D-4580

Maryland Virtual High School
Instructional Activity

Succession from Sand Dune to Maritime Forest on a Barrier Island

Authors: Aili Carlson
Sarah Clemmitt

Course: High School Science Elective in Earth Science pertaining to Coastal Processes or Oceanography

Duration: Two Weeks

Last Modified: December 6, 1995

The preparation of this report was supported by the
Gordon Stanley Brown Fund

administered by the System Dynamics Society.

Available from the Creative Learning Exchange • Acton, MA 01720 • (508) 287-0070

Succession from Sand Dune to Maritime Forest on a Barrier Island

Unit Purpose:

By building a computer model of a complex dynamic system, the student develops an understanding of the relationships among the many contributing variables. At first glance, asking high school students to design a model representing such an intricate system may seem inappropriate. However, the decisions they make about the relationships among variables enhances their understanding of barrier islands and develops their modeling skills.

Unit Objective:

The objective of this lesson is to develop a model which will simulate the succession from sand dune to maritime forest on a barrier island. Barrier islands are found off the east coast of North America. They develop from sand dunes into a complex ecological system involving sand dunes, barrier flats which frequently include a maritime forest, and salt marshes. This exercise deals not only with the design of a model, but also with the problems that arise when trying to model a complex set of interactions which are not completely understood by the scientific community and for which mathematical relationships are not readily available.

Materials:

STELLA, a modeling language for Mac and Windows platforms.
High Performance Systems, Inc.

Links to State Science Outcomes:

Learning Outcomes in Science for Maryland School Performance Assessment Program, Maryland State Department of Education (1994). Earth Science Concept Indicators, K-12 Progression.

- earth is changed over time by different natural and human forces.

Student Outcomes:

The student will gain an understanding of the development of a barrier island system, sand dune to maritime forest. By adding additional variables to the model, such as salt spray, the student will further define the growth of a barrier island. Although the model may not correlate well with the development of an actual barrier island, the student will begin to be able to predict the effects of various contributing factors on the system.

Student Assessments:

- Ask the students to design a basic model relating sand dune growth, vegetation growth, and forest growth. Since the relationships among these three variables are not well defined, the goal is to simulate the general trend of barrier island development.

- Ask the students to add a variable that contributes to the growth of the island, such as salt spray. How does this addition affect the model? What needs to be taken into account when this variable is added?

- Ask the student to evaluate the model. What are the benefits of this model? What are the limitations? What information is needed to improve this model? Why is the information difficult to gather?

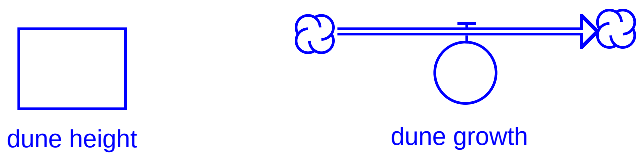
Barrier Island Model A:

The first model will focus on the general relationships between dune growth, vegetation growth, and forest growth. Assume that dune growth is linear at 4 meters per year. When the dune reaches 5 meters, vegetation begins to grow behind the dune at a constant rate. For example, with an initial dune height of 0 meters it will take 1 1/4 years for vegetation to begin to grow. When the dune reaches 15 meters, the environment behind the dune is suitable for a maritime forest to grow. Assume that the forest's growth rate is also linear.

A STELLA model can be built to represent this simplistic view of the growth of a barrier island.

The height of the dune is a STOCK (see figure 1). A STOCK, or reservoir, is something that gains and loses value. The growth of the dune is a FLOW, the rate of change which affects the stock.

Figure 1: Stock and Flow for a Dune



The mathematical equation for dune height is simply:

next_height = present_height + dune_growth*time_step

In this example, the model will begin with flat land. The dune height begins at 0. Assume that the dune grows at a steady rate, 4 meters per year. Therefore, in one year, the dune will grow
0 + 4 * 1 = 4 meters.

