THE RECOVERY AND ECOLOGICAL SUCCESSION OF THE TROPICAL MONTSERRAT FLORA FROM PERIODIC VOLCANIC ERUPTIONS

BU-1513-M **Summer 1998**

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Daniella Costo
Lisa Denogean
Akuba Dolphyne
and
Carrie Mello

Keywords: not provided.

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The Recovery and Ecological Succession of the Tropical Montserrat Flora From Periodic Volcanic Eruptions

Daniella Costo[*] Lisa Denogean[†] Akuba Dolphyne[‡]
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Abstract

The island of Montserrat, located in the British West Indies, experiences periodic volcanic eruptions that destroy major regions of the indigenous plant life and leaves lasting damage from volcanic pollution. This project intends to model the process that occurs as this damaged tropical ecosystem recovers from volcanic eruptions. We will use a stochastic model to study the ecological succession after volcanic disturbances. We expect to see a redistribution of the diversity of plant life according to the different levels of devastation. The simulations of recovery should show that after a period of time, a large region of the recovered plant life will reach an equilibrium without risk of extinction.

1 Introduction

Ongoing eruptions, beginning in 1995, have destroyed 2/3 of Montserrat's ecosystem, forcing evacuation from this area (*Soufriere Hills Volcano, Montserrat*). The volcanic tropical island of Montserrat is located in the British West Indies. The volcano on Montserrat experiences periodic activity and just recently began an actively eruptive phase. The continuous eruptions expel hot rock, ash, and other pollutants which disrupt the recovery of the ecosystem. Thousands of islanders were forced to leave their homes due to

[*]California State University, Sacramento
[†]California Polytechnic State University, Pomona, e-mail: denogean@earthlink.net
[‡]Wellesley College, Wellesley, MA, e-mail: adolphyne@wellesley.edu
[§]University of California, Riverside

the lethal pollution which substantially destroyed much of their subsistence agriculture.

As with any natural disaster or disturbance, the recovery of the environment depends on the success of a pioneering species. From this species, higher order plants dependent on this new growth also begin to reappear. The species in this region continue to recover until there is another disruption which destroys patches of re-growth. Within these patches, the pioneering species takes over and the succession starts again. This constant cycle allows for greater diversity as re-growth is occurring throughout the environment.

Diversity implies a better health of the ecosystem, since it means there will be a greater number of different species. As diversity increases, resilience of the ecosystem increases. A relatively homogeneous environment would be unstable - as it would be vulnerable to widespread destruction and the possibility of extinction of certain species. The maximum sustainable diversity occurs when an environment experiences periodic disturbance at an intermediate level. According to Michael Rosenzweig, the intermediate disturbance theorem states, "patches with very high disturbance rates do have very few species. But so do patches with very low disturbance rates. Diversity peaks over intermediate disturbance levels." (Page 36).

To describe the biological process of succession on Montserrat, we use a discrete time stochastic model as opposed to a deterministic approach. In a deterministic model, the state at any time can be computed exactly with a given initial condition. However, these models that give exact solutions are mathematically ideal and not seen in real-world observations. On the other hand, stochastic processes allow for "random" events that can affect the outcome. Using this type of model, we can have numerous simulations resulting in varying outcomes, starting with the same initial conditions. Stochastic models incorporate the fact that "chance" events make the future unpredictable, while in deterministic models the future is exactly known. (Adler 447-448)

1.1 Volcanic Destruction

Throughout the world, volcanoes have been a major destructive force. They clear away surrounding vegetation, ultimately allowing an ecosystem that would otherwise be more homogeneous to gain a greater level of diversity. This level of diversity depends on the amount of destruction caused by the volcano, which is determined by the amount of pollution produced by the

volcano. This pollution primarily consists of gas emissions, lava flow, pyroclastic flows, pyroclastic surges and tephra falls. All these pollutants kill foliage to different degrees in areas around the volcano.

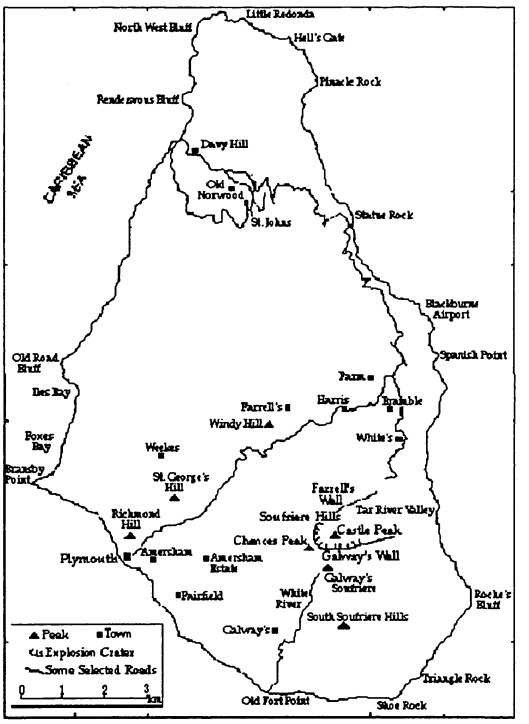
The area directly surrounding the volcano is the most polluted. This is due to the fact that lava and gases, the deadliest of the five pollutants listed, are found in this region. The principal gases emitted are steam, carbon dioxide, sulfur and chlorine compounds. These gases are emitted directly from the lava and are rapidly distributed through the risk areas by wind. These dilute gases are still lethal to plant life. (*Soufriere Hills Volcano, Montserrat*)

The main destruction in an area affected by high levels of pollution, is caused primarily by pyroclastic flows and surges. Pyroclastic flows, avalanches of hot, dry volcanic rock, travel farther from the volcano because they are dry, unlike lava. Pyroclastic surges travel above pyroclastic flows. Their behavior is similar to that of a fast moving hurricane. (Blong 33-36). Due to this behavior, they are extremely destructive.

