

# Ecology of Brazilian seagrasses: Is our current knowledge sufficient to make sound decisions about mitigating the effects of climate change?

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Recebido em 10.VI.2012. Aceito em 25.VI.2013.

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**ABSTRACT** – The objective of this study was to synthesize published information about environmental influences on seagrasses in Brazil, and to identify where further research is needed, particularly in the context of global climate change. Of the 84 articles published as of June 2013, only two used a climate change-related approach, as a result of joint efforts between national and international institutions. These studies indicated that climate change is the probable cause of the loss of seagrass populations in some areas of northeastern Brazil. The expansion of the species *Halodule wrightii* Ascherson into the Brazilian subtropical region may also have been a response to this phenomenon. Although data are available on the interactions of *H. wrightii* and *Ruppia maritima* L. with the environment, this knowledge is still preliminary. In general, knowledge of seagrasses on the Brazilian coast needs to be further developed, not only with respect to species ecology, but also within the context of climate change.

Keywords: Brazil, distribution, ecology, *Halodule wrightii*, review

**RESUMO** – **Ecologia de angiospermas marinhas brasileiras: o conhecimento atual é suficiente para tomar decisões sobre mitigação dos efeitos de mudança climática?** O objetivo deste estudo foi sintetizar informações publicadas acerca das influências ambientais sobre angiospermas marinhas brasileiras e lacunas de pesquisa, especialmente considerando o contexto das mudanças climáticas globais. Oitenta e um artigos foram publicados até junho de 2013, mas apenas dois artigos foram relacionados a mudanças climáticas globais, em esforços conjuntos entre instituições nacionais e internacionais. Tais estudos apontaram as mudanças climáticas como prováveis causas de perda de área de angiospermas em algumas áreas no nordeste do Brasil. Além disso, a dispersão da espécie *Halodule wrightii* Ascherson para a região subtropical brasileira também pode ter sido causada por este fenômeno. Embora existam dados disponíveis sobre interações ambientais de *H. wrightii* e *Ruppia maritima*, este conhecimento ainda é incipiente. De um modo geral, o conhecimento sobre angiospermas marinhas na costa brasileira necessita ser aprofundado não apenas sobre a ecologia das espécies, mas também dentro do âmbito das mudanças climáticas.

Palavras chave: Brasil, distribuição, ecologia, *Halodule wrightii*, revisão

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## INTRODUCTION

The contribution of greenhouse gases and human activities to global warming (Schneider, 1990; Pearce, 1991; Mahlman, 1997; Chandler *et al.*, 2002; Winkler, 2005), and the link between global warming and extreme weather events worldwide and sea-level rise are still debated (Khandekar *et al.*, 2005). This phenomenon can modify coastal ecosystems in both their structure and functioning, changing the physical and biological characteristics, resulting in a loss of marine biodiversity, fishery resources and shorelines (Vergara, 2005). As part of one of these ecosystems, seagrasses and the ecosystem services that they provide are threatened by several environmental factors that are currently changing or might change in the future (Short & Neckles, 1999; Duarte, 2002; Waycott *et al.*, 2007; Björk *et al.*, 2008).

Seagrasses are one of the most productive coastal ecosystems in the world, especially when associated with algae, with a production level equivalent to plants of annual commercial crops (Zieman & Wetzel, 1980; Duarte & Cebrian, 1996; Costanza *et al.*, 1997; Christian & Luczkovich, 1999; Orth *et al.*, 2006). These plants affect the food chain and their environment, including nutrient cycles and water flow, while they also protect the coastal region (Koch *et al.*, 2009; Hemminga & Duarte, 2000).

As a result of their strong influence on physical and chemical factors, seagrasses are known as “ecosystem engineers” (Jones *et al.*, 1994; Koch *et al.*, 2009). As such, they provide an ideal environment for reproduction, nesting, nursery and protection against predators for a wide variety of animals. They are a favorable area for predators to feed, and provide a direct source of food to megaherbivores and fish (Kikushi, 1974; Virnestein, 1987; Phillips, 1992; Duarte, 2000). Endangered fauna and other marine species that are ecologically and commercially important for the coastal zone require these environments to complete their life cycles (Starck & Davis, 1966; Kikushi, 1974; D’Incao, 1982; Sheridan & Livingston, 1983; Garcia *et al.*, 1996; Nakaoka *et al.*, 2001; Nakaoka, 2005; Short *et al.*, 2006a). In addition to the marine fauna, many coastal human populations depend on these plants for their survival, through activities such as commercial and subsistence fishing (Short *et al.*, 2006a).

In addition to climate change, seagrasses are threatened by local events and many anthropogenic impacts, as they are located at the interface between the terrestrial environment and the ocean (Short &

Wyllie-Echeverria, 1996). According to Orth *et al.* (2006), their sensitivity to environmental alterations and their ability to signal losses in the ecosystem characterize these plants as “biological sentinels” or “coastal canaries”. These authors also added that the widespread distribution of seagrasses across two wide climate zones (temperate and tropical) makes them excellent tools for the assessment of large-scale trends, in contrast to other comparable coastal habitats such as mangroves, coral reefs or salt marshes that are limited to only one of these regions.