Vegetation, however, does not begin to grow until the dune has reached 5 meters. Therefore, the equation for the rate of vegetation growth depends on dune height.

if dune_height >= 5 meters then vegetation_growth_rate = 2, else
vegetation_growth_rate = 0

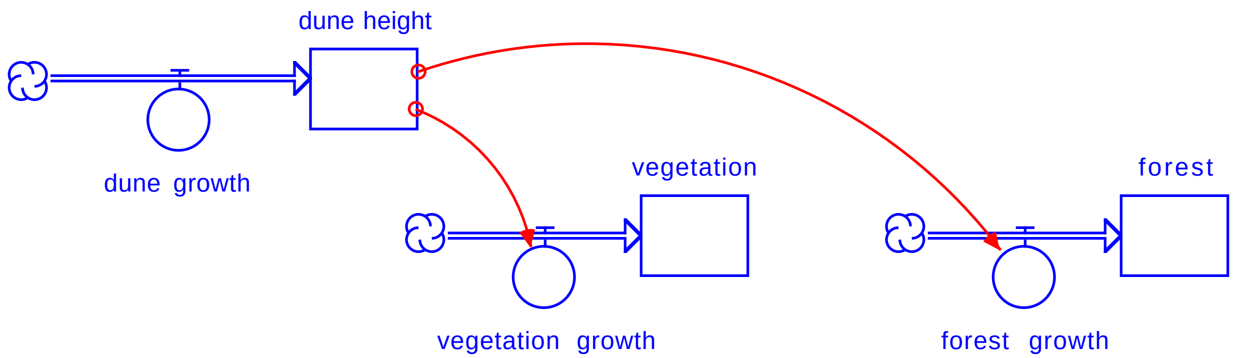
Given this equation for the vegetation_growth_rate, the equation for the amount of vegetation is simply:

next_vegetation = present_vegetation + vegetation_growth_rate*time_step

A similar equation is needed for the growth of the forest.

Since we are measuring annual growth of this system, it seems logical to use Euler's Method with a dt = 1. See figure 2 for a sample STELLA model of this simplistic system.

Figure 2: Model Diagram of Barrier Island Development Assuming Linear Growth



Initially, all the stocks must be set to zero. The growth of the dune is constant, and the growth of both the vegetation and forest are dependent on the height of the dune. The following are the equations used in the above model:

Figure 3: System Equations for Barrier Island Development Assuming Linear Growth

dune_height(t) = dune_height(t - dt) + (dune_growth) * dt
    INIT dune_height = 0
    INFLOWS:
        dune_growth = 4

forest(t) = forest(t - dt) + (forest_growth) * dt
    INIT forest = 0
    INFLOWS:
        forest_growth = if (dune_height >=15) then 1 else 0

vegetation(t) = vegetation(t - dt) + (vegetation_growth) * dt
    INIT vegetation = 0
    INFLOWS:
        vegetation_growth = if (dune_height >=5) then (2) else 0

Exercises and Discussion Questions:

1a. Using a calculator, determine what the height of the dune would be for the first 5 years of the model and sketch a graph of dune height as a function of time.

b. Using your STELLA model, run it for 5 years with a dt = 1 and create a graph of the results. Do your graphs match?

2. Calvin Calculator thought that the amount of vegetation after 5 years could be determined by the formula:

    final_vegetation = initial_vegetation + rate_of_growth * 5

    which would yield 0 + (2)*5 = 10. Explain the error in Calvin's logic.

