

# MODELLING, SIMULATION AND VISUALIZATION OF A MULTISPECIFIC PHILIPPINE SEAGRASS MEADOW

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**KEY WORDS:** Seagrass, Diffusion Limited Aggregation, *Thalassia hemprichii*, *Enhalus Acoroides*, *Cymodocea Rotundata*, Seagrass Dynamics, Seagrass Growth

## ABSTRACT:

Seagrass meadows are constantly under threat from natural and man-made stresses due to its shallow existence in the coastal environment. Restoration and preservation of seagrasses by means of rehabilitation or transplanting strategies is possible, but the studies have been limited. An agent-based model of a mixed Philippine seagrass meadow is presented. Three species were used for testing: *Enhalus acoroides*, *Thalassia hemprichii*, and *Cymodocea rotundata*. The model features parameter-based clonal growth of seagrass species, recruitment of new seagrass apices through basic flowering/seeding, and a crowding logic for multiple coexisting species in a single meadow. Seagrass clonal growth is modeled using a modified Diffusion-Limited Aggregation (DLA) model. Each species has a preconfigured set of parameters for clonal growth including rhizome elongation, branching rate, vertical elongation rate, rhizome branching angle and shoot age. Seed recruitment is applied through occasional flowering/seeding events configurable per species. We developed a simple three-species competition model which controls the growth and direct competition effects based on a configurable population size and comparison radius. Upon further calibration and validation, the model would enable more accurate long-term predictions for different rehabilitation and transplanting strategies of mixed seagrass meadows. Further improvements can also be implemented, particularly taking into account the environmental variables within the meadows such as light attenuation and salinity, among other factors.

## 1. INTRODUCTION

Seagrasses are marine flowering plants found mainly in shallow and brackish waters in gently sloping, protected coastlines horizontally, with leaves reaching upward and roots growing sideways and down. Their leaves have veins and air channels to allow gas and nutrient exchange while their roots and rhizomes are often buried to anchor the plant, store carbohydrates, and absorb nutrients.

There are around 60 species of seagrass found in the ocean throughout the world and at least 16 taxa of seagrass are found in the coastlines of the Philippines. Their ecological function make them a vital part of the marine ecosystem. Seagrasses provide food, shelter and nursery areas for numerous marine animals including prawns, fish, sea turtles and dugongs. Seagrasses contribute a lot to the blue carbon ecosystem. They capture and store large amounts of carbon from the atmosphere. They are estimated to be responsible for up to 11 percent of the organic carbon buried in the ocean (Fortes, Nadaoka, 2015). Seagrasses trap sediments which benefit corals by reducing sediment loads in water. Sediment banks accumulated by of seagrasses by means of rehabilitation or transplanting strategies is possible, but the studies have been limited.

## 2. SEAGRASS GROWTH, REPRODUCTION AND COMPETITION

Seagrasses grow both vertically and horizontally. Horizontally, the rhizomes and roots spread and branch out which forms a growth pattern of rhizomes and nodes where leaf shoots and roots grow. The branching out of these seagrass nodes forms a somewhat incoherent structure.

around the world. They belong to a group of plants called *monocotyledons* that include grasses, lilies and palms (McKenzie, 2008). Seagrasses grow both vertically and

seagrasses may eventually form substrates that can be colonized by mangroves (McKenzie, 2008).

Seagrass meadows are rated 3<sup>rd</sup> most valuable ecosystem globally (McKenzie, 2008), yet studies on seagrasses are limited in the Philippines. Seagrass meadows are fragile ecosystems that incur natural losses due to storms or herbivores, but most losses are the result of human activities (Fortes, n.d.). *Eutrophication* is a major long-term threat to seagrass ecosystems. It is a condition which results from waste waters drained into the ocean from industrial facilities. Aside from eutrophication, the effects of human activities such as boating activities for tourists and poor fishing practices lead to the destruction of meadows. (Fortes, n.d.)

