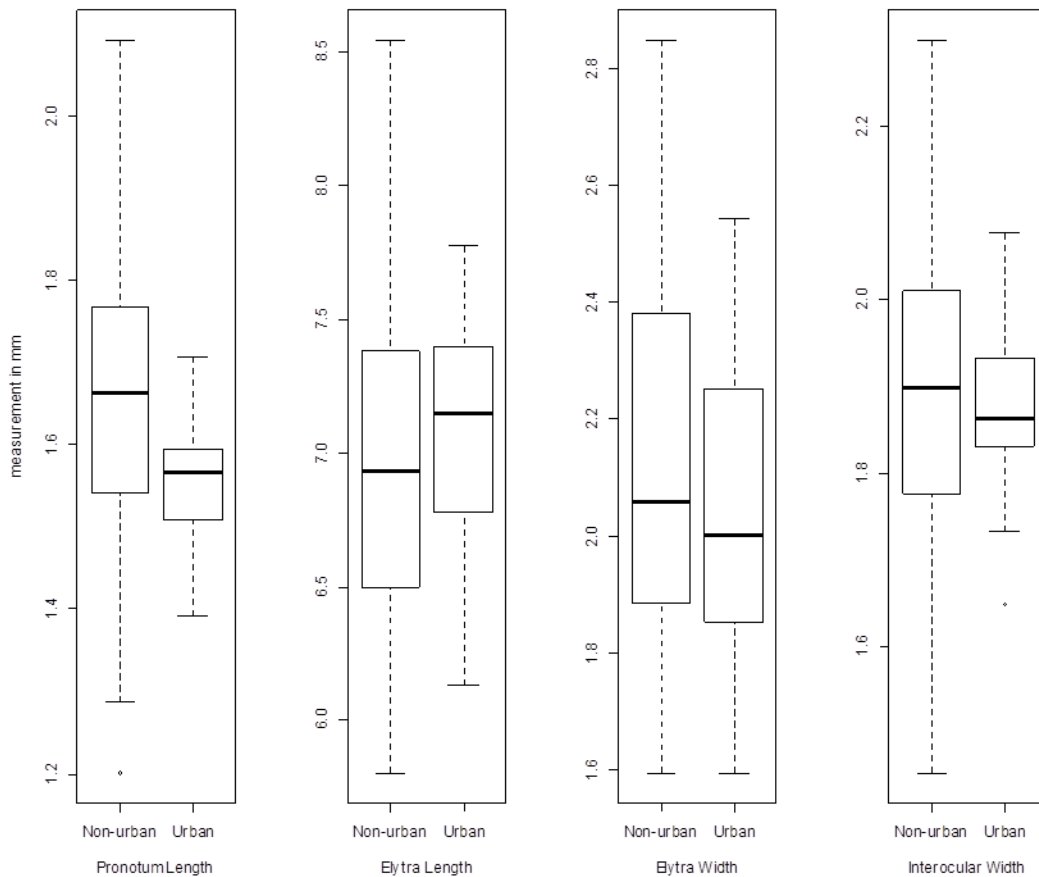


Figure 10. Boxplots showing the distribution of measurements for each of the four characters. Urban or non-urban status was determined based on results of the Urbanization and Conservation Index calculations. Therefore, Cumberland, Wassaw, Jekyll, and Sapelo were included in the “Non-urban” group, while St. Simons and Tybee samples were classified with “Urban.” Jekyll was included in non-urban because the beetles used in the analysis were from Site 8, the site that consistently grouped with non-urban, high conservation, and low recreation potential. Urban n=22, Non-urban n=62.

4. Discussion

4.1 Evaluating the Health of the Georgia Barrier Islands

It likely comes as no surprise to those familiar with the Georgia Barrier Islands that great variation exists between tourist beaches and those that are protected from development.

This variation can be said for all beaches across the world, and is a key concern at the

heart of coastal conservation everywhere. Part of our study included scoring the “health” of the islands visited to get metrics for comparison between islands representing a gradient of human disturbance, to evaluate how these known indicators perform in this part of the world, and to develop a baseline to view in relationship with beetle abundance.

The indices used performed surprisingly similarly to each other with respect to the first splitting of sites into two groups, as seen in our grouping analysis results which were nearly identical between the sites investigated with only Jekyll grouping slightly differently by index. The Georgia Barrier Islands represent a gradient of human disturbance as evidenced by different levels of development and tourism. However, these three indices identified a clear break between those of high urbanization and recreation value to those of low urbanization, and high conservation value. Jekyll Island was the only island that did not group consistently throughout the index assessments. This is likely because although Jekyll receives a great deal of tourism, it has many protected sites and a large community of research scientists working on sea turtle conservation. Therefore, it is at a junction between high urbanization and conservation.

