Title

Ric DeSantiago1,2,3 Rosa Rodriguez Martinez, Gerardo Castaneda, Aurora Veltran, David Lipson,1 and Jeremy D. Long1,2

1 Department of Biology, San Diego State University, San Diego, CA 98182 USA

2 Coastal and Marine Institute, San Diego State University, San Diego, CA 92106 USA

3 Department of Environmental Science and Policy, University of California Davis, Davis, CA 95616 USA

4 Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, Puerto Morelos, Quintana Roo, México

5 Moon Palace

6 Botanical garden / ECOSUR

Introduction

Macroalgae blooms have increased worldwide, presenting challenges to economies and threatening biodiversity across multiple countries (Lapointe 1997, Teichberg et al. 2010, Smetacek and Zingone 2013, Rodríguez-Martínez et al. 2023). Population growth and urbanization has resulted in escalated nutrient inputs into coastal waters, consequently amplifying eutrophication leading to macroalgae blooms (Teichberg et al. 2010). Beach-cast macroalgae that accumulate along shorelines and can obliterate coastal life by creating anoxic conditions, shading benthic taxa, and changing water chemistry (Hauxwell et al. 2001, Teichberg et al. 2010, Van Tussenbroek et al. 2017, Rodríguez-Martínez et al. 2019). Furthermore, macroalgae blooms can clog fishing nets, impede the passage of boats, and produce foul odors that can be a nuisance and may contribute to human health issues from hydrogen sulfide inhalation when left to decompose on the shore (Teichberg et al. 2010, Smetacek and Zingone 2013, Resiere et al. 2021, Rodríguez-Martínez et al. 2023). However, we still lack a full understanding of the impacts of the decomposing biomass on the ecology of locations where it is discarded after it is removed from beaches. Here, we look at the impacts of macroalgae decomposition on beaches and nearby forests dump sites using manipulative experiments to assess responses by flora and fauna in recipient habitats.

Since 2011, the shores of West Africa, Caribbean islands, and the Gulf of Mexico have experienced unusually elevated quantities of *Sargassum spp.* biomass (*S. fluitans and S. natans*; hereafter referred to as Sargasso; Gower et al. 2013, Rodríguez-Martínez et al. 2020, Chávez et al. 2020). Floating aggregations of Sargasso form extensive patches across the tropical and subtropical North Atlantic (Brooks et al. 2018), a phenomenon observed since the early 1800s (Uribe-Martínez et al. 2022), but massive beach landings are a relatively new occurrence. Both Sargasso species are holopelagic, lacking an attached benthic stage in their life cycle and reproducing vegetatively through fragmentation in the open ocean (Brooks et al. 2018, Uribe-Martínez et al. 2022). Consequently, Sargasso patches can attain sizes of up to 3000 km², with a biomass exceeding 20 million tons in the North Equatorial Recirculating Region of the southern Atlantic Ocean (Chávez et al., 2020, and references therein).

Sargasso has become the largest macroalgae bloom globally, with Mexico ranking among the countries most affected by beaching events (Torres-Conde et al. 2023). The northern sector of the Mexican Caribbean is estimated to receive annual volumes ranging from 10,790 to 40,932 m³ of biomass per kilometer of beach (Rodríguez-Martínez et al., 2023). Like other algae blooms, heightened nutrient loads resulting from deforestation and land-use changes (Wang et al. 2019), escalating oceanic temperatures(Wang et al. 2019, Johns et al. 2020), evolving upwelling patterns along the northeastern African coast (Wang et al. 2019), and mineral inputs from Saharan dust (Johnson et al. 2012), have all been associated with increases of Sargasso (Chávez et al. 2020). Anticipated shifts in climate and eutrophication suggest that these blooms will likely increase in frequency and magnitude (Smetacek and Zingone 2013, Rodríguez-Martínez et al. 2023).

Recent studies have elucidated the potential repercussions of Sargasso beaching events on the tourist industry (Vázquez-Delfín et al., 2021). Much of the Mexican Caribbean is characterized by pristine white-sand beaches, turquoise waters, rich biodiversity, and culture, making the region a hub for tourism (Rodríguez-Martínez et al., 2023). In 2021, the state of Quintana Roo attracted nearly 15 million tourists, generating an income of approximately US$10.8 billion (Rodríguez-Martínez et al., 2023). However, given the region's heavy reliance on the tourism industry, the removal of Sargasso has been imperative to maintaining the economy. Furthermore, it is evident that recipient coastlines have a limited capacity to naturally assimilate current influx magnitudes of Sargasso through natural processes.