During an eruption, a mixture of hot volcanic gas and tephra is ejected from the volcano forming a cloud of tephra particles . Tephra includes volcanic ash and larger rock fragments and is considered lower levels of pollution. (Blong 21). As the pollution cloud drifts away from the volcano, particles fall to the ground forming a blanket-like deposit of ash that gets thinner and finer as the cloud gets further away from the vent.

1.2 Soufriere Hills

The Soufriere Hills volcano, we are modeling, experiences a Pelean type of eruption. These eruptions are characterized by three main features. The first is the growth of a dome. This dome growth in the Soufriere Hills volcano is caused by the cluster of vents, which is a common feature of composite volcanoes. (Scarth 177-178, 53-56). There are five domes which make up Soufriere Hills. These five domes are Gage's Mt., Chance's Mt., Galway's Mt., Perch's Mt., and Castle's Peak. Castle's Peak is located in English's Crater, as shown on the following map (*Excite: Travel: Montserrat: Maps*).



Map of Montserrat

This is the only active vent and is the site we are modeling our project on (*Soufriere Hills Volcano, Montserrat*). The second main feature of Pelean eruptions is the frequency with which it erupts. These eruptive periods are typically separated by decades of inactivity. The third and probably the most distinguishing feature of Pelean eruptions is the thick accumulation of ejected material as the volcano's most prominent form of pollution. Pelean eruptions have a maximum coverage of only about 50 km^2(where Montserrat is 100 km^2). (Scarth 53-56). Although the Soufriere Hills volcano is not considered very explosive, it can be a devastating force to this small island.

2 EcoBeaker

By using a simulation program named *EcoBeaker*, we were able to run different scenarios for different degrees of disturbance in a simplified two species environment. This is used strictly as a simplification of a disturbance

scenario to analyze patterns of succession. We use a transition matrix in *EcoBeaker* to describe the rules of the succession that takes place after a disturbance. *EcoBeaker* incorporates the chance of fire or other devastation in random areas during the simulation. There is also a chance this disturbance will spread to adjacent areas. A map is displayed in EcoBeaker that starts with barren land and pictorially maps the re-growth process. This program also calculates the Simpson index to give the user a numerical representation of the species diversity.

2.1 EcoBeaker Theoretical Model

Looking at a simple and generalized two species model on *EcoBeaker*, we want to compare the degree of diversity obtained when we introduce disturbance into an environment. This environment consists of a population of strictly theoretical species 1 and 2. Without disturbance, species 1 tends to be more invasive, while species 2 is more pervasive; meaning species 1 grows well initially, while species 2 becomes more abundant as the system recovers.

To incorporate the succession rules, for this two species model, into the EcoBeaker simulation, the transition matrix used was:

$$P = \begin{array}{c} \\ 0 \\ 1 \\ 2 \end{array} \begin{array}{c} \begin{array}{ccc} 0 & 1 & 2 \end{array} \\ \begin{pmatrix} 1-p-q & p & q \\ 1-\alpha & \alpha & 0 \\ 1-\beta & 0 & \beta \end{pmatrix} \end{array}, \tag{1}$$

where p is the probability of pioneering by species 1, q is the probability of pioneering by species 2, α is the rate of sustainability of species 1, and β is the rate of sustainability of species 2. Since species 1 is more invasive, we choose p>q; and since species 2 is more pervasive, we choose $\beta > \alpha$. After a disturbance affects random areas our states 1 and 2 may become state 0, which is barren land.

2.2 EcoBeaker Simulations and Analysis

The following graphs correspond to the three different disturbance scenarios we ran:

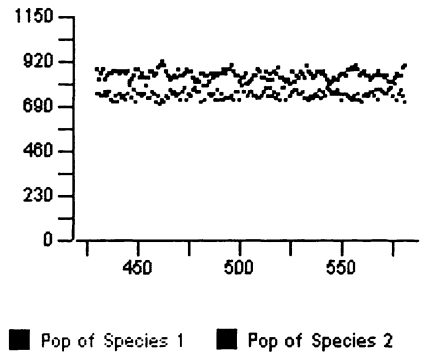


Figure 2.1 population vs time

The chance of land disturbance was 10% with was 10% with Simpson's diversity index of 1.900.

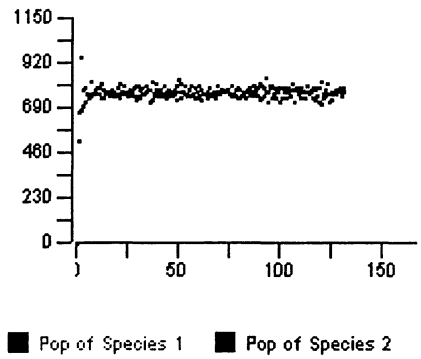


Figure 2.2 population vs time

There was an increase in the chance of land disturbance to 20%, with a corresponding species diversity of 1.994.

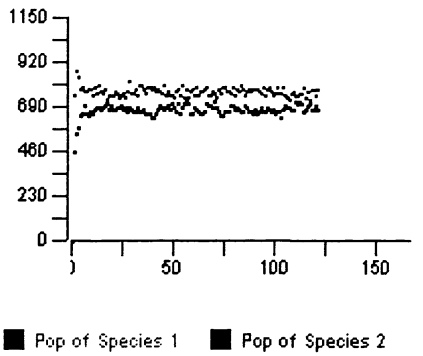


Figure 2.3 population vs time

This shows a diversity of 1.988 when there is a 30% chance of land disturbance.