3. Create a graph showing dune height, vegetation, and forest over 10 years.

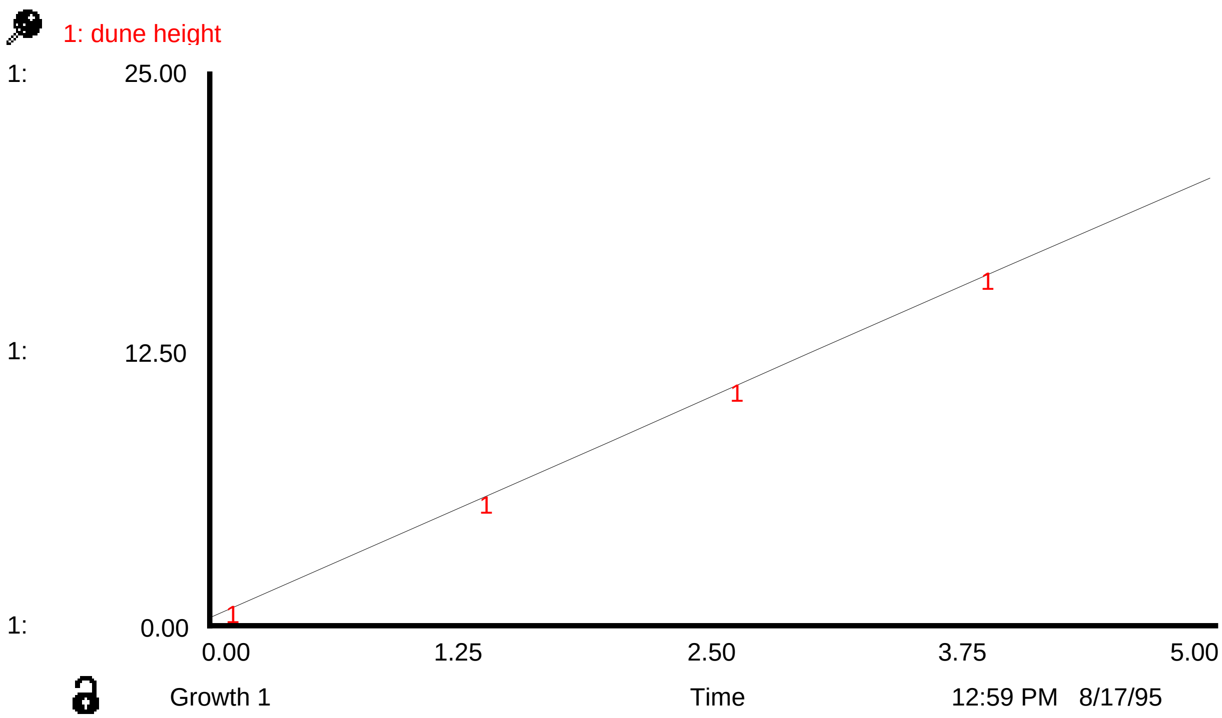
4. How large does the dune become in 5 years? In 10 years? Is this realistic? Why or why not?

Sample Solutions:

1. Figure 4: Dune Height Over Time

Time	Dune Height
0	0.00
1	4.00
2	8.00
3	12.00
4	16.00
Final	20.00

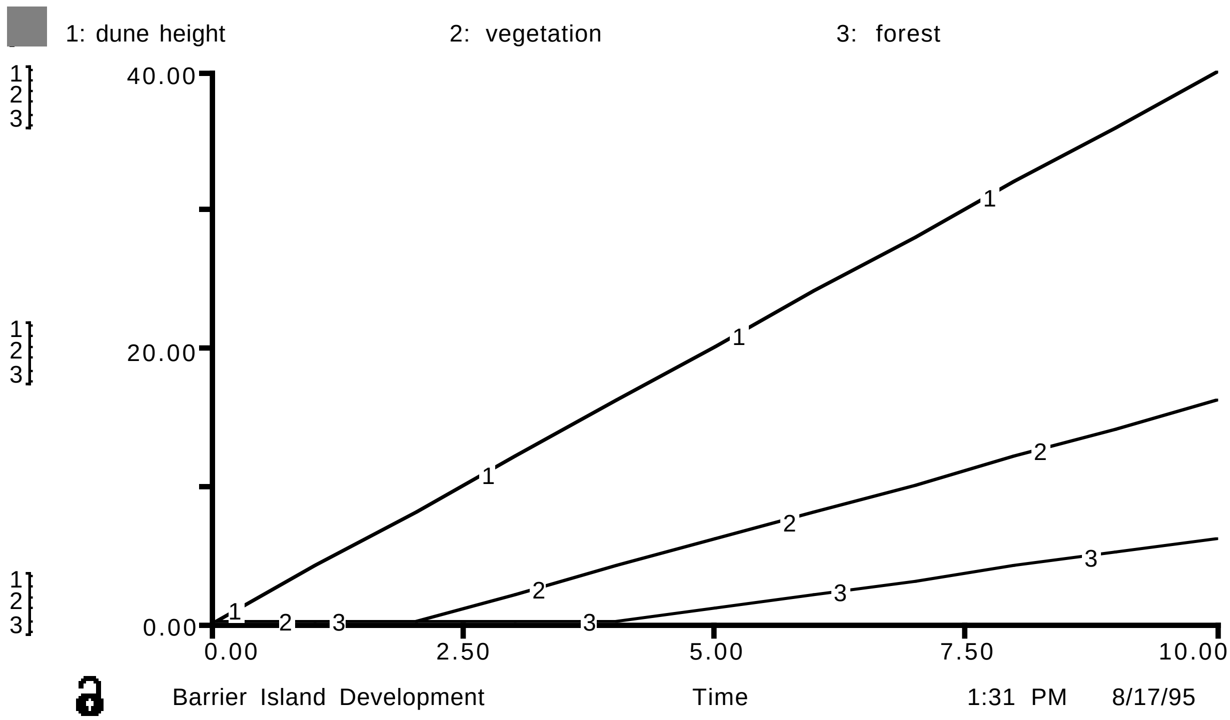
Figure 5: Dune Height Over Time



2. Calvin Calculator did not take into account that the vegetation does not start growing until the dune height is greater than 5 meters. Instead, Calvin Calculator needs to determine at what time, t, the vegetation starts growing. Then, the following equation will hold for all times after t:

final_vegetation = initial_vegetation + rate_of_growth * (5 - t)

3. Figure 6: Barrier Island Development Assuming Linear Growth



Students should notice that the vegetation graph does not begin to grow until time = 2 years, when we predicted that growth would occur at time = 1.25 years. The reason for this discrepancy is that setting dt = 1 means that values are only calculated at whole years. Suggest to the students that they change the dt to 0.25 to see if the vegetation will start to grow at the predicted time.

4. The dune height increases infinitely because nothing in the model prevents it from doing so. In reality, dunes reach some maximum height that is determined by the energy within the system.

Barrier Island Model B:

Model A assumes that all of the relationships are linear. You need to alter the model to simulate the actual trends in growth. As the dune gets taller, its growth rate decreases. Therefore, dune growth is inversely proportional to dune height:

dune_growth = 4 / dune_height

This is also true for the vegetation and the forest, except that the relationship is reversed. The more vegetation there is behind the dune, the easier it is for more vegetation to grow. So vegetation increases slowly at first and proceeds more rapidly with time. Vegetation growth is directly proportional to the amount of vegetation:

vegetation_growth = 0.03 * vegetation

Assume that once the vegetation begins to grow, it increases by a factor of 0.03. Assume that once the forest begins to grow, it also increases by a factor of 0.03.

Exercises and Discussion Questions:

1. Alter your model to include the above considerations.

2. Run the model and graph the dune height, vegetation, and forest. How have these changes affected your graph?

3. Create a table of dune height, vegetation, and forest. At what point does vegetation occur? At what point does the forest begin to grow? Does this time sequence make sense? Why or why not?

Sample Solutions: (These results were obtained by using a dt = 1.)