Seasonal or periodic landings of macroalgae typically confer benefits to beaches by serving as a foundation for, contributing to the fertilization of coastal dunes, and serve as a resource subsidy to food webs (Polis et al. 1997, Huxel and McCann 1998, Anderson and Polis 1998, Marczak et al. 2007, Yang et al. 2010, Spiller et al. 2010, Williams and Feagin 2010, Wright et al. 2013, Piovia-Scott et al. 2013). Beach dunes reinforced by beach-cast macroalgae play a crucial role in mitigating erosion and enhancing the resilience of coastlines against storm-driven wave action and sea-level rise (Williams and Feagin 2010, Bauer et al. 2023). Furthermore, Sargasso landings can provide a temporary food resource for detritivores and their predators (Spiller et al. 2010, Piovia-Scott et al. 2011, Wright et al. 2013, Kenny et al. 2017) and fertilize plants (Spiller et al. 2010, Piovia-Scott et al. 2013). However, previous studies about the impacts of Sargasso landings used quantities similar to natural deposits prior to current massive blooms. It is likely that some of advantages for recipient beaches are likely lost given the substantial scale of current Sargasso landings.

Without removal of Sargasso biomass from beaches, leachates and organic matter resulting from decomposition induce a reduction in oxygen and pH levels, alongside increased turbidity, sulfur, and ammonia concentrations in coastal waters (Van Tussenbroek et al. 2017, Chávez et al. 2020, Rodríguez-Martínez et al. 2023). For instance, a significant Sargasso beaching event in 2018 was associated with a faunal mortality event, where hypoxic conditions led to the demise of 78 species of neritic fish, crustaceans, echinoderms, mollusks, and polychaetes (Rodríguez-Martínez et al. 2019). Due to the various adverse effects of Sargasso decomposition on the coast, much of the biomass is moved to quarries, garbage dumps, and forest habitats. To this day, we lack an understanding of the ecological impacts of massive Sargasso dumping in these ecosystems.

Ecological theory suggests that local adaptation through coevolution would result in faster decomposition of litter on its own soil over foreign soil, a termed ‘*the home field advantage’* (Bocock et al. 1960, Gholz et al. 2000, Pugnaire et al. 2023). Thus beach-cast Sargasso should decompose more quickly over sand dunes than forest soil. Furthermore, terrestrial predator foraging in beach-cast macroalgae is a common feature in coastal ecosystems (Kirkman and Kendrick 1997, Rose and Polis 1998, Dugan et al. 2003, Colombini and Chelazzi 2003, Kenny et al. 2017), but less is known about terrestrial insect responses to this phenomenon. To our knowledge, this has not been tested with macroalgae deposits in forests. Moreover, previous work with Sargasso biomass showed a fertilization effect on plants on shorelines Bahamian islands and there have been efforts to use Sargasso as a fertilizer for vascular plants. Yet, the fertilization effect of Sargasso in forest has not been tested.

Here, we used manipulative experiments and surveys to test the effects macroalgae deposits on a beach and in a forest. To do this, we created Sargasso piles of realistic magnitudes with paired, unmanipulated controls, at both sites, and surveyed them over the course of a year. We estimated volume over time and sampled CO2 production, nitrate, and ammonium content on sediment below the piles. To test arthropod response, we used sticky traps and pitfall traps to measure flying and crawling abundance on piles and controls. We also conducted point intersect surveys to understand the impacts of this manipulation on plant abundance on plots proper and their perimeter. Furthermore, we measured decomposition of Sargasso at both sites using mesh bags to compare changes in biomass with and without access to arthropods.

Discussion

* Paragraph 1: Summarize results
* Paragraph 2: Caveats with fertilization
  + Only saw strong impacts on grass at the beach
    - Non-native Bermuda grass
    - Pioneer species, may see impact on other plants given enough time
* Current efforts to use algae in different way
  + No one solution is currently feasible so many grassroots efforts underway

**Figure legends**

**Figure 1**

Sargasso pile volume loss over sampling periods (August and November 2022, March and August 2023) as a percent (%) of original volume calculated for sargasso treatments in August 2022. Individual dots represent replicates at the beach (black) and the forest (white).

**Figure 2**

Percent decomposition of initial dry mass of large (gray bars) and small (white bars) mesh bags at beach (left column) and the forest (right column) in November 2022 (A) and March 2023 (B). Error bars represent mean ± SE. Note that no values are reported for large mesh bags at the beach in March 2022 due to vandalism, the lack of a bar does not indicate zero decomposition.