4.2 Modelling Tiger Beetle Abundance

The variables with the highest likelihood of predicting beetle abundance were the Conservation Index, Recreation Index, human abundance estimates, and the estimated amount of total habitable area for *H. d. media* on the island. Other tiger beetles used as bioindicators are known to prefer pristine environments (Hill and Knisley, 1994; Pearson and Cassola, 1992). Thus, the Conservation Index’s ability to predict abundance is

expected. This index was previously found to be the best predictor of abundance for another sensitive species, the crustacean *Emerita brasiliensis* (Decapoda: Hippidae) (Cardoso et al., 2016). The Recreation Index had a strong negative correlation with beetle abundance and was also an important predictor of beetle abundance. However, this may be a reflection of the Recreation Index's high correlation with another variable of importance, human abundance. These measures seem interchangeable, and while the Recreation Index includes more information, it ultimately measures the quality of a beach for human activities, and the number of humans at the beach would be the best assessor of that reality. Finally, we roughly measured the habitat size, using Google Earth and physical surveys, present on each island. This was also an important predictor of beetle abundance, establishing that a bigger habitat is more favorable for beetle population stability. Juvenile habitat size has been shown to limit adult abundance in stage-structured species such as insects (Halpern, 2004). Larval *H. d. media* live in vertical burrows in the sand, preying on smaller arthropods that encounter their burrows along the intertidal zone, putting them in the prime area for contact with beach tourists. Unlike the adults who can easily run or fly to evade walking people or vehicles, larvae are more at risk to be trampled and crushed.

4.3 Morphometric Analysis

Our statistical analyses of beetle morphometrics using standard ANOVA tests between site groups revealed no significant differences. However, a further examination of the data ranges revealed a pattern throughout the morphometric characters: size ranges were larger for the samples from non-urban beaches (Figure 10). Human impacts have been

shown to drive morphological changes in animals within small timeframes (Franssen, 2011; Franssen et al., 2013; Haas et al., 2010). In this case, less variation in size could be due to environmental constraints, such as reduced variation in food sources, or genetic effects due to a reduced gene pool. Alternatively, these patterns could be an artifact of a relatively small data set. On the islands classified as urban, there were very limited populations from which to collect specimens. For this reason, the data set is limited without remedy. Furthermore, extensive collection of a potentially threatened species is unadvisable. Therefore, anthropogenic pressures may be constraining morphological character size, but without further evidence cannot conclude that definitively.

4.4 Conclusions

Tiger beetles have previously been shown to be effective indicators of environmental health in other ecosystems (Cassola and Pearson, 2000; Pearson and Cassola, 2006; Rodríguez et al., 1998; Rolett and Diamond, 2004). Here we conclude that the tiger beetle, *Habroscelimorpha dorsalis media*, should be considered a valid indicator for beach ecosystems within its range. Patterns from our data show that beetle abundance decreases with high human interaction and recreation value, and increases in areas with high conservation value and available habitat. Furthermore, this species appears to be displaying constraints on morphology in areas with the most anthropogenic pressure.

While single indicators have been criticized for being an overly simplistic representation of a complex ecosystem, they have great benefits that should not be overlooked. Single indicators that well represent the status of an ecosystem have the potential to reduce the

time, energy, and ultimately the cost required to monitor habitats. Furthermore, they provide information in an accessible way that can be more easily understood by the public and policy makers. Finally, charismatic species are critical to public engagement and sentiment, which provides volunteers, public programs, and funding for conservation efforts. In this way, we assert that *H. d. media* can and should be considered when monitoring the health of Georgia's beaches, for the sake of the persistence of this species, and to aid in monitoring programs that allow for the continued enjoyment of humans and the health of these beach ecosystems.