Global climate changes may irreversibly affect these ecosystems. These phenomena have resulted in progressive alterations of a number of environmental factors that are directly or indirectly related to seagrasses, such as temperature, sea level, atmospheric CO<sub>2</sub>, light and ultraviolet radiation conditions (Short & Neckles, 1999; Duarte *et al.*, 2004). These alterations also modify the distribution, productivity and composition of seagrass communities, and consequently the coastal geomorphology, biochemical cycles, and local and regional biota (Short & Neckles, 1999; Duarte, 2000; Duarte *et al.*, 2004). Specific studies of the environmental influences on seagrasses may provide useful information ranging from diagnoses of regional problems to predictions of climate-change effects. This knowledge is essential for predicting the future of marine life, given the importance of seagrass ecosystems in the coastal and marine environment, and additionally because of the interactions with a number of other ecosystems.

Researchers throughout the world have studied interactions among environmental factors and seagrasses, observing, for example, the effects of currents (Fonseca & Kenworthy, 1987; Gambi *et al.*, 1990; Koch, 2001; Koch *et al.*, 1994), turbidity (Preen & Marsh, 1995), light (Dennison & Alberte, 1985; Gordon *et al.*, 1994; Koch, 2001; Ruiz & Romero, 2001; Campbell *et al.*, 2007; Ralph *et al.*, 2007), nutrients (Hemminga *et al.*, 1999; Lee *et al.*, 2007), salinity, and temperature (McMillan, 1978; Pulich, 1985; Masini *et al.*, 1995; Short & Neckles, 1999; Koch *et al.*, 2007a, b; Lee *et al.*, 2007) on these plants. However, few studies have treated tropical species.

Brazil has around 20,000 hectares of seagrasses located close to coral reefs and coastal lagoons (Creed, 2003). The species reported on the Brazilian coast are *Halodule wrightii* Ascherson, *Halodule emarginata* Hartog, *Halophila decipiens* Ostenfeld, *Halophila baillonii* Ascherson and *Ruppia maritima*

Lipkin (Short *et al.*, 2007). The most widespread species is *H. wrightii*, from Piauí to Paraná (Den Hartog, 1972; Oliveira-Filho *et al.*, 1983; Short *et al.*, 2007; Sordo *et al.*, 2011) and the most widely distributed is *Ruppia maritima*, which can even be found in estuarine areas (Oliveira-Filho *et al.*, 1983; Marques & Creed, 2008). *Halophila decipiens* is generally associated with *H. wrightii* and is found in the same areas; *Halophila baillonii* occurs only in the state of Pernambuco; and *Halodule emarginata* can be found from the state of Bahia to São Paulo (Oliveira-Filho *et al.*, 1983).

Because of their sensitivity to environmental alterations and their ecological and economic roles, knowledge of seagrasses is essential for the understanding and mitigation of the effects of global climate change on coastal areas. The aim of this study was to synthesize information about environmental influences on Brazilian seagrasses and research gaps, within the context of global climate change.

### Environmental influences on Brazilian Seagrasses

This review included original articles published in indexed scientific journals until June 2013. A total of 84 articles about seagrass ecosystems in Brazil were found. The studies were classified according to the following subjects: taxonomy, ecology and biodiversity (17%), species ecology (17%), associated biota (36%), seagrasses as feeding habitats of megaherbivores (14%), reviews and pharmacological properties (8%), and the influence of anthropogenic impacts or climate extremes (8%) (Table 1).

Some information relating to environmental influences had been recorded mainly from indirect observations, in which the studies did not undertake tests, but cited some observations about these influences (*e.g.*, Andrade-Lima, 1957; Laborel-Deguen, 1963; Kempf, 1970; Silva *et al.*, 1987; Corbisier, 1994). Additional information was obtained through quantification and spatiotemporal variations of morphometric features and biomass (Corbisier, 1994; Creed, 1997; Magalhães *et al.*, 1997; Creed, 1999; Creed & Amado-Filho, 2009; Sordo *et al.*, 2011). However, direct observations of environmental effects on these angiosperms are rare in Brazil (Creed & Monteiro, 2000; Short *et al.*, 2006a, b), and there are no studies on the influence of these factors on the ecosystem as a whole (*i.e.*, seagrass and associated flora and fauna).

Most of the species-level studies examined environmental influences on *R. maritima*, such as

the effects of a variety of environmental factors on its life cycle and reproductive events (Cafruni *et al.*, 1978; Koch & Seeliger, 1988; Costa & Seeliger, 1989; Silva & Asmus, 2001; Colares & Seeliger, 2006). However, *H. wrightii* (58%) was the most-studied species, considering the total number of citations on these influences, especially in the state of Pernambuco in northeastern Brazil (29%). The studies on *R. maritima* were concentrated in the southern state of Rio Grande do Sul (38%).

In general, the recorded influences were related to bathymetry (*cf.* Coelho, 1965; Laborel-Deguen, 1963; Kempf, 1970, Cafruni *et al.*, 1978; Coutinho & Seeliger, 1984), types of substrate and sediment (*cf.* Laborel-Deguen, 1963; Kempf, 1970; Oliveira-Filho *et al.*, 1983, Oliveira *et al.*, 1997), physical and chemical variations (*cf.* Andrade-Lima, 1957; Laborel-Deguen, 1963; Kempf, 1970; Seeliger *et al.*, 1984; Costa & Seeliger, 1989; Corbisier, 1994; Costa *et al.*, 1997; Creed, 1997; Oliveira *et al.*, 1997; Creed & Monteiro, 2000; Colares & Seeliger, 2006), meteorological variations (*cf.* Coelho, 1965; Corbisier, 1994; Creed, 1997; Magalhães *et al.*, 1997; Costa *et al.*, 1997; Creed, 1999; Silva & Asmus, 2001; Creed & Amado-Filho, 2009; Sordo *et al.*, 2011), and extreme climate variation (Short *et al.*, 2006a, b).