Seagrass meadows are shown to be constantly under threat from natural and man-made stresses. Restoration and preservation

Diffusion Limited Aggregation (DLA) is used to describe the formation of fractals from random particles. It's a simple stochastic growth model that accurately simulates the growth patterns of objects such as snowflakes and galaxies (Kaandorp, 2012). The model starts with an immobile seed particle or in this case the main seed of the seagrass located at the center of a lattice and random walkers or the nutrient particles are initiated throughout the grid. In each iteration, if a walker or nutrient touches the seed, it becomes immobilized as well or the seed branches out, resulting in a fractal growth pattern (Rajur, 2015). The DLA model has been applied in biology to model the forms of bacterial colonies and dendritic hermatypic corals (Kaandorp, 2012). The formation of DLA has also been observed as early growth patterns of seagrasses (Renton et al., 2011). DLA is very

flexible and could be easily modified by a variety of parameters for it to reflect seagrass growth.

Vermaat (Vermaat et al., 1995) quantified leaf production, shoot demography and rhizome growth and branching for the common seagrass species in a mixed seagrass bed on the Bolinao reef flat. The seagrass that form this mixed bed encompass a considerable size range, from the smallest (*Halophila ovalis*) to the largest (*Enhalus acoroides*).

Table 1. Weight and size of the modules of seagrasses present in the mixed meadows at Bolinao (Luzon, The Philippines). Mean module biomass in dry weight was derived from large pooled samples (n > 30 modules); means are given ± 1 standard error; sample size is in parentheses; na: not applicable. Where multiple comparisons (modified LSD) revealed significant differences between species, these are indicated with different letters in superscript

	<i>Cymodocea rotundata</i>	<i>Cymodocea serrulata</i>	<i>Enhalus acoroides</i>	<i>Halophila ovalis</i>	<i>Halodule uninervis</i>	<i>Syringodium isoetifolium</i>	<i>Thalassia hemprichii</i>
Vertical internode weight (mg)	0.4	5.6	na	na	3.0	3.0	3.2
Horizontal internode weight (mg)	12.6	15.9	312.6	2.9	11.4	11.3	7.0
Leaf weight (mg)	35.6	44.2	568.4	3.5	18.3	44.9	79.3
Leaves per shoot	3.41 <sup>a</sup> ± 0.10 (79)	3.37 <sup>a</sup> ± 0.07 (107)	4.38 <sup>b</sup> ± 0.70 (40)	2 <sup>a</sup>	2.73 <sup>ab</sup> ± 0.11 (51)	2.07 <sup>ab</sup> ± 0.08 (61)	3.29 <sup>b</sup> ± 0.05 (309)
Shoot leaf area (mm <sup>2</sup> , single-sided)	3703 <sup>a</sup> ± 0.47 (51)	3322 <sup>a</sup> ± 0.88 (9)	35870 <sup>b</sup> ± 24.4 (37)	418 <sup>a</sup> ± 0.70 (10)	414 <sup>a</sup>	799 <sup>a</sup>	2656 <sup>a</sup> ± 2.32 (50)
Leaf length (mm)	222.6 <sup>a</sup> ± 0.26 (51)	92.2 <sup>a</sup> ± 1.36 (9)	500.8 <sup>b</sup> ± 1.82 (37)	15.4 <sup>a</sup> ± 0.09 (10)	48.9 <sup>ab</sup>	136.6 <sup>b</sup> ± 0.68 (5)	86.8 <sup>b</sup> ± 0.53 (50)
Leaf width (mm)	5.5 <sup>b</sup> ± 0.04 (51)	8.7 <sup>a</sup> ± 0.08 (9)	15.7 <sup>a</sup> ± 0.04 (37)	8.5 <sup>a</sup> ± 0.08 (10)	3.1 <sup>ab</sup> ± 0.03 (39)	1.8 <sup>a</sup> ± 0.08 (56)	8.7 <sup>a</sup> ± 0.04 (114)
Vertical shoot length (mm)	13.3 <sup>a</sup> ± 0.02 (59)	79.8 <sup>b</sup> ± 0.51 (90)	103.9 <sup>b</sup> ± 1.45 (27)	14.9 <sup>a</sup> ± 0.17 (10)	53.5 <sup>b</sup> ± 0.64 (39)	47.6 <sup>b</sup> ± 0.41 (56)	62.4 <sup>b</sup> ± 0.45 (114)
Vertical internode length (mm)	0.47 ± 0.04	4.49 ± 0.46	na	na	1.07 ± 0.56	7.77 ± 0.60	0.87 ± 0.06
Rhizome diameter (mm)	2.87 <sup>a</sup> ± 0.76 (5)	2.88 <sup>a</sup> ± 0.25 (2)	13.25 <sup>b</sup> ± 1.25 (3)	1.09 <sup>a</sup> ± 0.07 (8)	1.25 <sup>a</sup>	2.18 <sup>a</sup> ± 0.86 (5)	3.43 <sup>a</sup> ± 0.00 (7)
Horizontal internode length (mm)	13.5 <sup>ab</sup> ± 0.01 (98)	39.3 <sup>a</sup> ± 0.19 (66)	4.7 <sup>a</sup> ± 0.00 (28)	17.0 <sup>b</sup> ± 0.13 (45)	8.6 <sup>ab</sup> ± 0.14 (24)	25.3 <sup>a</sup> ± 0.11 (40)	3.7 <sup>a</sup> ± 0.01 (30)