REFERENCES

- Arndt, E., Aydin, N., Aydin, G., 2005. Tourism impairs tiger beetle (Cicindellidae) populations—a case study in a Mediterranean beach habitat. *Journal of Insect Conservation* 9, 201-206.
- Avgin, S.S., Luff, M.L., 2010. Ground beetles (Coleoptera: Carabidae) as bioindicators of human impact. *Munis Entomology & Zoology* 5, 209-215.
- Barber, D., Beck, J., Mangee, N., Saadatmand, Y., M, T., 2015. Tybee island tourism study. Armstrong State University Press.
- Barton, K., 2014. MuMIn: Multi-Model Inference.
- Beatley, T., Brower, D., Schwab, A.K., 2002. An introduction to coastal zone management. Island Press.
- Bessa, F., Gonçalves, S.C., Franco, J.N., André, J.N., Cunha, P.P., Marques, J.C., 2014. Temporal changes in macrofauna as response indicator to potential human pressures on sandy beaches. *Ecological Indicators* 41, 49-57.
- Blair, J., Parmelee, R., Wyman, R., 1994. A comparison of the forest floor invertebrate communities of four forest types in northeastern U.S. *Pedobiologia* 38, 146-160.
- Boevers, J., 2008. Assessing the utility of beach ecolabels for use by local management. *Coastal Management* 36, 524-531.
- Bousquet, Y., 2012. Catalogue of Geadephaga (Coleoptera, Adephaga) of America, north of Mexico. PenSoft Publishers LTD.
- Boyd, H.P., 1978. The tiger beetles (Coleoptera: Cicindelidae) of New Jersey with special reference to their ecological relationships. *Transactions of the American Entomological Society (1890-)* 104, 191-242.
- Boyd, H.P., Rust, R.W., 1982. Intraspecific and geographic variations in *Cicindela dorsalis* Say (Coleoptera: Cicindelidae). *The Coleopterists' Bulletin*, 221-239.
- Breitfuss, M., Dale, P., 2004. The Endangered Illidge's Ant Blue Butterfly (*Acrodipsas illidgei*) from an Intertidal Habitat Managed for Mosquito Control. *American Mosquito Control Association* 20, 91-93.
- Brown, A.C., Nordstrom, K., McLachlan, A., Jackson, N.L., Sherman, D.J., 2008. Sandy shores of the near future. *Aquatic Ecosystems*, 263.
- Brown, A.C., McLachlan, A., 2002. Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. *Environmental Conservation* 29, 62-77.

- Brown, C., Corcoran, E., Herkenrath, P., Thonell, J., 2006. Marine and coastal ecosystems and human well-being: synthesis.
- Brown, J., Boyce, M., 1998. Line transect sampling of Karner blue butterflies (*Lycaeides melissa samuelis*). *Environmental and Ecological Statistics* 5, 81-91.
- Cardoso, R.S., Barboza, C.A., Skinner, V.B., Cabrini, T.M., 2016. Crustaceans as ecological indicators of metropolitan sandy beaches health. *Ecological Indicators* 62, 154-162.
- Carroll, S.S., Pearson, D.L., 1998. The effects of scale and sample size on the accuracy of spatial predictions of tiger beetle (*Cicindelidae*) species richness. *Ecography* 21, 401-414.
- Cassola, F., Miskell, E., 2001. Two new tiger beetle species from north-western Tanzania (*Coleoptera, Cicindelidae*). *Fragmenta entomologica, Roma* 33, 21-41.
- Cassola, F., Pearson, D.L., 2000. Global patterns of tiger beetle species richness (*Coleoptera: Cicindelidae*): their use in conservation planning. *Biological Conservation* 95, 197-208.
- Cervantes, O., Espejel, I., 2008. Design of an integrated evaluation index for recreational beaches. *Ocean & Coastal Management* 51, 410-419.
- Colombini, I., Chelazzi, L., Gibson, R., Atkinson, R., 2003. Influence of marine allochthonous input on sandy beach communities. *Oceanography and Marine Biology: an Annual Review* 41, 115-159.
- Comor, V., Orgeas, J., Ponel, P., Rolando, C., Delettre, Y.R., 2008. Impact of anthropogenic disturbances on beetle communities of French Mediterranean coastal dunes. *Biodiversity and Conservation* 17, 1837-1852.
- Dale, V.H., Beyeler, S.C., 2001. Challenges in the development and use of ecological indicators. *Ecological Indicators* 1, 3-10.
- Daniels, J.C., 2009. Cooperative conservation efforts to help recover an endangered south Florida butterfly. *Insect Conservation and Diversity* 2, 62-64.
- Dauvin, J., Andrade, H., de-la-Ossa-Carretero, J., Del-Pilar-Ruso, Y., Riera, R., 2016. Polychaete/amphipod ratios: An approach to validating simple benthic indicators. *Ecological Indicators* 63, 89-99.
- David L. Pearson, C.B.K., Charles J. Kazilek, 2006. *A Field Guide to the Tiger Beetles of the United States and Canada: Identification, Natural History, and Distribution of the Cicindelidae*. Oxford University Press, New York, USA.
- Defeo, O., McLachlan, A., Schoeman, D.S., Schlacher, T.A., Dugan, J., Jones, A., Lastra, M., Scapini, F., 2009. Threats to sandy beach ecosystems: A review. *Estuarine, Coastal and Shelf Science* 81, 1-12.