Most of the information about influences on *H. wrightii* is related to its morphological variations (*cf.* Andrade-Lima, 1957; Laborel-Deguen, 1963; Kempf, 1970; Silva *et al.*, 1987; Corbisier, 1994; Creed, 1997; Magalhães *et al.*, 1997; Oliveira *et al.*, 1997; Creed, 1999; Creed & Monteiro, 2000; Short *et al.*, 2006b; Creed & Amado-Filho, 2009; Sordo *et al.*, 2011), with rare laboratory observations (*cf.* Laborel-Deguen, 1963). For *R. maritima*, experimental studies were also performed in addition to these information (*cf.* Ferreira & Seeliger, 1985; Silva & Asmus, 2001; Colares & Seeliger, 2006), including on its reproductive events (*cf.* Seeliger *et al.*, 1984; Koch & Seeliger, 1988).

The following sections summarize the information available in articles published until June 2013, regarding environmental influences on these species and their associated flora and fauna in Brazil.

### *Halodule wrightii* Ascherson

This species is found in shallow areas, from the sublittoral zone at low spring tides to a few meters deep, even though it has also been found at depths below 10 m, perhaps as a result of a high photophilic

requirement (Laborel-Deguen, 1963; Kempf, 1970). *H. wrightii* establishes itself on sites protected by reef rocks and coral reefs, which allow it to grow, and on shifting bottoms, where it forms shallow or sparse meadows. This species may also be found on seabeds that are rarely immersed at low tide, and on consolidated substrates (Laborel-Deguen, 1963; Oliveira-Filho *et al.*, 1983).

Sediment type may limit the presence of *H. wrightii* (Kempf, 1970). However, particle size does not sufficiently explain the bathymetric distribution of the meadows; the limits of occurrence of this species are determined by high sediment instability, strong wave action at low spring tides (Oliveira *et al.*, 1997) or exposure to air (Oliveira *et al.*, 1997; Magalhães *et al.*, 1997). However, these conditions are frequently found in meadows along the Ceará coast and may explain the low values of morphometric parameters and density of *H. wrightii* in the intertidal zone, as well as the small dimensions of the beds on rocky substrates (Barros K.V.S., personal observation).

The effect of wave action on the meadows is evident, and dislodges large numbers of plants (Andrade-Lima, 1957). Sometimes these plants are unearthed by erosion or buried by sediment, creating vertical branches (Laborel-Deguen, 1963). Currents are also an important physical factor influencing the meadows, causing their temporary destruction (Kempf, 1970) and fragmentation, or forming patchy meadows (Laborel-Deguen, 1963).

Heavy summer rains may lead to the removal of sediment, with subsequent erosion of the meadows and exposure of the rhizomes. The reduction in rhizome biomass allows macroalgae, such as *Gracilaria* spp. and other species, to invade the meadows (Silva *et al.*, 1987). Other studies have demonstrated that rainfall and storms on the east coast of Brazil seem to coincide with an increase in wind speed (*e.g.*, Magalhães *et al.*, 1997; Oliveira *et al.*, 1997; Sordo *et al.*, 2011). Wind speed likely has a negative impact on the meadows along the Brazilian eastern coast, causing alternate clearance and colonization events in small patches, recorded during the rainy season/winter (Magalhães *et al.*, 1997; Oliveira *et al.*, 1997; Sordo *et al.*, 2011), when stronger winds intensify the wave action (Oliveira *et al.*, 1997). In addition to the winds, the frequent cold fronts during the rainy season in southern Brazil also lead to increased wave action and turbidity, thus reducing the mud content in the meadow (Sordo *et al.*, 2011). On the coast of semiarid northeastern Brazil, winds gain strength during the dry season, causing leaves to break off and

resulting in subdivision of the meadows into smaller patches (Barros, K. V. S., personal observation).

The morphological features of *H. wrightii* may be influenced by a variety of environmental factors (Creed & Monteiro, 2000), and different parts of the plant may be influenced by specific or multiple stresses (Creed, 1997). Seagrass morphometry, biomass and density increase with depth (Magalhães *et al.*, 1997; Creed & Monteiro, 2000; Short *et al.*, 2006b). Leaf size may be influenced by hydrodynamics and light, although these do not influence leaf width (Creed & Monteiro, 2000). Changes in biomass may be related to variations in temperature (Corbisier, 1994; Oliveira *et al.*, 1997), yet in submerged plants, variations in salinity and temperature may not be sufficient to cause the variation patterns of this species along the Brazilian coast (Creed, 1997). Vegetative growth is seasonally regulated in *H. wrightii*. At the locations studied along the Brazilian east coast, these plants develop more during the dry season, with increased size and biomass (Corbisier, 1994; Creed, 1997; Magalhães *et al.*, 1997; Creed, 1999; Creed & Amado-Filho, 1999; Sordo *et al.*, 2011).

#### ***Halophila decipiens* Ostenfeld**

This species is usually associated with *H. wrightii*, and forms small patches where muddy sediment, fine mud or calcareous mud is dominant (Laborel-Deguen, 1963). It is found in extremely calm waters, more sheltered than areas where *H. wrightii* occurs. *H. decipiens* is always found submerged, yet displays a wide bathymetric distribution, at depths ranging from 30 cm to 40 m (Laborel-Deguen, 1963; Kempf, 1970), with dense patches in shallow areas (Laborel-Deguen, 1963).