Figure 1. Weight and size of the modules of seagrasses (Vermaat et al., 1995).

The length of the vertical internodes of *Cymodocea rotundata*, *Thalassia hemprichii* and *Enhalus acoroides* showed distinct annual cycles. This indicates seasonal changes in vertical growth. *C. rotundata* and *T. hemprichii* also showed 2 minima in a year with an absolute minimum in early January, the time of the shortest day-length, and a secondary minimum in August/September. These minima were also observed in seasonal leaf marking studies.

The plastochron interval estimates for *Enhalus acoroides* were relatively high at around 35.6 days each interval, compared to *C. rotundata* and *T. hemprichii* with intervals of about 11.4 days and 10.9 days respectively. Comparing the number of leaves produced in a year suggests slow leaf turnover for *E. acoroides* with 2.5 leaves shoot<sup>-1</sup> year<sup>-1</sup>.

Horizontal rhizome growth rates were lowest for *Enhalus acoroides* with 5 cm yr<sup>-1</sup>. Rhizomes branched at angles of about 60° but no branches were observed in the large sample of horizontal rhizomes of *Thalassia hemprichii* examined. Branch production per year tended to correlate positively with horizontal rhizome growth.

*Enhalus acoroides* and *Thalassia hemprichii* had fairly long-lived shoots, with median ages of about 1.5yr and maximal observed longevities of 9.8 and 6.1 yr, respectively. The oldest *Cymodocea rotundata* shoot sampled had an age of 4.1 yr. Mortality rates ranged from 0.2 (*E. acoroides*) to 2.9 units yr<sup>-1</sup> (*C. serrulata*). *T. hemprichii* and *C. rotundata* had positive net recruitment rates considerably larger than the standard errors estimated for the mortality rates. This suggests that they were proliferating in the mixed meadow.

*Thalassia hemprichii* and *Enhalus acoroides* have longer-lived and larger shoots which allow them to occupy space more permanently, and accumulate and retain resources for extended periods of time. The smaller species are arrested in a permanent state of colonisation imposed by this high shoot mortality rate and the need for fast, continuous rhizome growth to provide the required shoot flux. Co-dominance of *E. acoroides* in terms of biomass only resulted to 10% annual contribution compared to the 74% contribution of *T. hemprichii*. This difference can be explained by the lower horizontal rhizome growth, leaf turnover, larger shoot size, as well as the considerable reproductive effort of *E. acoroides*.

The co-dominant *Enhalus acoroides* is unlikely to be subjected to significant interference by the other species because its leaf surface is raised above that of others, and its rhizomes send their roots deeper into the sediments.