- Desender, K., Turin, H., 1989. Loss of habitats and changes in the composition of the ground and tiger beetle fauna in four West European countries since 1950 (Coleoptera: Carabidae, Cicindelidae). *Biological Conservation* 48, 277-294.
- Doney, S.C., Ruckelshaus, M., Duffy, J.E., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., Polovina, J., Rabalais, N.N., Sydeman, W.J., Talley, L.D., 2012. Climate Change Impacts on Marine Ecosystems. *Annual Review of Marine Science* 4, 11-37.
- Drummond, M., 2009. 5-Year Status Review of Northeastern beach tiger beetle (*Cicindela dorsalis dorsalis*), in: Service, U.S.F.a.W. (Ed.). Gloucester, Virginia, Virginia Field Office.
- Drummond, M.R., 2002. The effects of geophysical factors on the distribution of the Northeastern Beach Tiger Beetle, *Cicindela dorsalis dorsalis* Say.
- Erwin, T., Pearson, D., 2008. A treatise on the Western Hemisphere Caraboidea (Coleoptera). Their classification, distributions, and ways of life. Volume II (Carabidae-Nebriiformes 2-Cicindelitae). Pensoft, Sofia-Moscow 33.
- Erwin, T.L., 2007. A Treatise on the Western Hemisphere Caraboidea (Coleoptera): Their Classification, Distributions, and Ways of Life. Trachypachidae, Carabidae-Nebriiformes. Pensoft.
- Evans, M., Forsythe, T., 1985. Feeding mechanisms, and their variation in form, of some adult ground-beetles (Coleoptera: Caraboidea). *Journal of Zoology* 206, 113-143.
- Fanini, L., Marchetti, G.M., Scapini, F., Defeo, O., 2009. Effects of beach nourishment and groynes building on population and community descriptors of mobile arthropodofauna. *Ecological Indicators* 9, 167-178.
- Fattorini, S., Maltzeff, P., Salvati, L., 2015. Use of insect distribution across landscape-soil units to assess conservation priorities in a Mediterranean coastal reserve: the tenebrionid beetles of Castelporziano (Central Italy). *Rendiconti Lincei* 26, 353-366.
- Fenster, M.S., Knisley, C.B., Reed, C.T., 2006. Habitat preference and the effects of beach nourishment on the federally threatened northeastern beach tiger beetle, *Cicindela dorsalis dorsalis*: Western Shore, Chesapeake Bay, Virginia. *Journal of coastal research*, 1133-1144.
- Franssen, N.R., 2011. Anthropogenic habitat alteration induces rapid morphological divergence in a native stream fish. *Evolutionary Applications* 4, 791-804.
- Franssen, N.R., Harris, J., Clark, S.R., Schaefer, J.F., Stewart, L.K., 2013. Shared and unique morphological responses of stream fishes to anthropogenic habitat alteration. *Proceedings of the Royal Society of London B: Biological Sciences* 280, 20122715.
- Gerlach, J., Samways, M., Pryke, J., 2013. Terrestrial invertebrates as bioindicators: an overview of available taxonomic groups. *Journal of insect conservation* 17, 831-850.

