SeaweedPaddock: Initial Modeling and Design for a *Sargassum* Ranch

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***Abstract*—This paper describes the "SeaweedPaddock" system to profitably grow and harvest open-ocean *Sargassum sp.* as a sustainable source of macroalgal biomass and biofuel. The US Department of Energy Advanced Research Projects Agency - Energy (ARPA-E) initiated the MacroAlgae Research Inspiring Novel Energy Research (MARINER) program to develop technologies to eventually sustainably harvest macroalgae at $80 per dry metric ton (DMT). The University of Southern Mississippi team is characterizing an unmoored SeaweedPaddock; analyses include tow speed and energy required to avoid hazards, farm design to minimize biomass loss, economical harvesting, and nutrient supply. Initial results indicate that nighttime "smart towing" could allow the SeaweedPaddock system to produce macroalgae at full scale at costs below the ARPA-E goal provided that *Sargassum* grows at sufficient rates during the day after having been confined all night in a moving fence and that sufficient nutrients are made available. Cost projections for a successful, intensive, scaled system could be competitive with current prices for fossil fuels.**

Keywords*—Sargassum; fluitans; natans; aquaculture; biofuel; unmoored; HYCOM; seaweed; cattle feed

I. INTRODUCTION

Since at least the 1970s *Sargassum fluitans* and *natans* (hereafter referred to as *Sargassum*) have been recognized as a potential source for industrial conversion [1] and specifically for biofuels by the mid 1980s [2]. These species naturally cohabit the North Atlantic and Caribbean and are unique among macroalgae in that they spend their entire life-cycle floating unattached in the open ocean [3]. *Sargassum* forms the basis of complex communities [4] with some assemblages forming low-density mats hundreds of square kilometers in size. Most often *Sargassum* is present as small windrows consisting of tens to hundreds of individual plants. Certain epiphytes have formed symbiotic relationships with the *Sargassum* so that an estimated 40% of the plant's nitrate (N) is supplied from the atmosphere [5]. Although animals attracted to the *Sargassum* release nitrogen, principally in the form of ammonia, and phosphorus (P), as soluble reactive phosphorus, to the algal communities through their excreta, growth is often limited by nutrient availability, especially P [6][7].

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Many nations have reported inundations of *Sargassum* indicating its significant biomass yield [8]. *Sargassum* communities thrive away from shore in standard 35-ppt salinity and often congregating in gyres. These communities are nurseries and hunting grounds for many endangered and commercially valuable animals [4].

SeaweedPaddock's purpose is to unlock the potential of *Sargassum* for economical biofuels as well as for livestock feed and chemical production through a coordinated movement of semi-autonomous, remotely monitored drone-tugs ("shepherds") that have a SeaFence strung between them (Fig. 1). It is unmoored, drifting in the day to maximize paddock area to disperse *Sargassum* to promote growth. At night, it is linearly reconfigured for ease of towing. This way, the SeaweedPaddock can manoeuvre to avoid storms, obstacles, shore wash-up, or areas inhabited by wild assemblages of *Sargassum*.

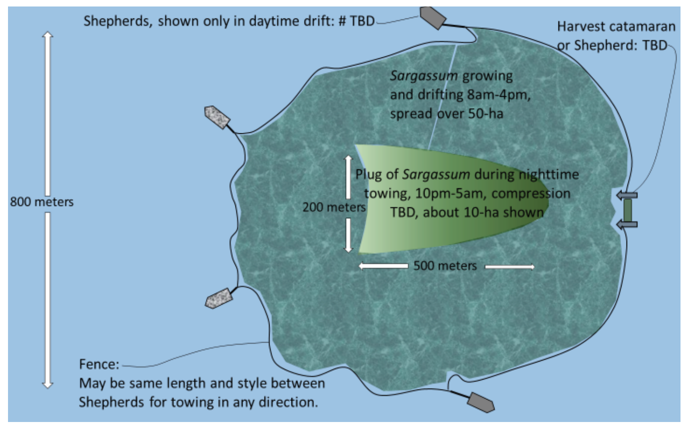

Fig. 1. Simplified conceptual SeaweedPaddock with possible dimensions for daytime drifting and night-time towing with 5:1 compression size shown in green. The fence and shepherds are shown only in their daytime drift positions.