Figures 2.1, 2.2 and 2.3 are representative of the stable distribution of species after different levels of land disturbance. In figure 2.1 with 10% disturbance, species 2, the pervasive species, became more abundant than species 1. Therefore, this disturbance was not enough to allow for species 1 to maintain a significant population. In figure 2.2, with a disturbance of 20%, both species persisted at near equal levels after an initial recovery period. With this rate of intermediate disturbance, there was the greatest amount of diversity. The index value of 1.994 is about as high as can be expected for a two species model. As diversity increases this number will asymptotically approach 2, since it is a measurement of the number of different species found in any given area and it is bounded by the number of species that exist. In figure 2.3, species 1 persisted at greater levels due to an increased chance of disturbance which allowed for more settlement by this invasive species.

2.3 EcoBeaker Conclusions

As shown by the simulations above, there is always a point at which a level of intermediate disturbance allows for the maximum attainable diversity possible. In our model of the Montserrat volcanic activity, we would like to see if the frequency of eruptions will allow for sufficient diversity. Ideally, the disturbance rate of volcanic eruptions will yield a large amount of diversity, such that the ecosystem is able to attain an equilibrium without any species

being driven to extinction. We will attempt to forecast this equilibrium distribution of plant life.

We were unable to use *EcoBeaker* to simulate our model because *EcoBeaker* displays random disturbance within a patch of land, unlike the disturbance of volcanic activity. Volcanic disturbance, in particular, periodically destroys specific hazard areas that are shaped by the landscape of the region and magnitude of the eruption. Therefore, we worked on creating a program in *MatLab* to run simulations using predetermined destruction and hazard areas.

3 Model Building

3.1 Approximation of Volcanic Activity

Due to the unavailability of adequately simplified data on the frequency and magnitude of volcanic activity on Montserrat, there was the need to approximate volcanic activity from a related phenomenon–earthquakes.

In 1897-9,1933-6 and 1966-8, and leading into the current eruptive phase, there have been series of earthquakes in Montserrat. These earthquake swarms were accompanied by an increase in volcanic activity. There was enough evidence for scientists to suggest that there is a causal inter-relation between the two phenomena (Mac Gregor 14). R. J. Blong describes this causal inter-relation: Volcanogenic earthquakes are produced by various phenomena. "Most ... result from movement of magma, formation of cracks through which it can move, and gas explosions within the conduit" (Blong, 84).

Volcanologists do debate about the relationship between earthquakes and volcanic activity, since not all volcanic activity is preceded by earthquakes. However, "earthquakes occur before most eruptions", and in the case of Montserrat, all volcanic activity since 1897 has been accompanied by earthquakes (Blong, 86). Therefore, our approximation of volcanic activity on Montserrat using earthquakes is fairly reasonable and accurate.

3.1.1 Approximation Procedure

Using a detailed seismological chart of the earthquake swarms and gas emissions from the Soufriere Hills volcano from January 1933 to December 1937 (Perret 20a), we were able to approximate the magnitude and frequency of volcanic activity. We chose a time period of 1 week instead of, for example,

a month, in order to obtain as much and as accurate data as possible from our chart. Within this week period, we noted volcanic activity when there were gas emissions coinciding with a high frequency of earthquakes. This relationship was indicative of the swarm of earthquakes that characterize the periods of volcanic activity on Montserrat. During the weeks we considered to be active, we classified the magnitude of volcanic activity into small, medium and large in order to simplify our model.

3.1.2 Transition Matrix for Frequency and Magnitude of Volcanic Activity

Doing this week by week determination of the occurrence and magnitude of volcanic activity gave us the following data in Table 3.1. Using this data, we constructed a 4x4 transition matrix governing the frequency of occurrence of volcanic activity and the magnitude of activity.

Sequence	Time(weeks)	Eruption Type	Time(weeks)	Eruption Type	Sequence
1	**1**	S	**1**	M	23
2	**1606**	N	**12**	N	24
3	**1**	S	**1**	M	25
4	**11**	N	**3**	N	26
5	**1**	S	**1**	M	27
6	**6**	N	**2**	N	28
7	**1**	M	**1**	M	29
8	**11**	N	**1**	S	30
9	**1**	M	**3**	N	31
10	**14**	N	**1**	S	32
11	**1**	M	**1**	N	33
12	**4**	N	**1**	M	34
13	**2**	S	**6**	N	35
14	**2**	N	**1**	S	36
15	**1**	M	**11**	N	37
16	**1**	N	**1**	S	38
17	**1**	M	**29**	N	39
18	**5**	N	**1**	S	40
19	**1**	M	**16**	N	41
20	**3**	N	**1**	S	42
21	**1**	L	**1588**	N	43
22			**1**	S	44

Table 3.1: Volcanic Activity (in weeks)

From the data in Table 3.1, we calculated the number of weeks with inactivity which were directly followed by another week of inactivity. The number of weeks with no activity which were directly followed by weeks of small, medium and large magnitudes of activity were similarly calculated. This exercise gave us the following information:

	N	S	M	L
N	3314	9	10	1

Table 3.2: Number of different activity types observed following the state N.

That is, there was a total of 9 weeks of inactivity which were each followed

by a week of small volcanic activity, and so on, where the total number of weeks with inactivity =3314+9+10+1=3334

From this data, the probabilities of having a week of inactivity or small, medium or large magnitudes of activity directly following a week of inactivity, were calculated by dividing each entry in figure 3.2 by the total number of weeks of inactivity (3334). This gave us the following data:

	N	S	M	L
N	0.9940	0.0027	0.0030	0.0003

Table 3.3: Probability of each event type recurring, given current state N.