- Glaser, J., 1977. Letters from our readers. *Cicindela* 9, 12.
- Golfieri, B., Hardersen, S., Maiolini, B., Surian, N., 2016. Odonates as indicators of the ecological integrity of the river corridor: Development and application of the Odonate River Index (ORI) in northern Italy. *Ecological Indicators* 61, 234-247.
- Gonçalves, S.C., Anastácio, P.M., Marques, J.C., 2013. Talitrid and Tylid crustaceans bioecology as a tool to monitor and assess sandy beaches' ecological quality condition. *Ecological indicators* 29, 549-557.
- González, S.A., Yáñez-Navea, K., Muñoz, M., 2014. Effect of coastal urbanization on sandy beach coleoptera *Phaleria maculata* (Kulzer, 1959) in northern Chile. *Marine pollution bulletin* 83, 265-274.
- Graf, W.L., 1987. *Geomorphic Systems of North America*. Geological Society of Amer.
- Haas, T.C., Blum, M.J., Heins, D.C., 2010. Morphological responses of a stream fish to water impoundment. *Biology letters* 6, 803-806.
- Halpern, B.S., 2004. Habitat bottlenecks in stage-structured species: hermit crabs as a model system. *Marine Ecology-Progress Series* 276.
- Harvey, A., Zukoff, S., 2011. Wind-powered wheel locomotion, initiated by leaping somersaults, in larvae of the southeastern Beach Tiger Beetle (*Cicindela dorsalis media*). *PloS one* 6, e17746.
- Hill, J., Knisley, C., 1994. Northeastern beach tiger beetle (*Cicindela dorsalis dorsalis* Say) recovery plan. US Fish and Wildlife Service, Hadley, Massachusetts.
- Hori, M., 1982. The biology and population dynamics of the tiger beetle, *Cicindela japonica* (Thunberg). *Physiological Ecology Japan* 19, 77-212.
- Ikeda, H., Kubota, K., Kagaya, T., Abe, T., 2006. Niche differentiation of burying beetles (Coleoptera: Silphidae: Nicrophorinae) in carcass use in relation to body size: estimation from stable isotope analysis. *Applied Entomology and Zoology* 41, 561-564.
- Kirwan, M.L., Guntenspergen, G.R., D'Alpaos, A., Morris, J.T., Mudd, S.M., Temmerman, S., 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters* 37.
- Kitching, I.J., 1996. Identifying complementary areas for conservation in Thailand: an example using owls, hawkmoths and tiger beetles. *Biodiversity & Conservation* 5, 841-858.
- Knisley, C., Hill, J.M., 1992. Effects of habitat change from ecological succession and human impact on tiger beetles. *Virginia Journal of Science* 43, 133-142.
- Knisley, C., Hill, J.M., 1992. Effects of habitat change from ecological succession and human impact on tiger beetles. *Virginia Journal of Science* 43, 133-142.

- Knisley, C., Schultz, T., 1997. The biology of tiger beetles. Virginia Museum of Natural History, Martinsville, VA.
- Knisley, C.B., 1984. Ecological distribution of tiger beetles (Coleoptera: Cicindelidae) in Colfax County, New Mexico. *The Southwestern Naturalist*, 93-104.
- Knisley, C.B., 1987. Status survey of two candidate species of tiger beetles, *Cicindela puritana* G. Horn and *C. dorsalis* Say. , in: Service, F.R.t.U.S.F.a.W. (Ed.), Newton Corner, MA, p. 37 pp.
- Knisley, C.B., Hill, J.M., Scherer, A.M., 2005. Translocation of Threatened Tiger Beetle *Cicindela dorsalis dorsalis* (Coleoptera: Cicindelidae) to Sandy Hook, New Jersey. *Annals of the Entomological Society of America* 98, 552-557.
- Knox, G., 2001. The ecology of seashores. *Limnology and Oceanography* 47, 1268-1268.
- Lacy, R.C., 1987. Loss of genetic diversity from managed populations: interacting effects of drift, mutation, immigration, selection, and population subdivision. *Conservation Biology* 1, 143-158.
- Lagisz, M., 2008. Changes in morphology of the ground beetle *Pterostichus oblongopunctatus* F.(Coleoptera; Carabidae) from vicinities of a zinc and lead smelter. *Environmental Toxicology and Chemistry* 27, 1744-1747.
- Laparie, M., Lebouvier, M., Lalouette, L., Renault, D., 2010. Variation of morphometric traits in populations of an invasive carabid predator (*Merizodus soledadinus*) within a sub-Antarctic island. *Biological invasions* 12, 3405-3417.
- Leatherman, S.P., 1997. Beach rating: a methodological approach. *Journal of coastal research*, 253-258.
- LeConte, J.L., 1987. Revision of the Cicindelidae of the United States. *Transactions of the American Entomological Society* XI, 46-47.
- Leng, C.W., 1902. Revision of the Cicindelidae of boreal America. *Transactions of the American Entomological Society* 28, 93-186.
- Leonard, J.G., Bell, R.T., 1998. Northeastern tiger beetles: a field guide to tiger beetles of New England and eastern Canada. CRC Press.
- Lucrezi, S., Schlacher, T.A., Robinson, W., 2009. Human disturbance as a cause of bias in ecological indicators for sandy beaches: Experimental evidence for the effects of human trampling on ghost crabs (*Ocypode* spp.). *Ecological Indicators* 9, 913-921.
- MacRae, T.C., 2009. A Treatise on the Western Hemisphere Caraboidea (Coleoptera). Their classification, distributions, and ways of life. Volume II (Carabidae-Nebriiformes 2-Cicindelidae). *The Pan-Pacific Entomologist* 85, 199-201.
- Maddison, D., Baker, M.D., Ober, K., 1999. Phylogeny of carabid beetles as inferred from 18S ribosomal DNA (Coleoptera: Carabidae). *Systematic Entomology* 24, 103-138.