**Figure 3**

Nitrate content (mg/L) over sampling periods (August and November 2022, March and August 2023) by site (beach A,C and forest B,D). Nitrate content in the top panels (A,B) were extracted from tissue in sargasso plots (gray bars) and nitrate content in the bottom panels (C,D) were extracted from sediment in sargasso and control (black bars) treatments. Error bars represent mean ± SE. Note that control plots did not produce measurable levels of nitrates, thus, they are shown as solid black lines rather than bars.

**Figure 4**

Grams of CO2 per m2 over an hour in control and sargasso plots at the beach (A) and forest (B) from samples collected with ‘gas collectors’ November 2022. Respirometer CO2 (units) readings from beach (C) and forest (D) control and sargasso plot centers (gray bars) and edges (white bars) in August 2023. Error bars represent mean ± SE.

**Figure 5**

Mean percent cover of plot interiors over sampling period (August and November 2022, March and August 2023) at the beach (A) and forest (B). Shapes represent grass (▲) and other plants (●) and colors represent control plots (gray) and sargasso plots (black). Error bars represent mean ± SE. Lower panels show the effect sizes by sampling period associated with the panel above (i.e., panel C effect sizes associated with panel A, and panel D effect sizes are associated panel B). Effect sizes were calculated using Cohen’s d (sargasso vs. control) for grass (▲) and other plants (●).

**Figure 6**

Mean percent cover of plot perimeter over sampling period (August and November 2022, March and August 2023) at the beach (A) and forest (B). Shapes represent grass (▲) and other plants (●) and colors represent control plots (gray) and sargasso plots (black). Error bars represent mean ± SE. Lower panels show the effect sizes by sampling period associated with the panel above (i.e., panel C effect sizes associated with panel A, and panel D effect sizes are associated panel B). Effect sizes were calculated using Cohen’s d (sargasso vs. control) for grass (▲) and other plants (●).

**Figure 7**

Mean crawling arthropod abundance in pitfall traps over sampling period (August and November 2022, and August 2023) in the beach (left column, panels A, C, E) and the forest (right column, panels B, D, F). Arthropod abundances are separated by controls (A, B) and sargasso (C, D). Effect size plots are associated with plots above (i.e., panel E effect sizes are associated with panels A and C, panel F effect sizes are associated with panels B and D). Effect sizes were calculated using Cohen’s d (sargasso vs. control). Shapes represent Amphipoda (●), Arachnida (▲), and Hymenoptera (■) and error bars represent mean ± SE.

**Figure 8**

Mean flying arthropod abundance in pitfall traps over sampling period (August and November 2022, and August 2023) in the beach (left column, panels A, C, E) and the forest (right column, panels B, D, F). Arthropod abundances are separated by controls (A, B) and sargasso (C, D). Effect size plots are associated with plots above (i.e., panel E effect sizes are associated with panels A and C, panel F effect sizes are associated with panels B and D). Effect sizes were calculated using Cohen’s d (sargasso vs. control). Shapes represent Amphipoda (●), Arachnida (▲), and Hymenoptera (■) and error bars represent mean ± SE.

**Supplementary Figure 1**

Percent cover of grass (light gray bars) and other plants (dark gray bars) over sampling periods (August 2022, November 2022, and March 2023). Sargasso treatment panels (A) include beach (left column) and forest (right column). Control treatment panels (B) include beach (left column) and forest (right column). Panel rows indicate distance from treatment plots (0m, 0.75m, and 1.5m). Error bars represent mean ± SE.

**Supplementary Figure 2**

Proportion of cover categories in plot interiors over sampling periods 1 (August 2022), 2 (November 2022), 3 (March 2023), and 4 (August 2023) in the beach site. Columns designate treatment type (left is control and right is sargasso) and rows represent treatment block.

**Supplementary Figure 3**

Proportion of cover categories in plot interiors over sampling periods 1 (August 2022), 2 (November 2022), 3 (March 2023), and 4 (August 2023) in the forest site. Columns designate treatment type (left is control and right is sargasso) and rows represent treatment block.

**Supplementary Figure 4**

Proportion of cover categories in plot perimeter over sampling periods 1 (August 2022), 2 (November 2022), 3 (March 2023), and 4 (August 2023) in the beach site. Columns designate treatment type (left is control and right is sargasso) and rows represent treatment block.

**Supplementary Figure 5**

Proportion of cover categories in plot perimeter over sampling periods 1 (August 2022), 2 (November 2022), 3 (March 2023), and 4 (August 2023) in the forest site. Columns designate treatment type (left is control and right is sargasso) and rows represent treatment block.