For example, the probability of experiencing a week of small volcanic activity directly after a week of inactivity is 0.0027.

The entire process was repeated for weeks of small, medium and large activity. This gave us the following transition matrix which governs the probability of experiencing volcanic activity and also gives the probability of experiencing any given magnitude of activity.

$$P = \begin{array}{c} \\ N \\ S \\ M \\ L \end{array} \begin{array}{c} \begin{array}{cccc} N & S & M & L \end{array} \\ \begin{pmatrix} 0.9940 & 0.0027 & 0.0030 & 0.0003 \\ 0.9091 & 0.0909 & 0.0000 & 0.0000 \\ 0.9091 & 0.0909 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 1.0000 & 0.0000 \end{pmatrix} \end{array} \tag{2}$$

3.2 Pollution and Polluted Areas

3.2.1 Types of Pollution Modeled

As described in section 1.1, volcanoes produce various types of pollution which cause different types and magnitudes of devastation. In order to simplify our model, we do not model the specific effects of the different types of volcanic hazards . Instead, we classified volcanic pollution and its effects into two types: high pollution (HP) and low pollution (LP). HP was defined as pollution and devastation caused by the more severe types of volcanic hazards, such as lava and pyroclastic flows. LP included milder forms of pollution such as tephra fall. Over time, HP areas recover and are classified as LP areas. LP areas, in turn, decay into unpolluted or negligibly polluted areas that we classify as barren land (B).

3.2.2 The Polluted Areas

The severity of the effects of most volcanic hazards decreases as one moves further away from the volcanic center. In our model, we took this pattern of devastation and deposition of pollutants into account by defining 3 areas, A, B and C, which experience decreasing levels of devastation and pollutant deposition. In A, which is closest to the volcano, there is total devastation of plant life by hazards such as lava and severe pyroclastic flows and surges. This level of devastation was chosen because of the negligible survival rate of such severe volcanic hazards (*Soufriere Hills Volcano, Montserrat*). The A area is covered with thick deposits of volcanic pollutants and is therefore considered to be a 100% high pollution (HP) area.

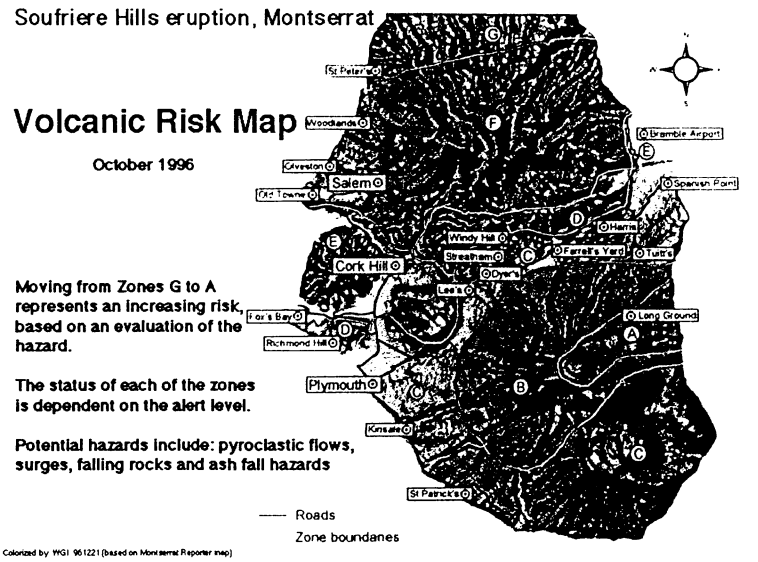
Area B was defined as having 75% devastation of plant life. This figure was approximated from the 90% mortality rate of humans from pyroclastic flows. Since B experiences less severe flows and plants can generally withstand such hazards more than humans can, we decided that a 75% level of devastation of plant life was a reasonable approximation of what occurs in the B area. The devastated area is covered by high pollution. The remaining area is covered by plant life that escaped destruction and by low pollution. The exact manner in which this is done is discussed in the computer modeling section 5.2.

Area C is found farthest from the volcanic center. This region experiences the least severe effects of the volcanic hazards. The extent of devastation was therefore approximate to be 60%, in comparison to 75% for area B. The affected areas are covered by low pollution only. There is no high pollution present. This reflects the lower degree of devastation that C experiences. The remaining area is covered by plant life that escaped destruction.

3.2.3 The A, B, and C Areas

Our A, B and C areas were defined on the map of Montserrat using a risk map of the island constructed for the ongoing volcanic activity (see next page). Since we do not consider increasing magnitudes and intensity of volcanic activity in our model (see section 6.2), we assumed that the present activity corresponded to our definition of a large volcanic activity. We therefore defined our A, B, and C areas for large volcanic activity as the regions of very high, high and low risk from volcanic hazards respectively, given on the risk map. Since eruptions of lower intensity produce proportionally smaller

risk regions, the A, B, and C areas for low and medium volcanic activity were approximated and drawn as smaller regions within the risk areas given by the risk map.



3.3 Modeling Plants

Our primary interest in the consequences of the volcanic activity on Montserrat is the ability of the ecosystem to recover from the effects of volcanic hazards. This process of recovery involves ecological succession. We therefore needed species that would portray this clearly: a pioneering species, a second order species and a higher order species. All ecological systems have competition between the species that inhabit or make up the system. Therefore, in order to obtain more realistic results, we decided to include an element of competition between the second order and higher order plant species. The second order species was consequently chosen to be a pervasive species that can succeed the higher order plant, along with the other species in our ecological succession.