Previous analyses of different seagrass species in SE Asian meadows identified *Enhalus acoroides* and *Thalassia hemprichii* as constant species and *Cymodocea rotundata* as one of the pioneering species.

Table 2. Number of leaves produced per shoot per year, and the corresponding plastochron intervals (PI), rhizome elongation and branching rates, and shoot spacing on the rhizomes, of the seagrasses present in the mixed meadows at Bolinao (Luzon, The Philippines). Means are given ± 1 standard error; sample size is in parentheses; na: not applicable; -- data were not collected. Leaf PI in *Halophila ovalis* was calculated as half the measured rhizome PI of 4.4 d, because a pair of leaves is produced for each rhizome internode. Vertical elongation rate for *Halodule uninervis* was averaged over the Silau and Pislatan stations

	<i>Cymodocea rotundata</i>	<i>Cymodocea serrulata</i>	<i>Enhalus acoroides</i>	<i>Halophila ovalis</i>	<i>Halodule uninervis</i>	<i>Syringodium isoetifolium</i>	<i>Thalassia hemprichii</i>
PI (d)	11.4 ± 0.3 (29)	12.7 ± 1.2 (3)	35.6 ± 1.8 (46)	2.2 (12)	9.6 (36)	33.2 (59)	10.9 ± 0.31 (59)
Leaves shoot <sup>-1</sup> yr <sup>-1</sup>	32.5 ± 0.8 (69)	29.3 ± 3.0 (90)	11.5 ± 0.6 (90)	na	165.9 (39)	11.0 (56)	34.8 ± 0.9 (115)
Vertical elongation rate (cm shoot <sup>-1</sup> yr <sup>-1</sup> )	1.5 ± 0.1 (69)	13.1 ± 1.8 (90)	33.9 (90)	5.3 (90)	141.0 (39)	28.4 (56)	134.7 (115)
Horizontal elongation rate (cm apex <sup>-1</sup> yr <sup>-1</sup> )	33.9 (69)	78.3 (90)	5.3 (90)	141.0 (90)	28.4 (39)	134.7 (56)	20.6 (115)
Horizontal elongation rate (internodes apex <sup>-1</sup> yr <sup>-1</sup> )	0.77 ± 0.03 (98)	0.68 ± 0.21 (15)	1 (15)	0.5 (15)	0.87 ± 0.19 (46)	4.84 ± 2.10 (14)	1.60 ± 0.28 (17)
Rhizome branching angle (degrees)	39.5 ± 4.9 (9)	56.6 ± 4.1 (25)	72.0 ± 4.2 (27)	53.5 ± 6.8 (9)	58.0 ± 9.0 (7)	na	na
Branching rate (branches apex <sup>-1</sup> yr <sup>-1</sup> )	1.15 (9)	0.29 (25)	13.4 (27)	0.39 (9)	2.93 (7)	<0.01	<0.01
Horizontal internodes between shoots	7.52 ± 0.10 (98)	1.61 ± 0.21 (66)	14.22 ± 2.48 (28)	1 (24)	5.17 ± 1.50 (40)	1.50 ± 0.12 (40)	20.18 ± 2.11 (28)
Shoot spacing along the rhizome (cm)	4.8 (98)	5.3 (66)	6.9 (28)	1.7 (24)	2.7 (40)	3.7 (40)	6.9 (28)
Distance between horizontal branches (cm)	68.1 (98)	19.2 (66)	10.5 (28)	62.8 (24)	45.9 (40)	>2846.0 (40)	>2846.0 (28)

Figure 2. Number of leaves produced per shoot per year, rhizome elongation and branching rates and shoot spacing on the rhizomes of seagrasses present in the mixed meadow at Bolinao, Pangasinan (Vermaat et al., 1995).