Reproductive structures were found at the end of summer in Rio de Janeiro (Casares & Creed, 2008), and at least 20 seeds per fruit were recorded in beds of Pernambuco (Laborel-Deguen, 1963). Laboratory observation of germination showed that the shoots grow in just a few days and quickly cover the surface of the aquarium. The effect of tides, as well as annual tidal changes, may cause the disappearance of *H. decipiens* beds (Laborel-Deguen, 1963).

#### ***Ruppia maritima* Linnaeus**

This species can be found in estuarine and protected areas. In lagoon environments, *R. maritima* has been recorded in shallow areas with depths from 0.25 to 2.5 m (Coelho, 1965; Coutinho & Seeliger,

1984; Cafruni *et al.*, 1978), and on sand-mud or mud-sand bottoms (Cafruni *et al.*, 1978). Peaks of vegetative and reproductive biomass occur at the end of spring and the beginning of autumn in southern Brazil (Cafruni *et al.*, 1978). On the oriental northeastern coast of Brazil, however, reproductive and vegetative peaks were recorded during the rainy season, and only a few specimens were found during the summer. The increased biomass during the rainy season dies at the beginning of summer and becomes part of the lagoon bed (Coelho, 1965). On the coast of the semiarid northeast region, *R. maritima* also decreases in biomass and may disappear during the dry season (Siqueira *et al.*, 2011), in contrast to its cycle in southern Brazil (Cafruni *et al.*, 1978; Costa *et al.*, 1997; Silva & Asmus, 2001).

Biomass reduction may occur as a result of an increase in respiration rates, fruit formation, and removal of blades and stems. Rain and sediment erosion caused by a combination of wind, wave and current action end the life cycle of *Ruppia*, by removing the plants (Silva & Asmus, 2001). Changes in abundance, density and diversity may be associated with rainfall anomalies and extreme events such as storms and wind-generated waves. Strong river discharge and anomalous flows increase the turbidity and water level in an estuary, lowering the salinity and moving sediment from shallow areas (Müller-Júnior *et al.*, 2009). When water and sediment movement are moderate, other factors such as water level, water transparency, temperature and salinity affect the rates of growth, biomass, allocation of resources and production of flowers (Costa *et al.*, 1997). After germination and stem development, *R. maritima* grows rapidly and subsequently stabilizes (Silva & Asmus, 2001). Because of these interactions, the growth of the plants is concentrated in the spring and summer, with a decline of the meadows in the winter, as seen in Lagoa dos Patos, state of Rio Grande do Sul (Costa *et al.*, 1997). Decomposition may occur at pHs close to neutral (Siqueira *et al.*, 2011).

In Lagoa dos Patos, the maximum numbers of flowers and fruit occur in shallower depths, between 0.25 and 0.4 m. These structures are absent below 0.4 m, suggesting the importance of factors such as depth, transparency and light penetration for the allocation of resources in these plants (Costa & Seeliger, 1989). Additionally, *R. maritima* may increase leaf and shoot production under higher radiation (Colares & Seeliger, 2006). Epiphytes and floating algae may be considered intensifiers of the vegetative and reproductive cycles of these plants,

and there may be a synchrony between the growth of epiphytes and flowering (Silva & Asmus, 2001). Also in Lagoa dos Patos, larger biomass of *R. maritima* may be associated with more-stable salinity and/or less-intense urban or industrial influences (Müller-Júnior *et al.*, 2009).

Germination appears to be controlled by temperature and salinity, suggesting that this event varies according to latitude (Seeliger *et al.*, 1984). This phenomenon was associated with high temperatures, low salinities and desiccation, with a possible induction of seeds produced in previous years. Furthermore, temperatures lower than normal temperature may damage the seeds (Koch & Seeliger, 1988).

Although no specific studies have examined the effects of climate change on these species, these reactions are fundamental for predicting their responses to environmental changes.

### Associated Flora and Fauna

While exposed to environmental influences, seagrasses may also affect the structure of their associated flora and fauna. Some *Gracilaria* and other algal species, mainly rhodophytes, colonize openings in the meadows when the biomass of rhizomes is reduced (Silva *et al.*, 1987). Additionally, the biomass of some algae, such as *Caulerpa*, shows variations similar to the variation of the *H. wrightii* biomass, probably because both species are influenced by the same factors (Silva *et al.*, 1987). On the coast of Pernambuco, algal biomass was negatively correlated with precipitation rates and phosphate concentrations, and positively correlated with water temperature and salinity. Within the meadows, species of *Gracilaria* also vary according to seasonal changes, and are negatively influenced by the movement of sediment during the rainy season, which also may expose the rhizomes of *H. wrightii* and *Caulerpa* spp. (*cf.* Silva *et al.*, 1987).

In lagoon environments, winds, salinity and the presence of consolidated substrate have been indicated as important factors for the occurrence and distribution of algae in the meadows (Pedrini *et al.*, 1997). Tubular and filamentous species of green algae, including epiphytic algae, seem to be more resistant to variations in salinity than *R. maritima* (Pedrini *et al.*, 1997).