- Mawdsley, J.R., Schlesinger, M.D., Simmons, T., Blanchard, O.J., 2013. Status of the tiger beetle *Cicindela hirticollis* Say (Coleoptera: Cicindelidae) in New York City and on Long Island, New York, USA.
- McGeoch, M.A., 1998. The selection, testing and application of terrestrial insects as bioindicators. *Biological Reviews of the Cambridge Philosophical Society* 73, 181-201.
- McLachlan, A., Defeo, O., Jaramillo, E., Short, A.D., 2013. Sandy beach conservation and recreation: guidelines for optimising management strategies for multi-purpose use. *Ocean & coastal management* 71, 256-268.
- Mettler, L., Gregg, T., 1969. *Population Genetics and Evolution*. Prentice Hall, Lincoln, UK.
- Nagano, C.D., 1980. Population status of the tiger beetles of the genus *Cicindela* (Coleoptera: Cicindelidae) inhabiting the marine shoreline of southern California. *Atala* 8, 33-42.
- Nasirian, H., Vazirianzadeh, B., Sadeghi, S.M.T., Nazmara, S., 2014. *Culiseta subochrea* as a bioindicator of metal contamination in Shadegan international wetland, Iran (Diptera: Culicidae). *Journal of Insect Science* 14, 258.
- Niemeijer, D., de Groot, R.S., 2008. A conceptual framework for selecting environmental indicator sets. *Ecological Indicators* 8, 14-25.
- Nordstrom, K.F., 2000. *Beaches and dunes of developed coasts*. Cambridge University Press : Cambridge, United Kingdom, United Kingdom.
- Noriega, R., Schlacher, T., Smeuninx, B., 2012. Reductions in ghost crab populations reflect urbanization of beaches and dunes. *Journal of Coastal Research* 28, 123-131.
- Noss, R.F., Platt, W.J., Sorrie, B.A., Weakley, A.S., Means, D.B., Costanza, J., Peet, R.K., 2015. How global biodiversity hotspots may go unrecognized: lessons from the North American Coastal Plain. *Diversity and Distributions* 21, 236-244.
- Nourisson, D.H., Bessa, F., Scapini, F., Marques, J.C., 2014. Macrofaunal community abundance and diversity and talitrid orientation as potential indicators of ecological long-term effects of a sand-dune recovery intervention. *Ecological Indicators* 36, 356-366.
- Nygren, G.H., Bergström, A., Nylin, S., 2008. Latitudinal body size clines in the butterfly *Polyommatus icarus* are shaped by gene-environment interactions. *Journal of Insect Science* 8, 47.
- Ondich, B.L., Andrews, K.M., 2013. A History of Sea Turtle Tagging and Monitoring on Jekyll Island, Georgia, USA. *Marine Turtle Newsletter* 138, 11-15.
- Orians, G.H., 1969. On the evolution of mating systems in birds and mammals. *American Naturalist*, 589-603.
- Pearson, D.L., 1988. Biology of tiger beetles. *Annual review of entomology* 33, 123-147.