The flowering frequencies of *E. acoroides*, *T. hemprichii* and *C. rotundata* were observed by examination of flowering scars on seagrass shoots. Only 5.6% of the 269 *C. rotundata* shoots inspected had flowered and two of them flowered twice, translating to a flowering event for every 15 shoots in a year. Only 17% of 346 *T. hemprichii* shoots inspected and several had flowered more than once, translating to a flower produced for every 8 shoots in a year. None of the shoots of *T. hemprichii* and *C. rotundata* were observed to have flowered until they reached half a year of age, and the probability of flowering remained uniform after their first year of life. 97.7% of the 42 *E. acoroides* shoots examined were from 20 shoot clusters, and had flowered several times. Only the shoots in one of the clusters had never produced a flower in any of the shoots present. This translated to an average of 2.8 flowering events shoot<sup>-1</sup> yr<sup>-1</sup> (for every shoot

in a year (Duarte et al., 1997). Seed dispersal strategies and survival rate also vary for each species (Orth et al., 2006).

Table I. The average biomass of flowers of the Philippine seagrass species examined, and their annual production of flower biomass.

	<i>C. rotundata</i>	<i>T. hemprichii</i>	<i>E. acoroides</i>
Flower mass (mg DW flower <sup>-1</sup> )	1.9	53.2	550
Flowering frequency (flowers shoot <sup>-1</sup> yr <sup>-1</sup> )	0.065	0.122	3.1
Shoot density (shoots m <sup>-2</sup> )	171	548	21
Flower biomass production (g DW m <sup>-2</sup> yr <sup>-1</sup> )	0.021	3.56	35.8
Leaf production (g DW m <sup>-2</sup> yr <sup>-1</sup> )	199	1511	139
Flowering effort (% above-ground production)	0.01	0.23	20.5

Annual flower production was calculated as the product of the average number of flowers shoot<sup>-1</sup> yr<sup>-1</sup>, the average flower biomass, and shoot density. Shoot density and leaf production from Vermaat et al. (1995).

Figure 3. Annual production of flower biomass of *C. rotundata*, *T. hemprichii* and *E. acoroides* from Duarte, et al (Duarte et al., 1997).

Lastly, the elucidation of the nature of the interactions among seagrass species provides a key to understanding the maintenance of the high biodiversity and production that characterizes pristine SE Asian coastal ecosystems. Seagrass meadow competition has been tested among SE Asian seagrasses. The experiments were performed in a multi specific seagrass meadow growing off Silaqui Island, Bolinao, Pangasinan in the reed lagoon at an average depth of about 0.8 m. It's dominated by *Thalassia hemprichii*, followed by *Enhalus acoroides* and, in order of decreasing biomass and production, *Cymodocea rotundata*, *Syringodium isoetifolium*, *Halodule uninervis*, *Cymodocea serrulata* and *Halophila ovalis*. The cumulative removal from the community of shoots of seagrass species in order of increasing requirements of resources for plant growth having no effects on the development of the existing species were expected. The experiment results show that species interactions in this multispecific seagrass meadow are asymmetric (Duarte et al., 2000).

### 3. METHODOLOGY

The following serves as the Overview, Design Concepts, and Details (ODD) of the proposed model. The ODD is a standardized protocol used to describe agent-based models. It includes a detailed explanation of how each step in the simulation is carried out, what agents are being simulated, the effects of the virtual environment as well as the effects of the agents on each other.

Seagrasses grow both sexually and asexually. For their asexual reproduction, the application of a modified Diffusion-Limited Aggregation has been created using data from Vermaat (Vermaat et al., 1995) describing characteristics of seagrasses in a meadow in Bolinao, Pangasinan. Sexual reproduction has been applied using data from Duarte (Duarte et al., 1997). Lastly, the interactions between *Thalassia hemprichii*, *Enhalus acoroides* and *Cymodocea rotundata* were described by applying Bongolan's proposed interaction model.

#### 3.1 Overview

**3.1.1 Purpose:** The model aims to describe and simulate the dynamics of seagrasses in Bolinao, Pangasinan. In particular, the *Enhalus acoroides*, *Thalassia hemprichii* and *Cymodocea rotundata* species parameters (Vermaat et al., 1995) are used to simulate species growth and dynamics.