As well as the algae, the fauna also uses seagrasses as substrate and protection. Because they affect both the inside and outside of the sediment, seagrasses also

influence the spatiotemporal distribution of benthic macrofauna, even though environmental factors in general determine the distribution of this group in these ecosystems (Barros & Rocha-Barreira, 2009). Sediment type, which also influences the seagrasses, may influence the macrofauna even more than do variations in salinity and temperature (Corbisier, 1994). The meiofauna is concentrated in the upper centimeters of the sediment, and decreases with depth (Kapusta *et al.*, 2002).

Macrofauna within seagrass beds may be more diverse and denser than in adjacent, non-vegetated areas. Non-vegetated areas may contain a different array of species, which, although less diverse than in vegetated areas, nonetheless contribute to the diversity of the area (Corbisier, 1994; Casares & Creed, 2008; Rosa & Bemvenuti, 2007; Cruz-Neta & Henry-Silva, 2013). Some macrofauna groups, such as certain polychaetes, display a preference for non-vegetated areas (Corbisier, 1994).

The increased faunal density and diversity within the meadows compared to adjacent areas may also be associated with seasonal factors and not necessarily with differences between areas with or without seagrasses (Rosa & Bemvenuti, 2007). Nematodes, however, show no differences in vegetated and non-vegetated sediments, and may be more strongly influenced by the macrophyte architecture (Da Rocha *et al.*, 2006).

Physical factors may also significantly affect the fauna associated with seagrasses. Some organisms may benefit from the protection afforded by the seagrass, but may also be influenced by the same environmental factors that influence the plants, as discussed for the associated algae. Junqueira *et al.* (1997) observed that a population of *Lytechinus variegatus* (Lamarck, 1816) was vulnerable to the same factors that occasionally reduce the meadows, such as tidal currents, desiccation and high temperatures.

In a lagoon environment, crustaceans and fishes within and outside the meadows may display different responses to environmental factors such as depth, transparency, water temperature, and salinity, in accordance with the habits of each species. Low water transparency may be more important for protecting juveniles from predators than the presence of seagrasses (Garcia *et al.*, 1996; Garcia & Vieira, 1997).

The importance given to these ecosystems in the context of threatened species, such as the manatee and the green turtle, should also be extended to include the benthic micro- and macrofauna, because of their significant role in the transfer of energy

and in attracting visiting species, including species of economic value. Relationships among flora and seagrasses, visiting megafauna, and environmental factors may determine the permanence of the upper levels of the trophic chain, and therefore coastal productivity.

#### ***Possible preliminary records of climate change effects on seagrass meadows in the Brazilian coast***

In spite of the small number of reports on abiotic influences on seagrass meadows in Brazil and the few studies specifically on climate influences, some information related to possible influences of climate change can be highlighted. Formerly, the southernmost limit reported for *H. wrightii* on the Brazilian coast was the state of São Paulo (23° 30'S; 45° 7.4'W) (Oliveira-Filho *et al.*, 1983), but this seagrass has been recorded since 2004 in the state of Paraná (25° 20'S; 48° 20'W) (Sordo *et al.*, 2011), in southern Brazil, where the climate is subtropical. This expansion may be related to increased temperatures in southern Brazil.

In Tamandaré, in northeastern Brazil, *H. wrightii* meadows have decreased in biomass and density by 5% annually (Short *et al.*, 2006a, b). The authors related this decline to a 3°C increase over the historic mean temperature, which has altered the rainfall and storm patterns. This phenomenon also affected the hydrodynamics of the coastal zone, causing sediment transport and alterations in the area covered by the meadows, with a subsequent decline in seagrasses and fisheries, and leading to ecological and economic losses in the entire region (Short *et al.*, 2006b).

On the coast of semiarid northeastern Brazil, where rainfall has been below the historical mean in recent decades (Marengo, 2008; Marengo & Valverde, 2007), a reduction in coverage area and density of the *H. wrightii* bed at Fortaleza has been observed since 2006 (K. V. S Barros, personal observation). In this area, burnt leaves are also frequently observed during the dry season (Picanço, T.N.V; Barros, K.V.S. & Rocha-Barreira, C.A., non-published data), especially associated with exposure during low spring tides. In southern Brazil, the rainfall regime also causes significant changes in *R. maritima* meadows, since the freshwater discharge influences temperature, salinity and light attenuation, which regulate the distribution and abundance of this species in Lagoa dos Patos (Costa & Seeliger, 1998; Silva & Asmus, 2001). Therefore, expected alterations in rainfall patterns due to climate change

may cause major damage to the meadows in different ways, depending on the species and region.

Thus, some changes in the seagrass ecosystems because of climate alterations have been documented in Brazil. However, monitoring of these seagrass meadows is relatively recent and few sites were observed in past years, so that these data are only preliminary. In order to obtain further information and confirm these possible effects of climate influence, these meadows should be continuously monitored in coming years.

### Gaps in these Brazilian environmental studies

Few Brazilian studies recorded environmental influences on seagrasses, while most of such data are still detached from the life cycle of the species. Furthermore, the ecology of some Brazilian species such as *Halodule emarginata*, *Halophila bailonii* and *Halophila decipiens* is unknown. Thus, responses of these last species to local events and climate changes are difficult to predict, especially considering the several climates that influence the Brazilian coast. For other species, although the knowledge on environmental interactions is still incipient, useful ecological data related to climate change phenomena are available especially for *Halodule wrightii* in Northeastern Brazil (Short *et al.*, 2006a,b) and *Ruppia maritima* in Lagoa dos Patos (Odebrecht *et al.*, 2010).