Since we wanted to study the effects of pollution on the plant life, we also thought that studying a plant resistant to pollution would produce interesting results. For example, considering a scenario of very frequent and destructive volcanic activity, if we did not model any resistant plants, it would be possible for us to see no plant regrowth in the constantly polluted

areas. This situation that would not be entirely accurate if it was possible for these resistant plants to be present. Thus, our plants were chosen to incorporate realistic properties and hence, accurately portray what actually happens on Montserrat.

3.3.1 Theoretical Plants

We initially intended to model specific plant species found on Montserrat. However, due to the unavailability of adequate numerical data describing the process of ecological succession for these plants, it was necessary to use strictly theoretical plants. We were advised to take this approach on consulting Prof. Peter Marks of the Ecology department at Cornell University. We therefore defined four theoretical plants whose characteristics were approximated from the descriptions of species found on Montserrat. These species include *Phyllanthus mimosides*, a pervasive shrub found in Montserrat's secondary rain forest; *Sloanea* -the burrwood tree- which is found to a lesser degree in this secondary rain forest; and *Clusia alba*, a resistant species found in the gas polluted areas near the volcanic vents of the Soufriere Hills volcano.

3.4 Plant Definitions and Rules Governing Ecological Succession and Pollution Decay

Estimations of the time periods during which pollution decay occurs is discussed in the assumptions section.

1. HP, High Pollution Areas: This is land devastated and polluted by severe volcanic hazards, as defined in section 3.31. The pollution decays over an average of 2 years into LP. HP is not succeeded directly by any other elements of the matrix since no plants can grow in high pollution.

2. LP, Low Pollution areas: This is land devastated and polluted by less severe volcanic hazards. This land can sustain the resistant species, R, after 1 year. The pollution can also decay in the absence of the resistant species, into unpolluted or negligibly polluted land (B), in 3 years. Low pollution areas are never colonized by any of the other plant species, since they are not resistant to pollution.

3. B, Barren Land: This is unpolluted or negligibly polluted land which is not as yet colonized by any plants. Unpolluted land does not lie barren for long. It can be colonized by the pioneering species P within 1 year. R cannot colonize this area for reasons discussed in the paragraph

below. The other plants, S and HO, are high order species in the process of ecological succession, and therefore cannot colonize barren land.

4. R, The resistant species: R is a resistant plant that flourishes as a pioneering plant in low pollution areas (LP) all over the island. R colonizes LP areas within 1 year. As a pioneering species, R can only be succeeded by the second order pervasive species (S). This occurs over an average of 2 years. It cannot be taken over by P since P, as a pioneer species, colonizes only barren land. It is also not taken over by HO, since R, as a type of pioneer species, is not a high enough order plant in this succession. R does not colonize unpolluted, barren land. This is because most such resistant species are not very good competitors. In the presence of optimal conditions, non-resistant plants usually colonize at a much faster rate than the resistant species do.

5. P, The Pioneer Species: P is a non-resistant, pioneer species which colonizes barren unpolluted land within 1 year. By its definition as a pioneering species, P cannot take over any other plant species. Its growth produces conditions (e.g. shade) that enable other less hardy plants in the succession to take root. It therefore paves the way for colonization of land by other plants in the ecological succession. P is taken over by the pervasive species (S) within 2 years.

6. S, The Pervasive, Second Order Species: As a second order species, S cannot grow on barren land, since it needs the conditions provided by pioneer species in order to survive. However, when other plants have colonized the land, it very easily takes them over. In this case, S takes over the two pioneering species R and P. For each plant, this succession occurs over an average of 2 years. As a pervasive species, S competes with the higher order species (HO) and takes it over in 2 years. S therefore succeeds all the plants in this succession at an equal rate.

7. HO, The Higher Order Species: By its definition as the plant highest in our ecological succession order, HO cannot colonize barren land or succeed either of the pioneering species, R and P. HO takes over S, high enough order plant in this succession, within an average 5 year period. HO can be taken over by S again within 2 years. This shorter period is an indication of S's highly competitive nature and the ease with which it takes over other plant species.

3.4.1 Transition Matrix For Succession and Decay

In order to model the decay of pollution and the process of ecological succession of our plants, we constructed a transition matrix that incorporated the rules discussed above (3.4). This was done by converting the time periods of pollution decay and ecological succession into probabilities, using an exponential probability function derived by Dribble et al. (Isaacs 545). This function gives the probability of the recurrence of an event within a given future time period using a known mean return period of the event. The function is given by:

$$(1 - e^{-t/m}), \tag{3}$$

where t is the future period of concern and m is the mean return period of the hazard.

In our model, since our time step is a week, t was chosen to be 1, and m was also given in weeks. The values assigned to m were the time periods needed for pollution to decay, or succession to take place, depending on which probability was being determined. After calculations using this probability function, we obtained the following transition matrix for ecological succession and decay of pollution :

$$P = \begin{array}{c} \\ HP \\ LP \\ R \\ B \\ P \\ S \\ HO \end{array} \begin{array}{c} \begin{array}{ccccccc} HP & LP & R & B & P & S & HO \end{array} \\ \begin{pmatrix} 0.9904 & 0.0096 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.9746 & 0.0019 & 0.0064 & 0 & 0 & 0 \\ 0 & 0 & 0.9904 & 0 & 0 & 0.0096 & 0 \\ 0 & 0 & 0 & 0.981 & 0.019 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.9904 & 0.0096 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.9962 & 0.0038 \\ 0 & 0 & 0 & 0 & 0 & 0.0096 & 0.9904 \end{pmatrix} \end{array} \tag{4}$$

4 Checking Parameters

Since our succession and pollution decay parameters were found mainly by estimation, we decided to use the simulation process in *EcoBeaker* to check the accuracy of our parameters. We used the estimated transition matrix for our model to run these simulations. Although *EcoBeaker* does not simulate a disturbance in the same way as required for a volcanic eruption, it provided a

good measure of the distribution of our plant species when there is a random disturbance.