#### 3.1.2 Entities, State Variables and Scales of Seagrass:

- Leaf length (mm)
- Rhizome Diameter (mm)
- Shoot Leaf Area (sq. mm)
- Rhizome Branching Angle (degrees)
- Maximum number of branches
- Horizontal Elongation Rate (cm per year)
- Max Shoot Age (days)
- Seeding Maturity (days)
- Seeding Probability
- Seed Dispersal Radius (mm)
- Number of Seeds Dispersed
- Recruitment Rate (new shoots per year)

**3.1.3 Process Overview and Scheduling:** The simulation is initialized through the generation of the grid, food particles and initial seedlings. During each step, the seedlings go on a random walk and the modified DLA model is being done. When a particle sticks and branching should happen, the competition model was used to determine the node's recruitment probability. During the same step, their shoots grow to a species-specific length and area.

A rhizome can reach seeding maturity and seeds could be dispersed randomly over a specified radius. The number of seeds dispersed depends on the seed survival rate and the amount of seeds each species can produce per rhizome. The recruitment of seeds would also depend on the recruitment probability from the competition model.

#### 3.2 Design Concepts

**3.2.1 Emergence:** Seagrasses are clonal plants that share a similar structure and present a highly organized growth. Seagrass growth stems from the horizontal branching of ramets, their nodes which can be composed of leaves, a piece of rhizome, roots, flowers, etc (McKenzie, 2008). The resulting pattern should be a function of the characteristics of the different seagrass species and their interaction with each other.

The characteristics of the resulting seagrass meadow can be described by the shoot density ( no. of shoots/square meter.)

**3.2.2 Objectives :** The goal of seagrasses is to grow and expand. A positive shoot density that fits the data (Vermaat et al., 1995) could describe the growth and interaction within the seagrass meadow.

**3.2.3 Sensing:** When making decisions in branching out, for a specific radius, the agent itself would know the population of the seagrasses occupying the radius. It would then produce a probability on whether or not it expands horizontally. Seagrasses are shown to not grow if it's too crowded (Renton et al., 2011).

**3.2.4 Interaction:** Agents interact through competition for space and food nutrients in the grid.

**3.2.5 Stochasticity:** The random walk and initialization of particles represent the nutrients in water. This stochasticity is from the modified DLA model as well as the idea of nutrients for seagrasses in random motion in water.

**3.2.6 Collectives:** Seagrass agents can be classified by species. Specifically, seagrasses can be classified as *Thalassia hemprichii*, *Enhalus acoroides* and *Cymodocea rotundata*.

**3.2.7 Observation:** Seagrasses shoot density to observe consistency of seagrass dynamics is collected by taking the

number of shoot population per seagrass species and then dividing by the total grid area. The shoot density taken monthly is then displayed as a dynamic graph to be analyzed.

### 3.3 Details

**3.3.1 Initialization:** The initial number of seedlings is a fraction of the shoot density from Vermaat on a 1000 square mm canvas size with 250 initial particles. The initialization of seedling positions would vary among simulations, although a parameter to save the current state of initialization is present as an option. Initial values on the number of seedlings and their locations are random, although the initial parameters for each species is from Vermaat (Vermaat et al., 1995).

**3.3.2 Input Data:** The model includes a fixed initial amount of nutrient and the speed of its random walk in the environment. Environmental variation by changing the amount of initial nutrients and varying speed could be implemented for further improvements of the model.

#### 3.3.3 Submodels

**3.3.3.1 Asexual Reproduction:** The clonal growth of seagrasses is implemented using a modified Diffusion-Limited Aggregation model. The DLA model consists of particles on a random walk which 'sticks' to any other particle encountered (Rajur, 2015). The aggregation results in the formation of irregularly shaped clusters. The model is modified using parameters from Vermaat (Vermaat et al., 1995).