1. Figure 7: Barrier Island Development Assuming Exponential Growth

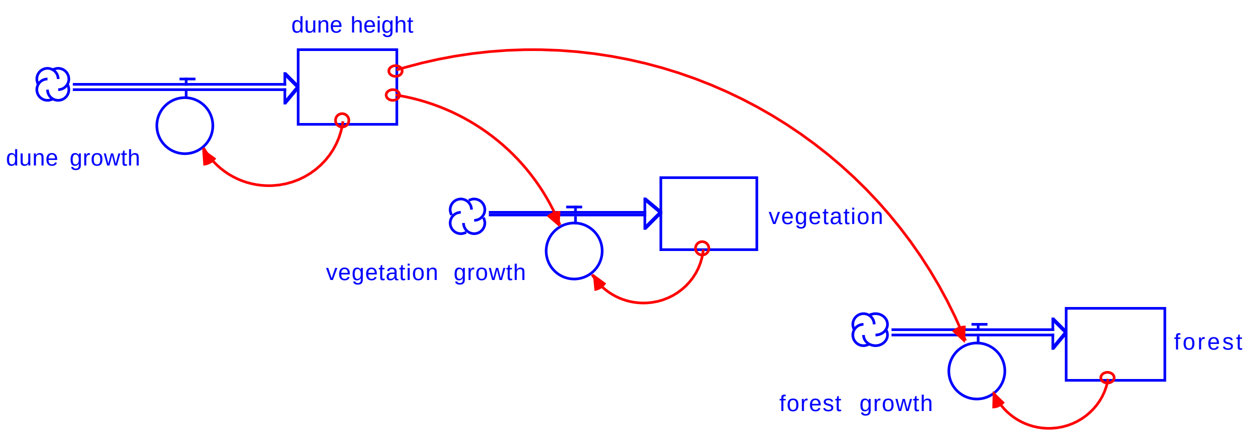


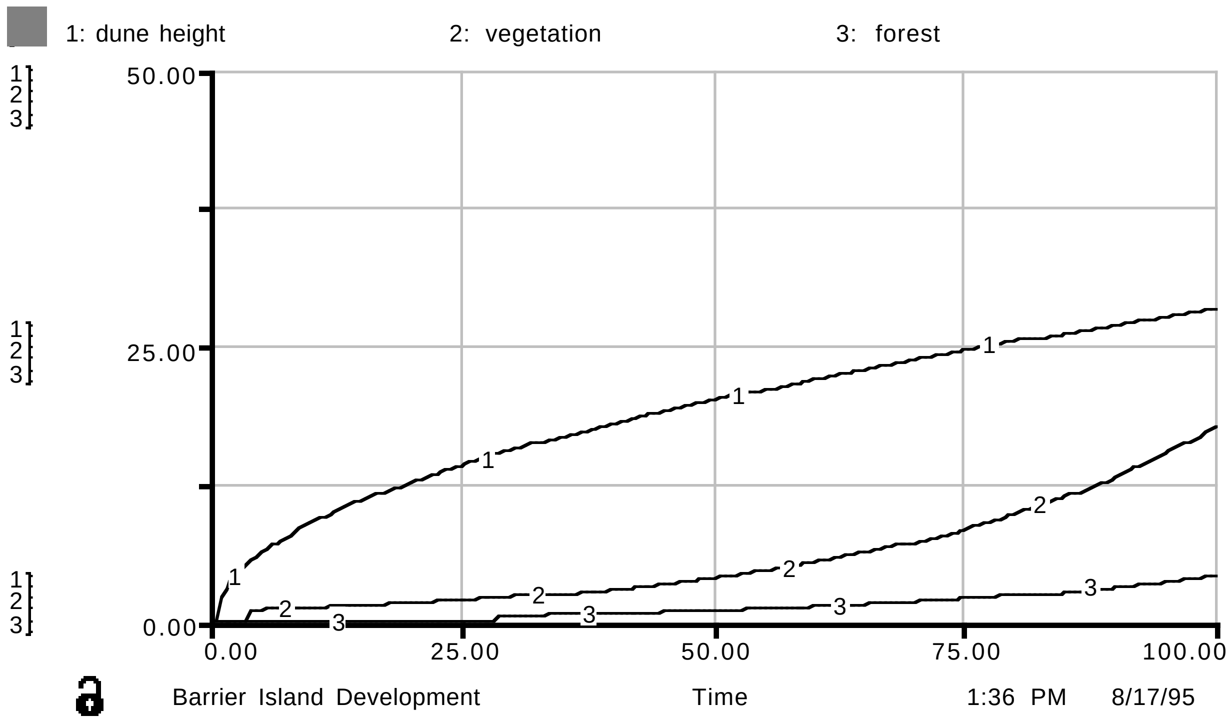
Figure 8: System Equations

dune_height(t) = dune_height(t - dt) + (dune_growth) * dt
INIT dune_height = 0
INFLOWS:
dune_growth = if (dune_height=0) then 4 else (4/dune_height)

forest(t) = forest(t - dt) + (forest_growth) * dt
INIT forest = 0
INFLOWS:
forest_growth = if dune_height>=15 then if (forest = 0) then 1 else forest*.03 else 0

vegetation(t) = vegetation(t - dt) + (vegetation_growth) * dt
INIT vegetation = 0
INFLOWS:
vegetation_growth = if (dune_height >= 5) then if vegetation=0 then 2 else vegetation*.03 else 0

2. Figure 9: Barrier Development Assuming Exponential Growth



Notice that the growth is no longer linear. For instance, by making the dune growth inversely proportional to the dune height, the graph has become logarithmic. Vegetation and forest growth are now affected by their previous levels. Therefore, their curves are exponential.

3. Figure 10: Barrier Island Development Assuming Exponential Growth

Time	Dune	Vegetation	Forest
0.0	0.00	0.00	0.00
10.0	9.13	**1.21**	0.00
20.0	12.81	1.63	0.00
30.0	15.63	2.20	**0.52**
40.0	18.02	2.96	0.70
50.0	20.12	3.99	0.95
60.0	22.03	5.38	1.28
70.0	23.78	7.24	1.72
80.0	25.40	9.76	2.32
90.0	26.94	13.14	3.12
Final	28.38	17.70	4.20

Vegetation begins at 10.
Forest growth begins at 30.

Yes, this time sequence makes sense. In an actual barrier island system the dune would grow first. The dune then creates a protected environment which allows vegetation to grow. The vegetation then produces nutrients allowing the forest to grow.