4.1 Succession with No Disturbance

We first ran the simulation based on the succession transition matrix only, with no periodic disturbance. This simulation was run to view the interactions of the species. The initial land was empty. For simplicity, in this simulation the empty land immediately changes to 50% high pollution and 50% low pollution. Once the land was entirely polluted, the plant species were able to recover by order of succession with no further disturbance. The following graph compares the population levels of the different species and diversity measurement over time.

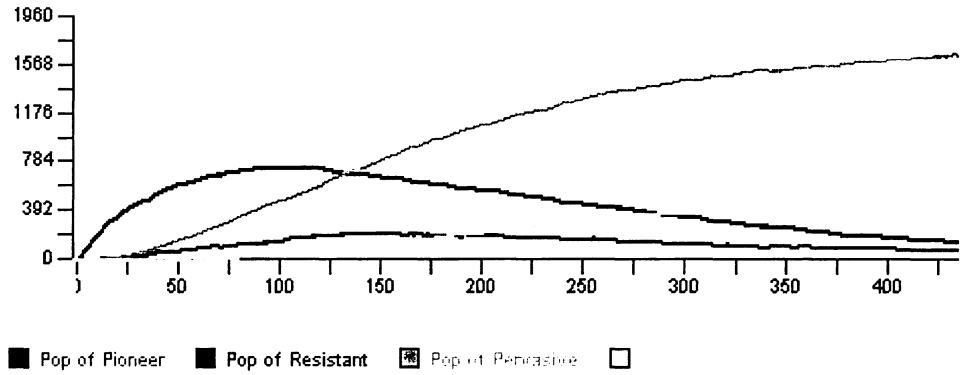


Figure 4.4 The recovery of plant species with no periodic disturbance (population vs time)

The following figures illustrate the regrowth of plant life based on the succession transition matrix in our model of Montserrat.

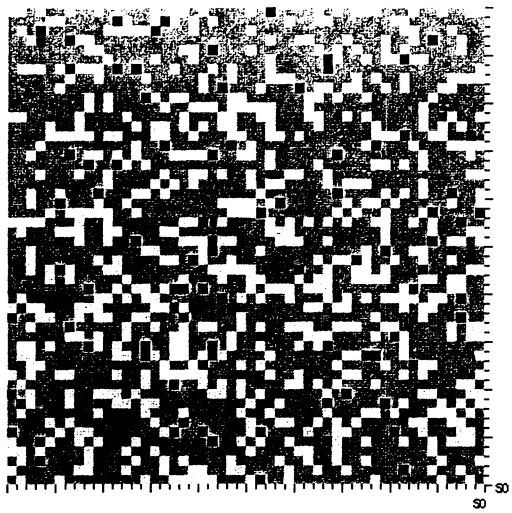


Figure 4.5 Initial recovery of plant life from polluted land

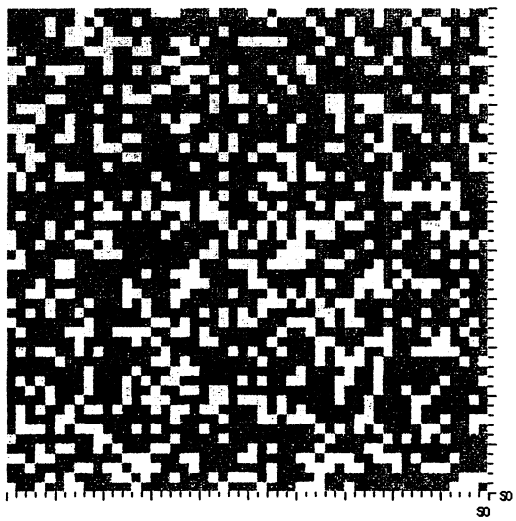


Figure 4.6 Long-run distribution of plant life with no disturbance.

As time progressed, the pervasive species was able to dominate pioneering and resistant. While maintaining a proportional relationship to the higher order species. These simulations allowed us a greater amount of certainty in the succession parameters we found, as this was what we expected to see, by definition of the theoretical species.

4.2 Succession with Periodic Disturbances

To check the interaction of all the parameters in the transition matrix, we introduced periodic disturbance to the environment. These parameters include succession, decay and disturbance rates. The probability of disturbance was based on the limiting distribution of our eruption transition matrix. This P^n is given by

$$\begin{matrix} N & S & M & L \end{matrix}$$
$$\begin{pmatrix} 0.9931 & 0.0033 & 0.0033 & 0.0003 \end{pmatrix} \tag{5}$$

We calculated the probability of any eruption happening by summing the long-run probabilities of a small, medium, or large eruption occurring (0.0033+0.0033+0.0003=0.007). So, the entered probability of a disturbance occurring at any time was 0.007.

The limitations of *EcoBeaker* did not allow us to be specific as to what size of disturbance would occur. In order to translate the different eruption levels in our model to this *EcoBeaker* simulation, we had to input a chance of the disturbance spreading. The chance of spread allowed for variations in the amount of coverage by a disturbance. This is another major difference in the use of *EcoBeaker*, in that our MatLab model will not include the chance of spread. It will only incorporate different levels of disturbance and predetermined pollution coverage for each of these different levels.