- Pearson, D.L., Cassola, F., 1992. World-wide species richness patterns of tiger beetles (Coleoptera: Cicindelidae): indicator taxon for biodiversity and conservation studies. *Conservation Biology* 6, 376-391.
- Pearson, D.L., Cassola, F., 2006. Are we doomed to repeat history? A model of the past using tiger beetles (Coleoptera: Cicindelidae) and conservation biology to anticipate the future, *Beetle Conservation*. Springer, pp. 47-59.
- Pearson, D.L., Knisley, C.B., Duran, D.P., Kazilek, C.J., 2006. *A Field Guide to the Tiger Beetles of the United States and Canada: Identification, Natural History, and Distribution of the Cicindelinae*. Oxford University Press.
- Pearson, D.L., Mury, E.J., 1979. Character divergence and convergence among tiger beetles (Coleoptera: Cicindelidae). *Ecology*, 557-566.
- Pearson, D.L., Vogler, A.P., 2001. *Tiger beetles: the evolution, ecology, and diversity of the cicindelids*. Cornell University Press.
- Peterson, E., Davis, R., Orndorff, H., 2000. 17 β -Estradiol as an indicator of animal waste contamination in mantled karst aquifers. *Journal of Environmental Quality* 29, 826-834.
- Rodríguez, J.P., Pearson, D.L., Barrera, R.R., 1998. A test for the adequacy of bioindicator taxa: are tiger beetles (Coleoptera: Cicindelidae) appropriate indicators for monitoring the degradation of tropical forests in Venezuela? *Biological Conservation* 83, 69-76.
- Rolett, B., Diamond, J., 2004. Environmental predictors of pre-European deforestation on Pacific islands. *Nature* 431, 443-446.
- Sadler, D., 2016. *Southeast: Riding the waves*. Georgia Trend Apr Ed.
- Schlacher, T.A., Jones, A.R., Dugan, J.E., Weston, M.A., Harris, L., Schoeman, D.S., Hubbard, D.M., Scapini, F., Nel, R., Lastra, M., 2014. Open-coast sandy beaches and coastal dunes. *Coastal conservation* 19, 37-92.
- Schlacher, T.A., Schoeman, D.S., Dugan, J., Lastra, M., Jones, A., Scapini, F., McLachlan, A., 2008. Sandy beach ecosystems: key features, sampling issues, management challenges and climate change impacts. *Marine Ecology* 29, 70-90.
- Schlacher, T.A., Thompson, L., 2012. Beach recreation impacts benthic invertebrates on ocean-exposed sandy shores. *Biological Conservation* 147, 123-132.
- Schlesinger, M.D., Novak, P.G., 2011. Status and conservation of an imperiled tiger beetle fauna in New York State, USA. *Journal of Insect Conservation* 15, 839-852.
- Sikes, D.S., 1998. Connecticut tiger beetle status survey (Carabidae: Cicindelinae) 1996-1998: Conservation status, taxonomy and ecology. Research final report to The Connecticut Department of Environmental Protection. , 72.

- Spake, R., Barsoum, N., Newton, A.C., Doncaster, C.P., 2016. Drivers of the composition and diversity of carabid functional traits in UK coniferous plantations. *Forest Ecology and Management* 359, 300-308.
- Stamatov, J., 1972. *Cicindela dorsalis* Say endangered on northern Atlantic coast. *Cicindela* 4, 78.
- Stein, B.A., Kutner, L.S., Adams, J.S., 2000. Precious heritage: the status of biodiversity in the United States. Oxford University Press on Demand.
- Sukhodolskaya, R., 2013. Intraspecific body size variation in ground beetles (Coleoptera, Carabidae) in urban–suburban–rural–natural gradient. *Acta Biol. Univ. Daugavp* 13, 121-128.
- Sukhodolskaya, R., Saveliev, A., 2014. Effects of ecological factors on size-related traits in the ground beetle *Carabus granulatus* L.(Coleoptera, Carabidae). *Russian Journal of Ecology* 45, 414-420.
- Sullivan, B., 2013. Sapelo island settlement and land ownership: an historical overview, 1865-1970. *Occasional Papers of the Sapelo Island NERR* 3, 1-24.
- R Core Team, 2013. R: A language and environment for statistical computing. , R Foundation for Statistical Computing. Vienna, Austria.
- Thomas, C., 1990. What do real population dynamics tell us about minimum viable population sizes? *Conservation Biology* 4, 324-327.
- Ward, M.A., Mays, J.D., 2014. Survey of a Coastal Tiger Beetle Species, *Cicindela marginata* Fabricius, in Maine. *Northeastern Naturalist* 21, 574-586.
- Weller, B., Ganzhorn, J.U., 2004. Carabid beetle community composition, body size, and fluctuating asymmetry along an urban-rural gradient. *Basic and Applied Ecology* 5, 193-201.
- Wenner, A.M., 1988. Crustaceans and other invertebrates as indicators of beach pollution, Marine organisms as indicators. Springer, pp. 199-229.
- Whitman, A., 2013. Climate Change and Biodiversity in Maine: A Climate Change Exposure Summary for Species and Key Habitats (Revised). Manomet Center for Conservation Science.
- Williams, A., Micallef, A., 2009. Beach management: principles and practice, in: Williams, A., Micallef, A. (Eds.), Beach management: principles and practice. Earthscan Publications Ltd, London; UK.
- Willis, H.L., 1967. Bionomics and zoogeography of tiger beetles of saline habitats in the Central United States (Coleoptera, Cicindelidae). University of Kansas Publications.
- Wilson, D., 1970. Three subspecies of cicindelids threatened with extermination. *Cicindela* 2, 18-20.