Suggest to the students that they could modify the model to have vegetation directly affect forest growth rather than having dune height affect it. If the arrow from the dune height stock to forest growth is removed and an arrow from the vegetation stock to forest growth is inserted, the students could experiment with equations to see the results.

Barrier Island Model C:

Now that approximate trends for dune growth, vegetation growth, and forest growth have been established, you need to introduce one of the following variables to the model.

salt spray
wind velocity
accumulation of suitable topsoil
crowding of plants
storm surges and overwash

Here is an example. Salt spray will affect the area behind the dune and is harmful to vegetation growth. Vegetation growth will increase as salt spray decreases. Assume if there is no vegetation then vegetation grows at a rate of (2 minus the salt spray) square meters per year. Salt spray is inversely proportional to dune height. When the dune height equals 20 meters, assume that salt spray no longer reaches the area behind the dune.

Exercises and Discussion Questions:

1. Create a new model incorporating one of the variables listed above. Run the new model and look at the graphs. You may need to adjust the equations, the graph scale, or the constants to achieve a realistic model. Try graphing the new variable and see how it relates to the development of a barrier island.

2. In a paragraph, explain the equations and constants you used as well as the results you achieved.

3. Your model probably does not realistically demonstrate the development of a barrier island. What are some of the factors missing from your model?

4. What problems did you encounter modeling a complex system such as this?

5. What is gained from creating a model where many of the equations and mathematical relationship are not well defined?

Sample Solutions:

1. The model below is one interpretation of the data. Depending on which factor the students choose to introduce, their models will differ.

Figure 11: Barrier Island Development Including Salt Spray as a Variable

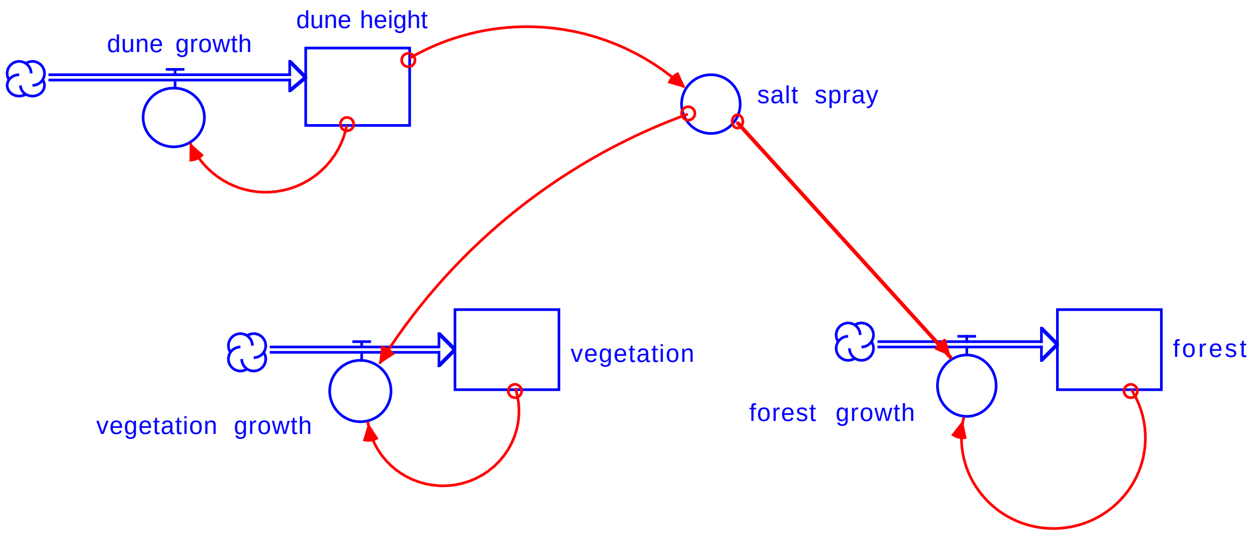


Figure 12: System Equations

dune_height(t) = dune_height(t - dt) + (dune_growth) * dt
INIT dune_height = 0
INFLOWS:
dune_growth = if (dune_height= 0) then 4 else 4/dune_height

forest(t) = forest(t - dt) + (forest_growth) * dt
INIT forest = 0
INFLOWS:
forest_growth = if (salt_spray=0) then if (forest = 0) then .25 else forest * .1 else 0

vegetation(t) = vegetation(t - dt) + (vegetation_growth) * dt
INIT vegetation = 0
INFLOWS:
vegetation_growth = if vegetation = 0 then 2 - salt_spray else (2 - salt_spray) * vegetation * .1

salt_spray = if (dune_height >= 20) then 0 else if dune_height < 1 then 15 else 20/dune_height