Although about three million DMT of seaweed are annually harvested globally [9], so far it has been too expensive to generate biofuels due to high infrastructure costs, labor intensity, and limited automation. Further, most seaweeds have complicated life cycles requiring a hatchery phase. SeaweedPaddock trades these traditional challenges for others: There is no need for a hatchery phase and free-floating *Sargassum* means that vast areas of open ocean can be used to convert sunlight into biomass. However, this requires long-distance communication and an economical method to transport the bulk material back to shore. Further, much of the area native to *Sargassum* mats is subject to hurricanes. Unmoored structures such as the Seaweed Paddock can experience less extreme loading than moored structures since relative water motion (and resultant hydrodynamic forces) over the entire structure reaches maximum at the tow speed, rather than the extreme surface current speed. During drift the system will experience only marginal relative currents. The mechanical effects of wear on the structure in high sea states are difficult to estimate; however, the plan is for the SeaweedPaddock to use tugs to escape the worst storms.

II. MODELING

SeaweedPaddock's testing ground is the Gulf of Mexico (GoM), which has significant stakeholder involvement and contains hundreds of offshore structures. Conditions change throughout the year. Feasibility for a farm is predicated on the benefits outweighing the costs and risks. This involves quantifying the base-line forces acting on a SeaweedPaddock and potential biomass generation.

A. Initial Drift and Tow Analysis

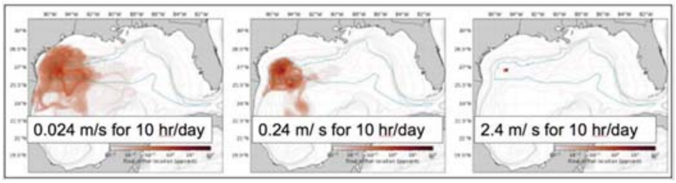

Fig. 2. Simulations of 40,000 particles released at an initial location (red dot in the right panel) and run forward in time for 30 days subjected to GoM currents resisted at towing speeds of 0.024, 0.24, and 2.4 m/s for ten hours each day.

An initial Drift-Tow Model by Kristen Thyng and Robert Hetland [10] calculated tow speeds needed to maintain position against normal currents. Fig. 2 shows 40,000 particles released at the same initial location and run for 30 days using 2012 velocity fields from HYCOM. Particles were subjected to forces to simulate being towed back toward the initial location at three speeds. The right panel used a speed of 2.4 m/s (4.7 knots) for 10 hr/day, which was needed to maintain the particles at their initial location. Otherwise the particles spread out over hundreds of km, as shown in the left two panels.

However, the team believes that "smart towing" could drift with the current at certain times, and tow when needed, greatly reducing required tow speeds, time, and commensurate fuel consumption (escaping a hurricane may require round-the-clock towing.)

B. Nutrient Analysis of Sargassum Biomass Potential in the GoM

The principal growth limitation factors include nutrients, light, temperature, and salinity. The maximum growth rate with optimal nutrients observed by Carpenter and Cox [11] was a doubling rate of 0.109/day for *S. fluitans* and 0.073 for *S. natans.* See literature survey [12] and summary [13] by Scott James.

However, growth rates in neritic (open ocean) waters tend to be lower. The team is preparing a model to estimate growth rates throughout the GoM.

Another factor is the impact on growth of natural movement of *Sargassum* throughout the GoM. Maureen Brooks produced a simulation movie [14], which shows a full year of HYCOM model results based on 7,300 particles (representing 20 *Sargassum* plants per day) released randomly throughout the GoM. Running the model for six different years, the 95^{th} percentile for calculated biomass was identified and used to normalize the results. Monthly satellite data for maximum chlorophyll index (ranging from 0 to 1) on 5×5-km^2 pixels throughout the GoM were used to build confidence in the model and to ensure that *Sargassum* growth estimates were realistic (in accord with satellite data from Gower and King [15]).