- Rhizome branching angle (degrees)
- Minimum branching angle difference (degrees)
- Number of maximum branches per shoot
- Horizontal elongation rate (cm per year)
- Branching rate (branches apex<sup>-1</sup> year<sup>-1</sup>)

**3.3.3.2 Sexual Reproduction:** Seagrasses are flowering plants and as a result produce seeds. The agents disperse seeds once they reach their seeding maturity and would depend on a seeding probability if they are going to produce seeds (Orth et al., 2006). The amount and frequency of seeds produce varies per species (Duarte et al., 1997). Other varying characteristics of seagrasses also result to varying seed dispersal radius and survival rate.

**3.3.3.3 Seagrass Dynamics:** Agents interact through a rigged competition for space and food nutrients in the grid. To show the competition for seagrasses a model proposed by Bongolan was used

$$\begin{aligned} dA/dt &= a_1A + a_2AB + a_3AC \\ dB/dt &= b_1B - b_2AB + b_3BC \\ dC/dt &= c_1C - c_2AC - c_3BC \end{aligned} \quad (1)$$

where A, B and C are populations of seagrasses and a, b and c coefficients are parameters for the relationships. dA/dt would then describe the dominant species who benefit from the competition and dC/dt would describe the most affected by the presence of other seagrasses in the meadow.

**3.3.3.4 Aging and Mortality:** Seagrass mortality is per shoot when they hit the maximum age from the Vermaat data (Vermaat et al., 1995). Seagrass age increments by 1 day per cycle.

**3.3.3.4 Above-Ground Growth:** The above-ground leaf shoot growth is stimulated by applying the pre-calculated leaf height

and leaf area of each species instance over a span of time based on its own age.

## 4. RESULTS AND DISCUSSION

A visualization and simulation of the model was presented using three species: *Thalassia hemprichii*, *Cymodocea rotundata* and *Enhalus acoroides*. The model simulated two years of its growth and was calibrated to fit the shoot density of Seagrasses in Bolinao (Vermaat et al., 1995).

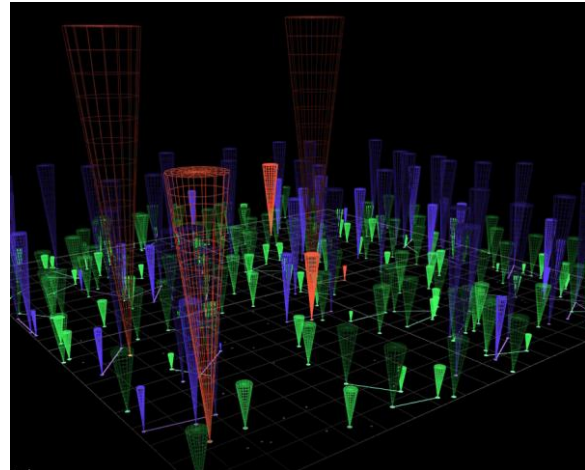


Figure 4. Screenshot of seagrass meadow simulation.

Calibration of the Bongolan model was conducted to fit the shoot density of Vermaat (Vermaat et al., 1995) to the shoot density of the model within 2 years. The coefficients used for the Bongolan model that best fitted the shoot densities are described below. The asymmetry of the relationship values reflect the experimental research of Duarte (Duarte et al., 2000).

	<i>E. acoroides</i>	<i>T. hemprichii</i>	<i>C. rotundata</i>
<i>E. acoroides</i>	0.26	0.71	0.71
<i>T. hemprichii</i>	-0.41	0.77	-0.38
<i>C. rotundata</i>	0.01	-0.08	0.28

Table 1. Table of coefficients for the Bongolan interaction model.

With 95% confidence, the average shoot density +- std error of the model based on multiple simulations is shown below. The shoot densities of Vermaat (Vermaat et al., 1995) and the model coincide with each other.

	<i>E. acoroides</i>	<i>T. hemprichii</i>	<i>C. rotundata</i>
Vermaat (Vermaat et al., 1995)	21 ± 3	548 ± 21	171 ± 22

Experiment model	21.8 ± 1.96	496.8 ± 11.47	145 ± 19.84
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Table 2. Shoot density average of experiment as compared to seagrass data (Vermaat et al., 1995).