Figure 13: Barrier Island Development Including Salt Spray as a Variable

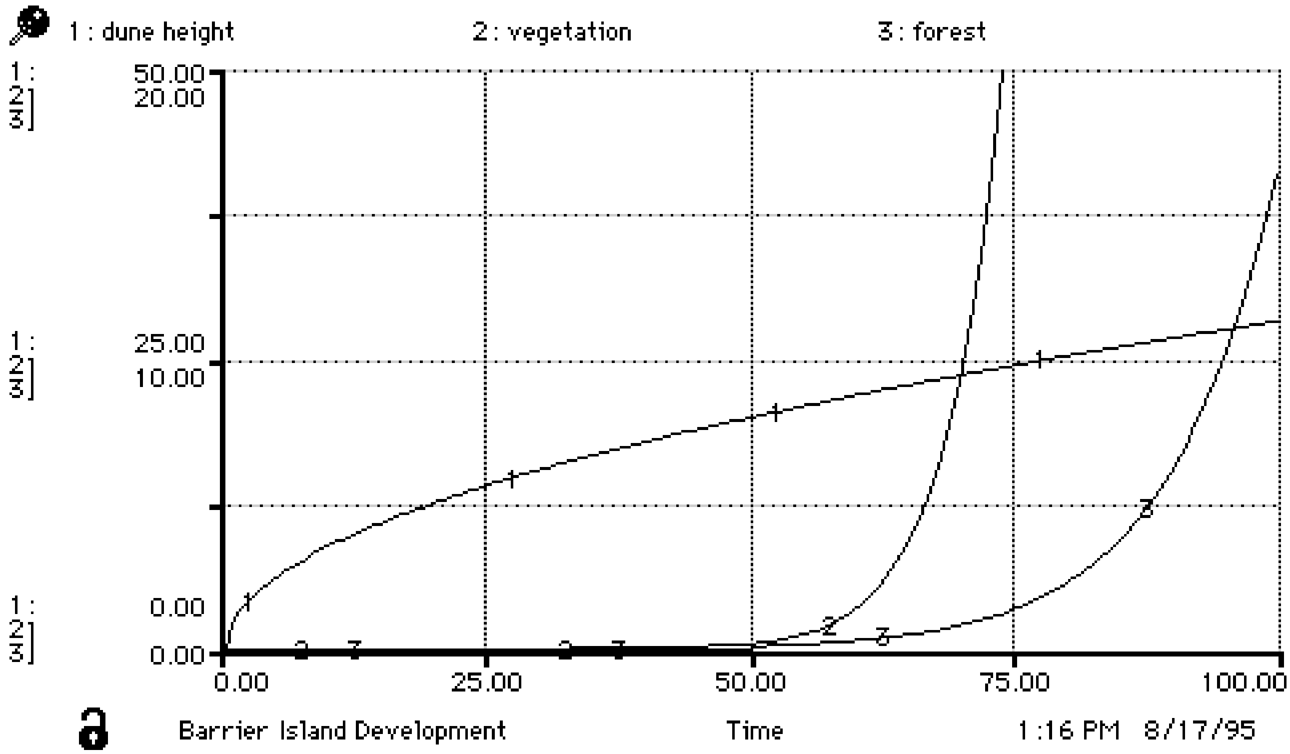
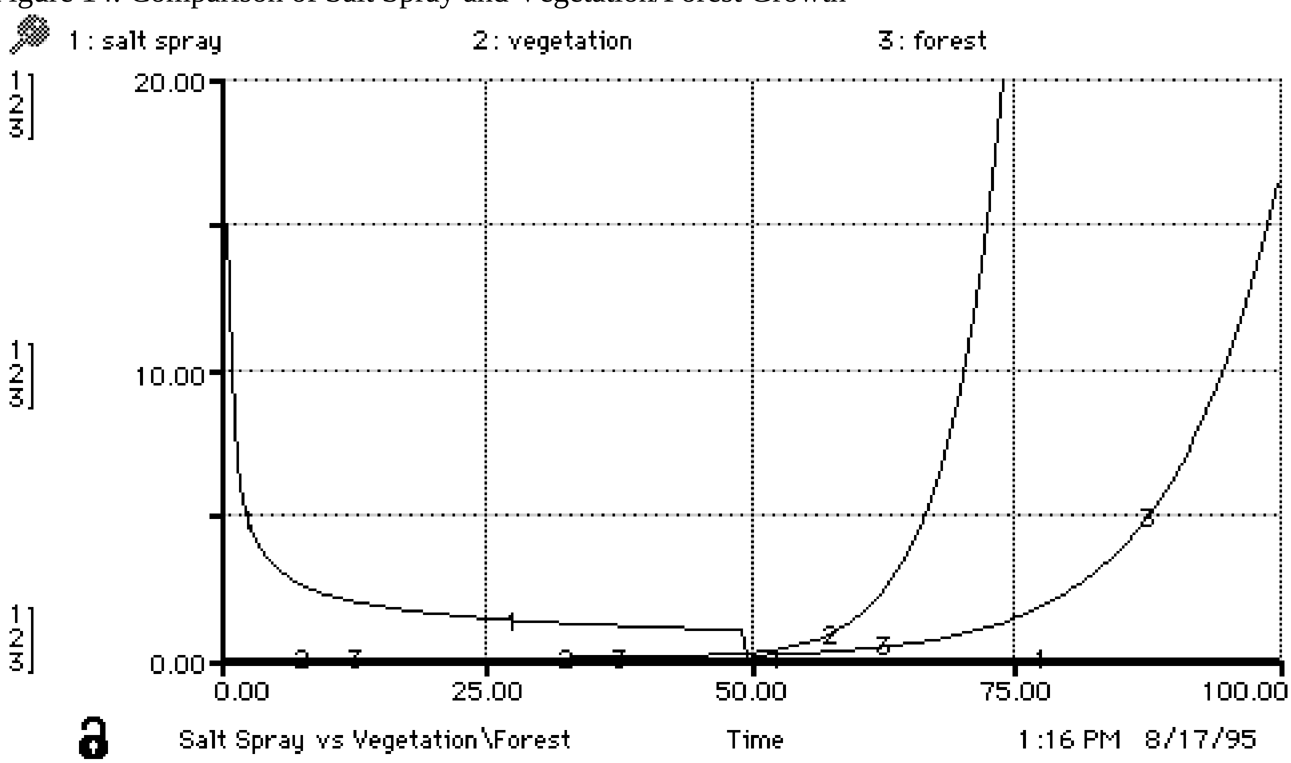