III. OCEAN RANCH DESIGN

The central requirements of a SeaweedPaddock are that: (1) it contain *Sargassum* within the SeaFence under tow, (2) it has enough towing power to avoid obstacles and storms, (3) the *Sargassum* inside the paddock grows sufficiently to produce significant biomass, (4) harvesting and regular operations do not yield significant by-catch, (5) it can be permitted as a remotely piloted vessel, and (6) after towing all night at 0.5 m/sec (1 knot), the *Sargassum* is not too compacted to prevent it from drifting apart and growing at a commercially viable rate during the day.

A. Towing

For modelling and technoeconomic analyses, the team is considering towing by diesel electric drone tugs developed by C.A. Goudey & Associates, a fellow MARINER awardee (Fig. 3), and/or those operated by ASV Global[1].

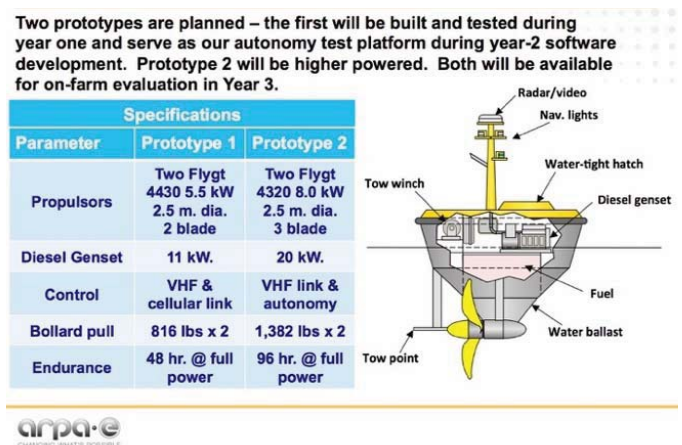

Fig. 3. Side view of C.A. Goudey & Associates' proposed drone tug.

[1] For more information, see https://www.asvglobal.com

B. SeaFence Design

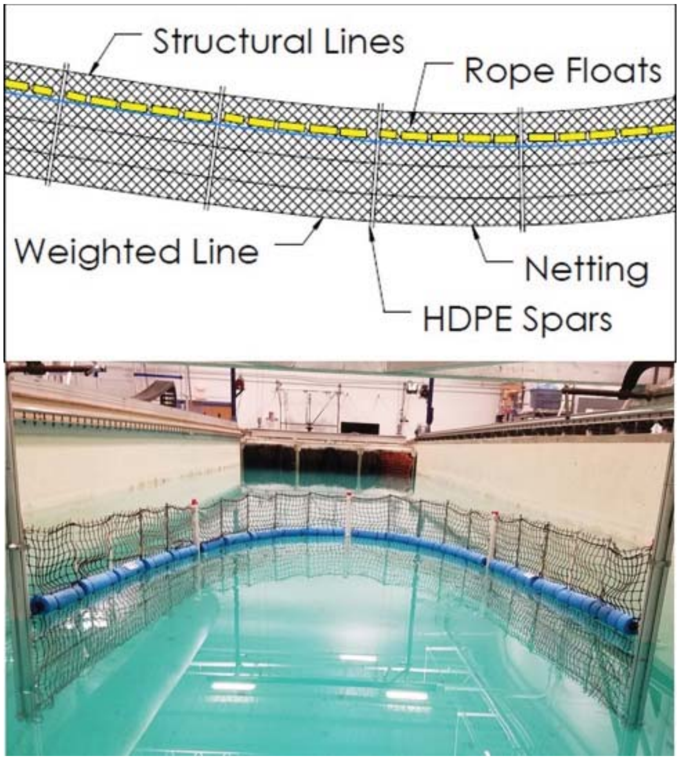

Fig. 4. Schematic of the fence design (top) and a picture of the model tested in the University of New Hampshire (UNH) wave tank (bottom).