The following graph illustrates the continuous growth process with a moderate level of disturbance. After any disturbance, there is an immediate loss of all species in the affected area. Directly following this disturbance, the populations of resistant and soon after, pioneer species increase due to their relatively exclusive growth in the disturbed areas. Given a period of time without further disturbance, the pervasive and higher order plants begin to reach their equilibrium distribution as the resistant and pioneer species decline.

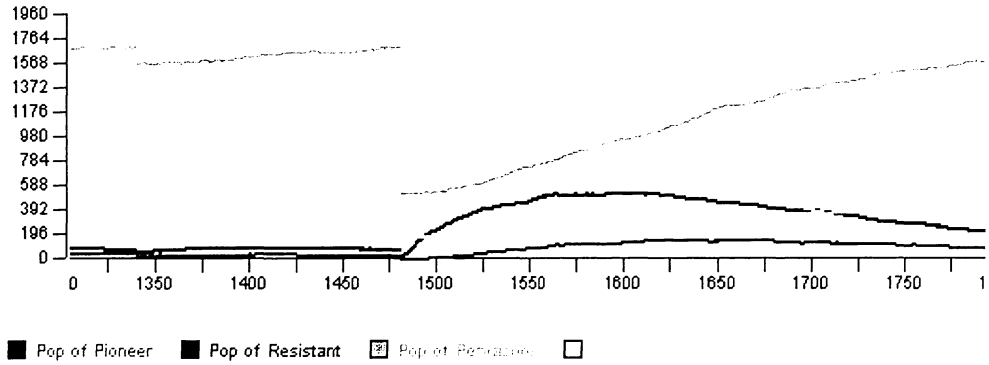


Figure 4.7 Populations of species with periodic disturbance of 0.007. The discontinuities in this graph are caused by sudden drops in the population levels due to the periodic disturbance. (population vs time)

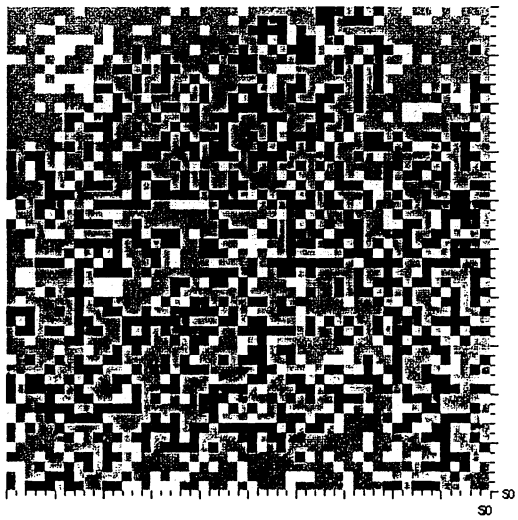


Figure 4.8 The recovery of plant life right after the moderate disturbance of 0.007.

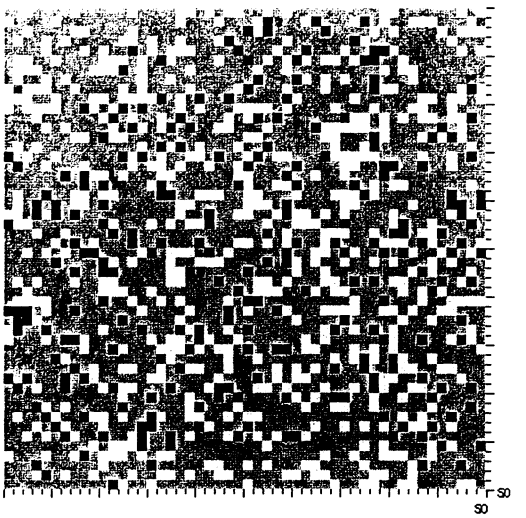
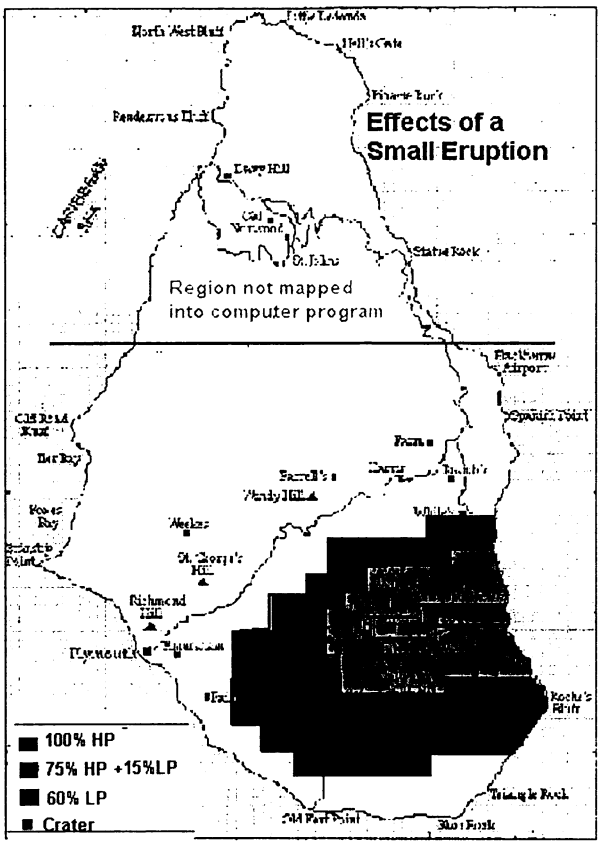