**Figures**

Figure 2. Mesh bag decomposition

A graph of different sizes of trees

Description automatically generated

Figure 3. Mesh bag arthropod counts

A group of white rectangular objects with black text

Description automatically generated

Figure 4. Nitrate content (g

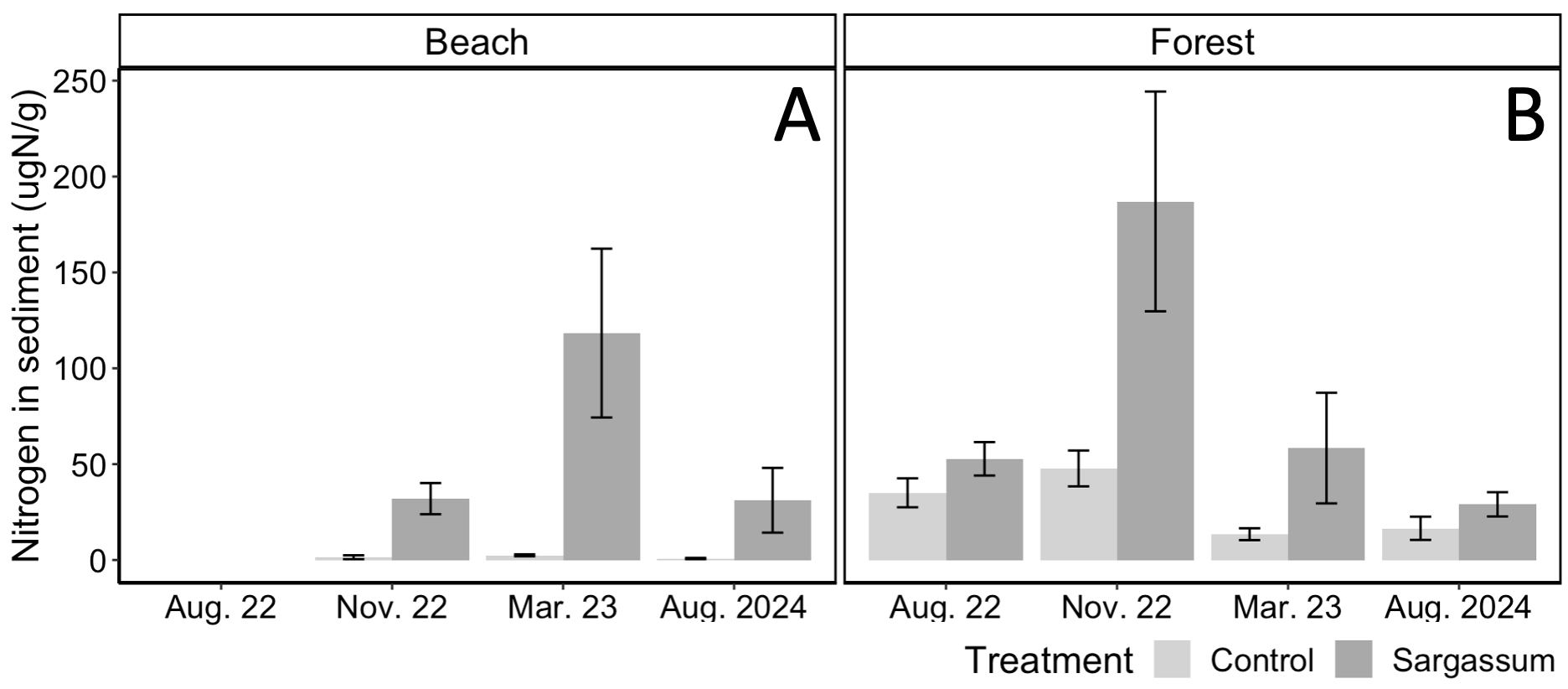
****

Figure 4. Soil respiration

A graph of different types of plants

Description automatically generated with medium confidence

Figure 5. Plot interior percent cover and effect sizes

A graph of different types of data

Description automatically generated with medium confidence

Figure 6. Plot perimeter percent cover and effect sizes

A graph of different types of data

Description automatically generated with medium confidence

Figure 7. Crawling arthropod counts and effect sizes

A graph of different types of growth

Description automatically generated with medium confidence

Figure 8. Flying arthropod abundance and effect sizes

A graph of different sizes and numbers

Description automatically generated with medium confidence

**Supplementary**

Figure 1. Plant percent cover from edges of sargasso piles

**A graph of different sizes and colors

Description automatically generated with medium confidence**

Figure 2. Plot interior percent cover categories (beach)

A chart of different colored squares

Description automatically generated

Figure 3. Plot interior percent cover categories (forest)

A chart with different colored squares

Description automatically generated

Figure 4. Plot perimeter percent cover categories (beach)

A chart of different colored squares

Description automatically generated

Figure 5. Plot perimeter percent cover categories (forest)

A chart with different colored squares

Description automatically generated