The UNH team has designed a unique, flexible, resilient, wave-following fence to contain *Sargassum* with minimal drag while avoiding marine animal entanglement, and the team has tested the design in a wave tank (Fig. 4).

C. Sargassum harvesting

The team is developing a continuous harvest system that feeds mats into impermeable geosynthetic container bags (Fig. 5). The harvest bag is impermeable and much like a plastic bag liner for a large trash compactor. The filling bag will be mostly above water so that water escapes around the hydraulic ram; the stuffed bag contains relatively little water (spaces between compacted seaweed are filled with air). When a bag is cinched, its net density might be only 500 kg/m^3. Removing air with a vacuum further crushes the macroalgae while lowering oxygen content to reduce aerobic microbial activity. This process may increase the net density to >900 kg/m^3. Submerging the bag to 500 m for storage will further decrease excess air release and increase the net density to >1,000 kg/m^3. A concept paper submitted to ARPA-E OPEN 2018 explains the benefits of collecting macroalgae in impermeable geosynthetic membrane bags for storage [16], especially during peak growth periods to even out product flow to the energy processor. Another paper describes how such bags can begin energy processing [17]. Since *Sargassum* mats are high in sulfur [8] relative to other seaweeds, such ensilage can facilitate anaerobic microbial reduction of sulfur.

We are exploring a variety of collection techniques. One option is the AlgeaNova system, which uses a conveyor belt to lift *Sargassum* and drop it into bags.[2] This system could be automated to continuously fill bags.

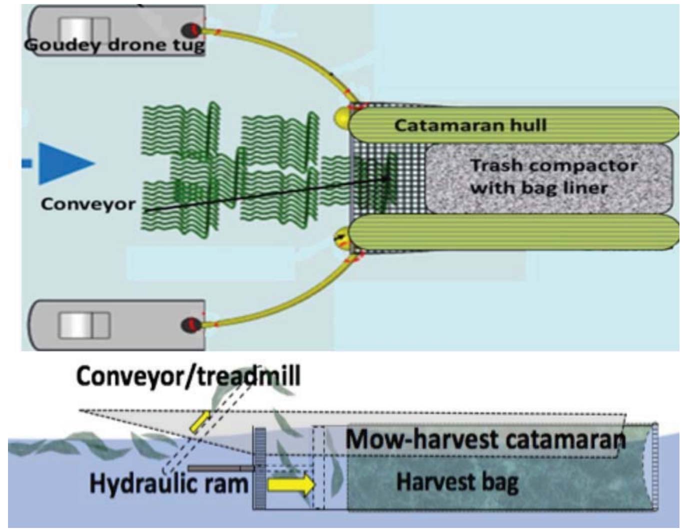

Fig. 5. Plan (top) and side views (bottom) of the harvest design

Another option is shown in Fig. 5 (top) where tugs tow wings to guide *Sargassum* onto a conveyor belt and into bags on a catamaran. The bags then are automatically sealed and released with a GPS signal attached for subsequent pickup. Fig. 5 (bottom) illustrates the elevation of the catamaran with a "trash compactor" to stuff the *Sargassum* into impermeable bags.