Shoot densities for each of the modelled species were then plotted into a graph. Using the previously described coefficients on the model, a stable and reproducible plot outcomes can be observed over multiple simulations. *Thalassia hemprichii* had the highest shoot density, followed by *Cymodocea rotundata*, with *Enhalus acoroides* being the least successful. Using random seed values for each run, multiple runs from the same coefficients yielded similar results over 2 years.

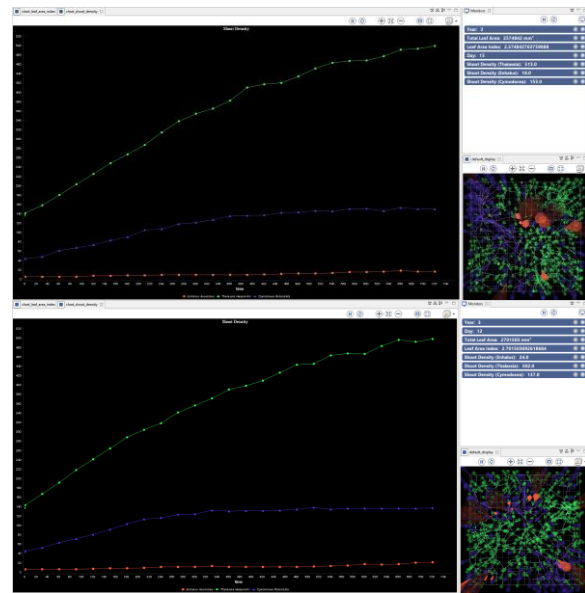
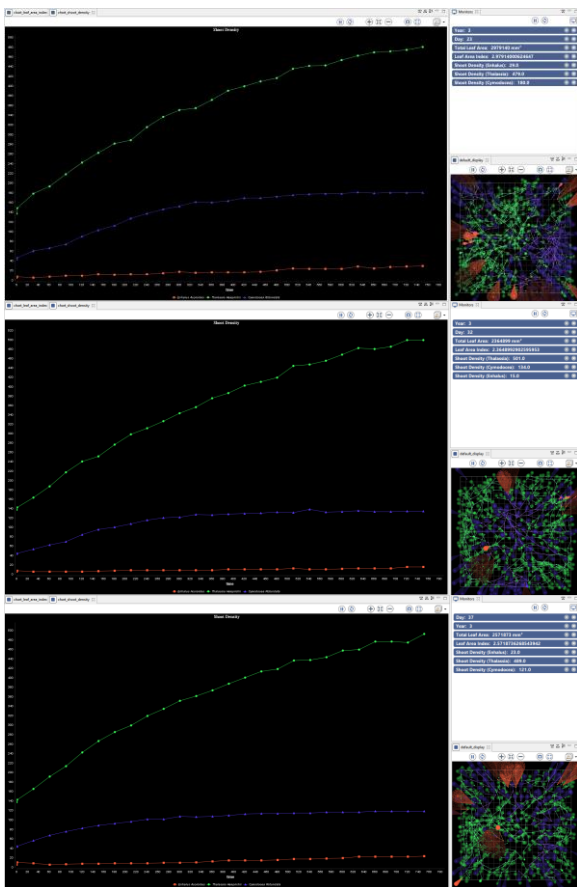


Figure 5. Screenshots of shoot density graph, values and seagrass visualization

## 5. CONCLUSION AND RECOMMENDATIONS

The study shows the modelling, simulation and visualization of a three-species seagrass meadow. The model features parameter-based modified-DLA clonal growth of seagrass species, recruitment of new seagrass apices through basic flowering/seeding, and a crowding logic for multiple coexisting species in a single meadow. Seagrass dynamics was also shown through the calibration of the competition model to fit the shoot density of seagrasses in a seagrass meadow (Vermaat et al., 1995).

Upon further calibration and validation, the model would enable more accurate long-term predictions for different rehabilitation and transplanting strategies of mixed seagrass meadows. Further improvements can also be implemented, particularly taking into account the environmental variables within the meadows such as light attenuation and salinity, among other factors.

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