Studies on environmental influences should follow a monitoring protocol in order to observe the climate effects along the coast, predict future effects of climate changes on these species, and consequently the ecological and economic implications for the coastal zone. At least two long-term monitoring programs are already in place along the Brazilian coast (SeagrassNet and Long-Term Ecological Research Network – PELD), but their scope is limited. Recently, a group of specialists all over the country had reviewed the knowledge gaps in order to start a new protocol in different parts of the coastline (Brazilian Monitoring Network for Benthic Habitats – ReBentos, related to the Brazilian Network for Climate Change – CLIMA).

Studies on seagrass carbon storage and sequestration, soil carbon stocks, effects of sea-level rise on the meadows and seagrass cover, essential to perform climate change predictions and to assess future losses, are still pending. Anthropogenic impacts on meadows also demands more attention, being fundamental for the implementation of

measures of protection and restoration of these environments. A specific legislation or the inclusion of these ecosystems into protected areas would have a fundamental role in the protection of their services for the coastal zone.

Currently, some groups are attempting to include seagrasses in existing protection programs. For Santos *et al.* (2011), megaherbivores conservation programs should also include the habitats where these species live. Pitanga *et al.* (2012) stated that the control of epiphyte, diversity and biomass, evaluation of water quality, sedimentation speed and the intensity of different impacts upon the meadows should be included in seagrass monitoring programs. For Björk *et al.* (2008), the protection and improvement of seagrass resilience is essential, as climate changes are inevitable. Management and monitoring are strongly recommended to ensure the survival of these plants.

However, conservation of these environments requires appropriate infrastructure. Duarte (2002) recommended a worldwide monitoring network using a quantitative model of responses to disturbances, along with an enhanced environmental education for coastal communities. Worldwide programs such as SeagrassNet and SeagrassWatch are good examples to be followed and, as mentioned above, at least two seagrass sites in Brazil are already monitored by the SeagrassNet Monitoring Program (Short *et al.*, 2006a,b).

As discussed above, there are significant knowledge gaps concerning important issues, especially related to climate change. Even though the participation on monitoring programs can help Brazilian scientists to address these issues, experimental projects and studies on total seagrass meadows extension need more attention.

### Possible influences of climate changes, mitigation measures and suggestions for monitoring

Although international research has focused on climate impacts, effective studies on seagrass meadows to assess the effects of climate change have yet to be conducted on the Brazilian coast. According to Short & Neckles (1999), the greatest impact of climate change on marine and estuarine seagrasses will be the redistribution of existing habitats and the relocation of species in order to continue developing within their tolerance zone, with other species possibly occupying their former habitats. Duarte *et al.* (2004) suggested that this redistribution may be even more

striking under oceanic circulation, since it may bring rapid changes in water temperature at the edges of the present bioregions. Distribution shifts to higher latitudes are expected for tropical and subtropical species (Duarte, 2002), such as the already observed expansion of *H. wrightii* into southern Brazil. This recent record could be explained by an increase in temperature due to systematic warming in southern Brazil between 1960 and 2002 (Marengo & Camargo, 2007). In this region, increased and decreased rainfall due to El Niño and La Niña events, respectively, may be harmful to the meadows of *R. maritima*. In Lagoa dos Patos, Odebrecht *et al.* (2010) reported that an El Niño event caused changes in estuarine water and sediment dynamics as well as physical and chemical water characteristics, drastically reducing the amount of this seagrass on the lagoon floor due to the increased shoreline erosion and reduced incidence of light on the bottom caused by high water levels. This produced changes in the species composition, abundance, and biomass of microalgae, macrobenthic fauna and flora, and fish assemblages, rather than local impacts such as pollution, dredging, and fisheries in the estuary.

Climate alterations with increases in rainfall and storms on the Pernambuco coast also caused reduction in biomass and density of *H. wrightii* meadows (Short *et al.*, 2006a, b). In the municipality of Fortaleza on the semiarid northeast coast, the decrease in rainfall since the 1970s in comparison with previous decades (Marengo & Valverde, 2007) may have caused reductions in the distribution area and density of *H. wrightii*. According to Rebouças (2004), climate change will decrease precipitation in regions where water is now scarce, such as the semiarid northeast. Specifically, global warming will affect the most important influence on rainfall on this coast, modifying the latitudinal positioning of the Inter-Tropical Convergence Zone – ITCZ (Marengo, 2006). Thus, intensification of the already long dry season (Aw climate, according to the Köppen classification) is predicted, which is even more harmful for seagrass ecosystems. In addition, wind velocity, which is an important factor in completing the life cycle of seagrasses (by dislodging the oldest leaves), may increase up to 20% by the year 2100 off the coast of northeastern Brazil (Lucena *et al.*, 2010), with an intensification of more than 100%, mainly in the northern sector of this region (Pereira *et al.*, 2013) where Fortaleza is located.

Burnt leaves observed in the meadow at Fortaleza, especially during dry seasons, probably

result from exposure to the air and intense irradiance levels. According to Erfteimeijer & Herman (1994), when a low spring tide occurs at midday, seagrass beds exposed to sunlight and air may suffer from desiccation or “burning” of their leaves, with deleterious effects. Waycott *et al.* (2007) added that this occurs in locations where temperatures reach 10°C above the seasonal average during this period of exposure (in relation to submersed conditions). Also according to these authors, these conditions subject seagrasses to extreme conditions, causing irreparable damage to their abundance and photosynthesis in the short term, or episodic changes, similar to what may be happening to the Fortaleza seagrass bed. Global warming, with reductions in rainfall and cloud cover, among other factors, may intensify this process in meadows exposed at low tide, and decimate those that already present burning.