D. Tow Shapes

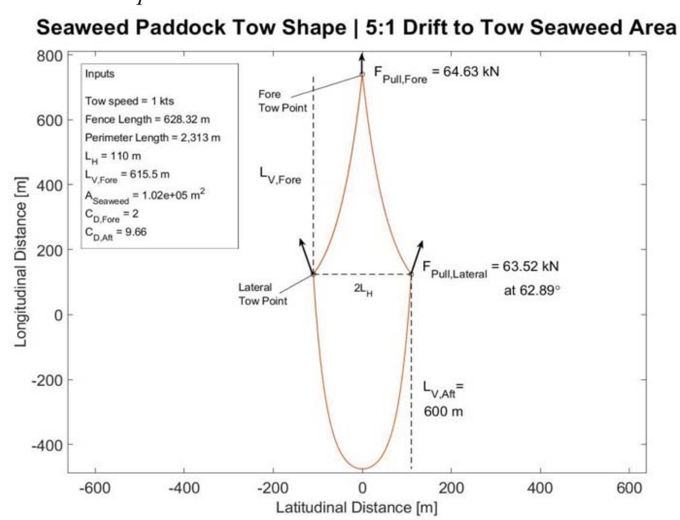

Fig. 6. Tow shape and forces upon reshaping the SeaweedPaddock to 20% of the maximum containment area during drift.

[2] See AlgeaNova at http://www.algeanova.com/en and a video at minutes 20-22 of https://www.youtube.com/watch?v=gE3EXxC4Mf8&feature=youtu.be

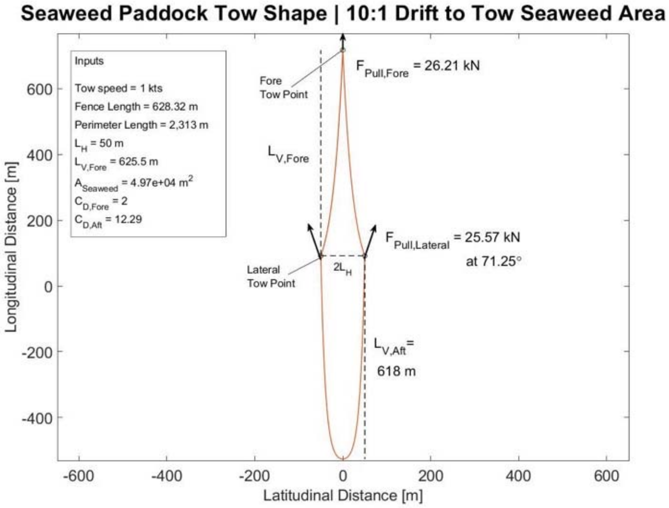

Fig. 7. Tow shape and forces if compress the Paddock to cover only 10% of the maximum containment area during drift.

The UNH team analyzed the forces required to tow the SeaweedPaddock. Using oil-boom analysis as a basis, the loads on different tow shapes were investigated. Although required tow force decreases with width, it is important to maintain enough space to avoid over-packing the *Sargassum* so that the mat can easily drift apart when the SeaweedPaddock returns to drift mode. Fig. 6 shows that when towing at 1 knot, a tow force of about 64 kN per tow vessel was required if the containment area is compressed to 20% of the maximum area during the normal daytime drift configuration. Fig. 7 shows that when the containment area is compressed to 10% of the drift area, the required tow force per vessel is only about 26 kN, saving 60% of the towing energy. Note that the tow force decreases with the square of the speed, so only 6.5 kN (1460 pounds) per vessel is required for the 10% area configuration at a half knot.

E. Power Systems

The team plans to use biofuel internal combustion engines in tugs plus solar PV with batteries. The team will include technoeconomic analyses (TEA) information for other energy sources as details become available and when those details reduce the $/DMT of harvested macroalgae. Texas A&M is developing a wave-energy device that is competitive with solar PV for powering offshore aquafarms. Wave-tank tests suggest the Surface Riding Wave Energy Converter (SR-WEC) could eventually have a levelized cost of electricity below $0.17/kWh. The SR-WEC's sliding magnet system and performance features are explained in their ARPA-E OPEN 2018 concept paper [18]

F. Towing to Market

C.A. Goudey & Associates is developing design and cost details for moving the bags from the farm site to a land-based or at-sea processing facility. They plan to develop and demonstrate 500-ton and 2,000-ton-capacity seaweed transport bags for initial prototype sea trials in 2019.