Figure 14: Comparison of Salt Spray and Vegetation/Forest Growth



2. Because the relationships used in this model are not well understood by the scientific community, the equations used to introduce salt spray into the model are not accurate. The equation 20/dune height was used because the relationship between salt spray and dune

height is inversely proportional. As the dune height increases the amount of salt spray decreases. The value 20 was arbitrarily chosen.

3. There are many other variables that contribute to the growth of a dune system besides salt spray. For example, the velocity of the wind, the accumulation of topsoil that will encourage plant growth, the crowding of plants which will inhibit plant growth, and storm surges that will overwash the dune and decrease its height.

4. The main problem with modeling complex systems is the lack of mathematical equations relating the variables. Without these the model can only be constructed from sparse data and/or a rudimentary understanding of the trends. This, of course, greatly limits the accuracy of the model. In addition, there are so many factors to consider that the model quickly becomes complicated. Many relationships have been overlooked. In a real world situation an apparently small variable which was overlooked can have a large impact on the system.

5. Although this model may seem to have little practical application, modeling simplified systems is an important step toward understanding complex systems. This rudimentary model should not be used to make crucial political and engineering decisions; however, by creating such a model you begin to understand the factors involved in the system. This provides a solid starting point for building a model that eventually can be used for practical applications.

References:

Leatherman, S.P. Barrier Island Handbook, College Park, Maryland: Coastal Publication Series, 1988.

Mendelssohn, I.A., Hester, M.W., Monteferrante, F.J., and Talbot, F. "Experimental Dune Building and Vegetative Stabilization in a Sand-Deficient Barrier Island Setting on the Louisiana Coast, USA." Journal of Coastal Research , Winter 1991,v7, n1, pp.137-149.

Scott, J. Between Ocean and Bay. Centerville, Maryland: Tidewater Publishers, 1991.