In addition to these preliminary observations on tropical species in Brazil, declines in meadows in temperate regions associated with climate change have also been recorded, such as *Zostera marina* in New Hampshire (USA), which has undergone a reduction of 9% per year in meadow coverage, biomass and density (Short *et al.* 2006a, b). Díaz-Almela *et al.* (2009) associated a decline of *Posidonia oceanica* (L.) meadows with the decade-long warming trend in the Mediterranean Sea. On the western Spanish coast, Díaz-Almela (2007) observed that meadows of *P. oceanica* are regressing due to both climate change and anthropogenic pressure. In an experimental study, Shaffer *et al.* (2008) observed that temperature is likely an important factor affecting the distribution of *Zostera japonica* Asch. & Graebn., and recorded significant declines in leaf elongation, growth and areal productivity at 30°C. In other parts of the world, irreversible losses are occurring, with meadow declines generally attributed to eutrophication (Short & Wyllie-Echevarria, 1996; Hemminga & Duarte, 2000; Burkholder, 2007). However, the causes of declines in these last areas require further investigation, taking into account the already proven negative effect of climate change on some meadows.

Among the genera occurring along the Brazilian coast, *Halodule* and *Halophila* may be better adapted to warming effects, as they include “pioneering” species that show rapid recovery due to their rapid vegetative growth and new shoot production with little carbon storage (Björk *et al.*, 2008). According to Short *et al.* (2007), the majority of species belonging to these genera are found in almost every bioregion

of the world, including *H. wrightii*, which occurs in almost all seagrass bioregions except in the coldest areas of the planet. As such, species of *Halodule* and *Halophila* may have potential for future restoration of areas suffering significant seagrass losses as a result of global warming. However, a complete understanding of all environmental influences on the reproductive and vegetative behavior of these species is needed.

With or without a long-term monitoring program, complementary studies on environmental influences on Brazilian species are needed and can be easily conducted. Considering the climate-change scenario, recording of meteorological factors, temperature and salinity, which can be quickly and easily obtained, is recommended. In addition to climate influences on the decline of seagrass meadows in Brazil (Short *et al.*, 2006a, b; Odebrecht *et al.*, 2007), the sustainability of these meadows depends on their ability to withstand shifts in salinity and chronic exposure to ocean temperature increases resulting from climate change (Short & Neckles, 1999). Some studies have shown that temperature may affect a number of vital processes in seagrasses (Bulthuis, 1983; Masini *et al.*, 1995; Short & Neckles, 1999; Koch *et al.*, 2007a), although salinity has less influence on tropical seagrasses (Koch *et al.*, 2007b). Monitoring of these factors may assist with prediction and mitigation.

Because some tropical species display a higher tolerance to global warming, and taking into account the pace of global climate change, there is an urgent need for studies on the relationships between tropical species and the environment, including specific studies on reproduction, laboratory experiments and transplantation, which may be an alternative for the restoration of damaged areas. Laborel-Deguen (1963) obtained excellent development of *H. wrightii* under laboratory conditions. Other investigators have observed that transplanted *Z. marina* and *H. wrightii* meadows may attract permanent and visiting fauna in abundances equal to or higher than those of adjacent natural meadows. According to these authors, the fauna reestablishes itself after a period of 2 to 3 years, but satisfactory results can be achieved by about one year after transplantation (*cf.* Fonseca *et al.*, 1990; Bell *et al.*, 1993; Fonseca *et al.*, 1996; Christensen *et al.*, 2004). In Galveston Bay, Texas (USA), this process was tested between 1975 and 1982 in order to restore meadows lost or damaged due to natural causes (Galveston Bay National Estuary Plan, 1995). Therefore, transplantation can be considered a viable

option for restoring the productivity of damaged meadows. However, Christensen *et al.* (2004) warned that environmental requirements and other features of the seagrass species should be considered before any large-scale restoration project is implemented.

Besides being an indicator of climate change on the Brazilian coast, *H. wrightii* can be considered one of the most resistant species to global warming (Björk *et al.*, 2008), considering that it can remain within its tolerance zone (Short & Neckles, 1999) in higher latitudes, after the predicted increase in global temperature. As a result of these features and since it is present in almost all seagrass bioregions (*cf.* Short *et al.*, 2007), this species can be considered an important subject for study, not only for diagnoses of climate-related changes, but also for restoration of damaged meadows. The widespread distribution of *H. wrightii* in almost all continents and at diverse latitudes allows studies to be conducted under the most diverse environmental conditions.

Overall, further studies should focus on understanding the environmental influences on vegetative and reproductive cycles of the species, and also on the associated biota along the entire tropical coast, aiming to mitigate future problems related to small environmental changes or even global climate change. The expected redistribution of the species, conservation strategies and transplantation will be fundamental to avoid losses of meadows, of species that are ecologically dependent on these ecosystems, and of other ecological and economic benefits arising from these habitats.

## FINAL CONSIDERATIONS

Specific information on the distribution, physiology, sexual reproduction and ecological information of *Halodule emarginata*, *Halophila baillonii* and *Halophila decipiens* is lacking. Information on the ecology of *Ruppia maritima* and *Halodule wrightii* is available, but their physiology needs to be explored. Climate and geographical location must also be considered, as these species occur in both tropical and subtropical areas.