G. Nutrient Supply

Towing through the GoM provides a small but continuous supply of inorganic nutrients in addition to those supplied by the *Sargassum* community. To supply additional nutrients for faster growth, the team is looking at the feasibility of pumping nutrient-laden water from 100 m. At full scale, recycling nutrients left over from the energy-extraction process could promote optimal growth.

H. Technoeconomic Analysis

The biggest unknown in the TEA is nutrient availability in the open ocean. Using only the surface nutrients SeaweedPaddock would encounter when towing at half a knot (0.5 m/s) for ten hours every night yields only 3 DMT/ha/year. But a breakthrough yield of 130 DMT/ha/year could result from using nutrient recycling and following the general principles learned from Lapointe's 1978 study [19], which are frequent but partial harvests to keep density between 2 and 8 DMT/ha. This assumes the availability of optimum nutrients recycled from the energy conversion process.

If everything works as planned, the TEA reveals that the overall cost could be as low as $30/DMT. But if things do not work well, it could be in the hundreds of dollars per DMT.

I. Phase 2 Demonstration

The team is currently designing a Phase 2 demonstration to test the key risk factors. Most of the uncertainty in the $30/DMT estimate rests on two inexpensively tested assumptions:

(1) Smart Towing and Harvesting: Thyng and Hetland's drift-tow computer model needs to include a computerized "predictive pilot" to combine current and wind predictions to optimize the nightly tow direction. For example, while the top priority is to avoid encounters with the shore or other facilities, it might be desirable to steer toward the center of upwelling eddies for more nutrients, toward a harvest collecting area, or toward over-wintering or pre-hurricane locations.

(2) Breakthrough yield: A mini-SeaweedPaddock could inexpensively include features to test the effect of nightly towing on *Sargassum* growth. A menu for Phase 2 could include:

- An artificial intelligence predictive pilot steering program to avoid collisions.
- Optimized steering to access natural nutrients, nutrient conversions, and pre-hurricane and over-wintering locations.
- Calibration of the pilot to monitor *Sargassum's* yield when stressed by nightly towing, including post-tow unpacking.
- Work with regulators to define a path to full-scale harvests.
- Confirmation of breakthrough yield with frequent harvesting, perhaps with a modified AlgeaNova system.[3]
- A test of upwelling to increase the supply of nutrients.

[3] See http://www.algeanova.com/en/

- Inquiries with NOAA and the Coast Guard concerning paths for permitting a Phase 2 demonstration.

IV. Discussion

The team will present its final report to ARPA-E in April 2019. This preliminary paper presents a snapshot of the work in progress. This and additional information will be presented at the Oceans18 Conference in Charleston. Later published papers will detail the solutions outlined above.

Although the primary purpose of this project is the generation of biomass for energy, an additional potential benefit is carbon sequestration. Orr [20] estimates that current annual carbon sequestration by wild Sargassum is > 4.3 x 10^{10} gC as recalcitrant (i.e. non-reactive) dissolved organic carbon (rDOC), and sinking fecal pellets of grazers, plus an unknown amount from dying Sargassum sinking into the deep ocean.

In addition, *Sargassum* is known as the "nursery" of the open ocean where many species' eggs and larvae develop. Expansion of this ecosystem throughout the GoM, Caribbean, and Atlantic Ocean could eventually increase quantities of fish. Also, primary biomass growth increases oceanic oxygen levels, which have been declining in many open-ocean environments [22].

Since *Sargassum* is already used as an additive for livestock feed, this could serve as an initial step into markets.

V. Conclusions

Preliminary results suggest a potentially low-cost growing and harvesting system for producing significant quantities of biomass, eventually providing billions of gallons of biofuels[4] without the use of any land, fresh water or added fertilizers.

More testing is needed to forecast the yield per hectare and $/DMT. However, current estimates show the possibility that a full-scale system could produce biofuels competitive with current prices for fossil fuels.

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[4] For example, 1000 Paddocks, at 50 acres each, could potentially provide over a billion gallons of biofuels per year.