Yang, B., Madden, M., Kim, J., Jordan, T.R., 2012. Geospatial analysis of barrier island beach availability to tourists. *Tourism Management* 33, 840-854.

Yarbrough, W., Knisley, C., 1994. Distribution and abundance of the coastal tiger beetle, *Cicindela dorsalis media*, in South Carolina. *Entomological News* 105, 189-194.

APPENDIX

Appendix A. Count method with time search along wrack line transect as shown. Jekyll Island.



Appendix B. McLachlan et al. (2013) Conservation Index (CI) criteria.

Category	Condition and Score					
Dunes	0 Absent, replaced by hard engineered structures	1 Severely disturbed and limited in extent	2 Extensive disturbance	3 Disturbed but largely intact	4 Well developed, little disturbance	5 Pristine and extensive
Endangered and iconic species	0 Absent	1 Present in low numbers, not nesting	2 Present in good numbers, may be nesting	3 Nesting/spawning present in large numbers		
Macrobenthic diversity and abundance	0 Low abundance, reflective and/or short beach	1 Intermediate	2 Species rich and abundant, dissipative and/or long beach			

Appendix C. McLachlan et al. (2013) Recreation Index (RI) criteria.

Category	Condition and Score					
Infra-structure	0 No infrastructure, difficult access	1 No infrastructure, limited access	2 Modest infrastructure reasonable access	3 Good access, some amenities	4 Good infra-structure and access	5 Excellent access, parking and amenities, including lifesaving
Safety and health	0 Extremely hazardous and/or polluted	1 Hazardous and/or polluted	2 Moderate hazards and clean	3 Low bathing hazards, clean and totally pollution free		
Physical carrying capacity	0 Limited, pocket beach, no backshore	1 Intermediate	2 Extensive beach with wide backshore			

Appendix D. González et al. (2014) Urbanization Index (CI) criteria.

Category	Low 0-1	Medium 2-3	High 4-5
Proximity to urban centers	Sector with rural character. Several km away from urban center on the beach.	Sector located c. 1 km from an urban center, showing some effects on the beach, such as noise, some lighting and nearby vehicles passing	Sector just meters from an urban center, the city virtually integrated. The beach is next to vehicular traffic, with evident noise and urban lighting
Buildings on sand	No nearby buildings appreciable	There are buildings close to the beach but not on the sand or dunes	There are buildings that occupy the space at the beach or in the dunes
Cleaning of the beach	The beach is not “cleaned” by mechanical means, with no sand removal	Although mechanically engaged for cleaning, this is done infrequently, no more than 1 time per week. No frequent removal of sand	Beach is repeatedly cleaned by mechanical methods more than once a week, which causes frequent removal of sand
Solid waste in the sand	No waste in the sand or the amount of waste on beach is minimal	In a short walk of a few meters, some solid waste can be seen on the sand, such as paper, plastic containers and cigarette butts	Clearly a high frequency of solid waste on the sand, including paper, plastic containers, cigarette butts, plastic debris, scrap wood and glass
Vehicle traffic on the sand	No vehicle tracks were observed on the sand. There is no vehicle access on beach	Although there are traces of vehicle passage, they are scarce. Vehicular crossing is not periodic and not constant. Vehicular access to the beach is relatively limited	There are many tracks, showing recurring vehicular traffic. Various vehicles have access to the beach
Quality of the night sky	Sky conditions are optimal for stargazing. The sky appears black, and hundreds of stars can be seen perfectly	The glow of artificial light moderately impaired conditions for stargazing. The sky appears dark gray, and some tens of stars can be seen with some difficulty	Given the high brightness of the artificial lighting, the conditions for stargazing are bad. The sky is gray and occasional stars can be seen. Light pollution is evident
Frequency of visitors	The area is visited by very few people, and those are located in	The sector has a moderate demand for use. Although it has	Sector in high demand from users, considered a high tourist beach.

	areas isolated from each other. Rural beach	tourists, based on either location or privacy, it does not have a large number of users	Public access urban beach
--	---	---	---------------------------