According to the articles reviewed here, the southward extension of the distribution of *Halodule wrightii* and the reductions of meadows in northeastern Brazil might be considered possible indicators of climate change in this country. However, specific articles observing the effects of climate change are still rare, and knowledge of seagrasses on the Brazilian coast needs to be expanded, not only

on the species' ecology but also within the context of climate change. Programs such as SeagrassNet and ReBentos are extremely important for obtaining this information in Brazil.

Additionally, taking into account that the genera *Halodule* and *Halophila* may be able to adapt to changes brought about by global warming, research on the life cycles of these species and their abiotic interactions is required. This knowledge may help to mitigate the effects of climate phenomena or even local events, as these species may be important tools for the restoration of damaged areas. Although data are available on the environmental interactions of some seagrass species, this knowledge is still preliminary.

### ACKNOWLEDGEMENTS

The first author would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes) for her doctoral scholarship. The authors would also like to thank Evamaria Koch for suggestion of the manuscript title; anonymous reviewers and Lezilda Torgan for their contribution.

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**Table 1.** Articles on Brazilian seagrasses published in indexed journals, arranged by subject, until June 2013.

Taxonomy <sup>1</sup> , ecology and biodiversity <sup>2</sup>	Species ecology	Associated biota		Feeding habitats	Anthropogenic <sup>3</sup> , extreme climate influence <sup>4</sup>	Revision <sup>5</sup> , pharmacology <sup>6</sup>
Andrade-Lima (1957) <sup>2</sup>	Seeliger <i>et al.</i> (1984)	D'Incao (1982)	Creed (2000)	Ferreira (1968)	Lacerda & Resende (1986) <sup>3</sup>	Filgueiras & Peixoto (2002) <sup>5</sup>
Laborel-Deguen (1963) <sup>2</sup>	Koch & Seeliger (1988)	Coutinho & Seeliger (1984)	Schwaborn <i>et al.</i> (2001)	Banks & Albuquerque-Neto (1985)	Creed & Amado-Filho (1999) <sup>3</sup>	Couto <i>et al.</i> (2003) <sup>5</sup>
Kempf (1970) <sup>2</sup>	Costa & Seeliger (1989)	Ferreira & Seeliger (1985)	Carvalho & Ventura (2002)	Oliveira (1991)	Amado-Filho <i>et al.</i> (2004) <sup>3</sup>	Magalhães & Cazuza (2005) <sup>5</sup>
Den Hartog (1970a) <sup>1</sup>	Costa <i>et al.</i> (1997)	Pedini & Silveira (1985)	Paula <i>et al.</i> (2003)	Creed (2004)	Amado-Filho <i>et al.</i> (2008) <sup>3</sup>	Figueiredo <i>et al.</i> (2008) <sup>5</sup>
Den Hartog (1970b) <sup>1</sup>	Creed (1997)	(1985)	Omena & Creed (2004)	Garcia <i>et al.</i> (2005)	Short <i>et al.</i> (2006a) <sup>4</sup>	Marques & Creed (2008) <sup>5</sup>
Den Hartog (1972) <sup>1</sup>	Magalhães <i>et al.</i> (1997)	Silva <i>et al.</i> (1987)	Esteves <i>et al.</i> (2005)	Ferreira & Gonçalves (2006)	Short <i>et al.</i> (2006b) <sup>4</sup>	Santos <i>et al.</i> (2011) <sup>5</sup>
Cafruni <i>et al.</i> (1978) <sup>2</sup>	(1997)	Pacobahyba <i>et al.</i> (1993)	Da Rocha <i>et al.</i> (2006)	Oliveira <i>et al.</i> (2006)	Pitanga <i>et al.</i> (2012) <sup>3</sup>	Silva <i>et al.</i> (2012) <sup>6</sup>
Lipkin (1980) <sup>1</sup>	Oliveira <i>et al.</i> (1997)	Corbisier (1994)	Melo-Júnior <i>et al.</i> (2007)	Vasconcelos-Filho <i>et al.</i> (2009)		
Oliveira-Filho <i>et al.</i> (1983) <sup>1</sup>	(1997)	Garcia <i>et al.</i> (1996)	Rosa & Bemvenuti (2007)	Guebert-Bartholo <i>et al.</i> (2011)		
Silva & Asmus (2001) <sup>2</sup>	Creed (1999)	Garcia & Vieira (1997)	Casares & Creed (2008)	Lima <i>et al.</i> (2011)		
Giulietti <i>et al.</i> (2005) <sup>2</sup>	Creed & Monteiro (2000)	Junqueira <i>et al.</i> (1997)	Barros & Rocha-Barreira (2009)	Silva <i>et al.</i> (2011)		
Amaral <i>et al.</i> (2010) <sup>2</sup>	Colares & Seeliger (2006)	Pedini <i>et al.</i> (1997)	Lima & Fernandes (2009)	Alves <i>et al.</i> (2013)		
Moura-Júnior <i>et al.</i> (2013) <sup>2</sup>	Barbosa <i>et al.</i> (2008)	Amado-filho & Pfeiffer (1998)	Müller-Júnior <i>et al.</i> (2009)			
	Marins <i>et al.</i> (2008)	Wandeness <i>et al.</i> (1998)	Pereira <i>et al.</i> (2010)			
	Sordo <i>et al.</i> (2011)	Alves & Araújo (1999)	Creed & Kinupp (2011)			