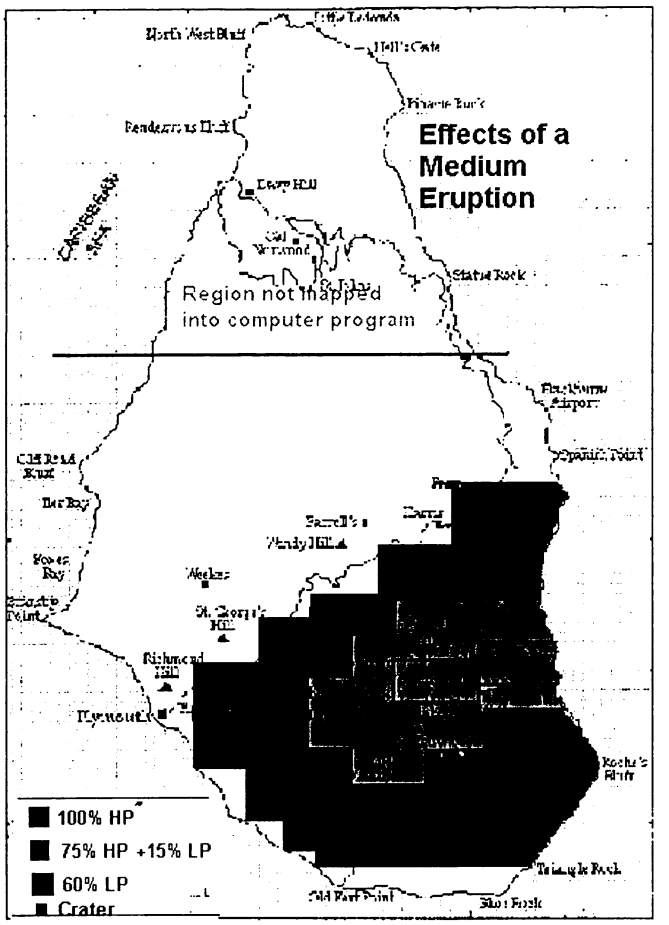
Figure 4.9 Continued recovery of species.

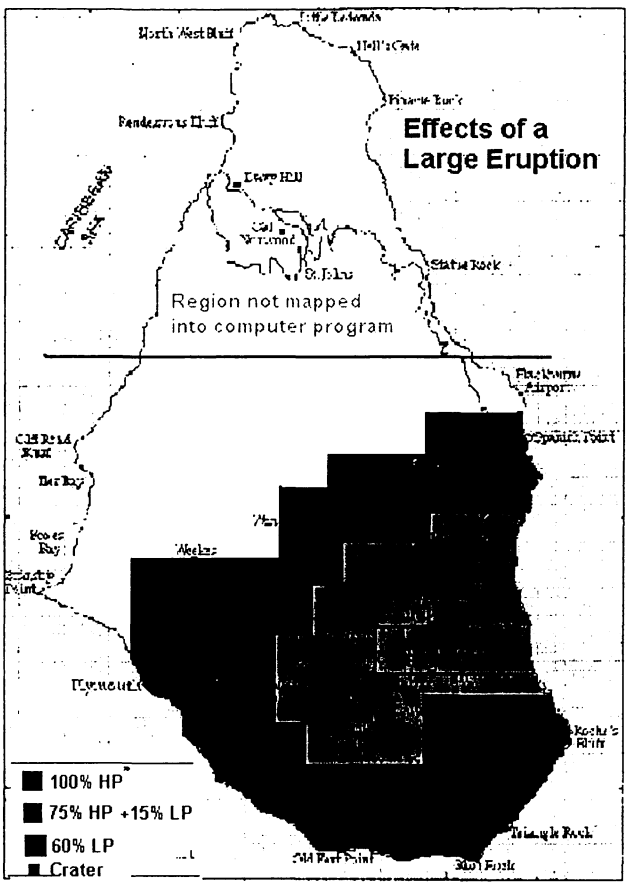
Unlike the long-run distribution of species in figure 4.6, a certain amount of diversity is maintained with periodic disruption, as seen in figure 4.9. Figure 4.9 shows the recovery that has occurred after the disturbance seen in figure 4.7. These graphs show us that the parameters we are using in our model accurately estimate the process of recovery and devastation, since these follow the general process of recovery as seen in any ecosystem.

5 Program Building

Our program in *MatLab* is designed specifically to the island of Montserrat. We focused only on the southern 2/3 of the island, which consisted of the previously mentioned A, B and C risk areas along with undisturbed habitat. We mapped the island into the computer program by using a representative grid of the area. Based on the risk map from the 1995 eruption mentioned in section 3.2.3, we determined hazard zones which would be most affected by the different types of pollution after a small, medium, or large eruption. The following pages display the A, B, and C pollution areas for each type of eruption.


Effects of a
Small Eruption
Region not mapped
into computer program
100% HP
75% HP +15%LP
60% LP
Crater


Effects of a Medium Eruption
Region not mapped into computer program
100% HP
75% HP +15% LP
60% LP
Crater



5.1 Implementation of Model

The program is designed to implement two separate transition matrices: the first is a transition matrix for the succession of plant species (3) from sec 3.41, and the second is a transition matrix of the state of activity of the volcano (2) from sec 3.12. The simulation begins with barren land and the succession matrix and the eruption matrix are immediately implemented. Each square on the map is constantly affected by the probability distribution contained in the transition matrices, which determine whether or not there will be a change at each time step. The change can be viewed easily by the color-code associated with each state:

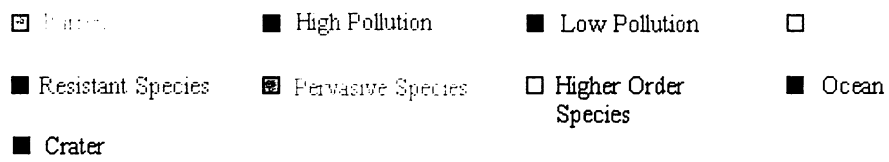


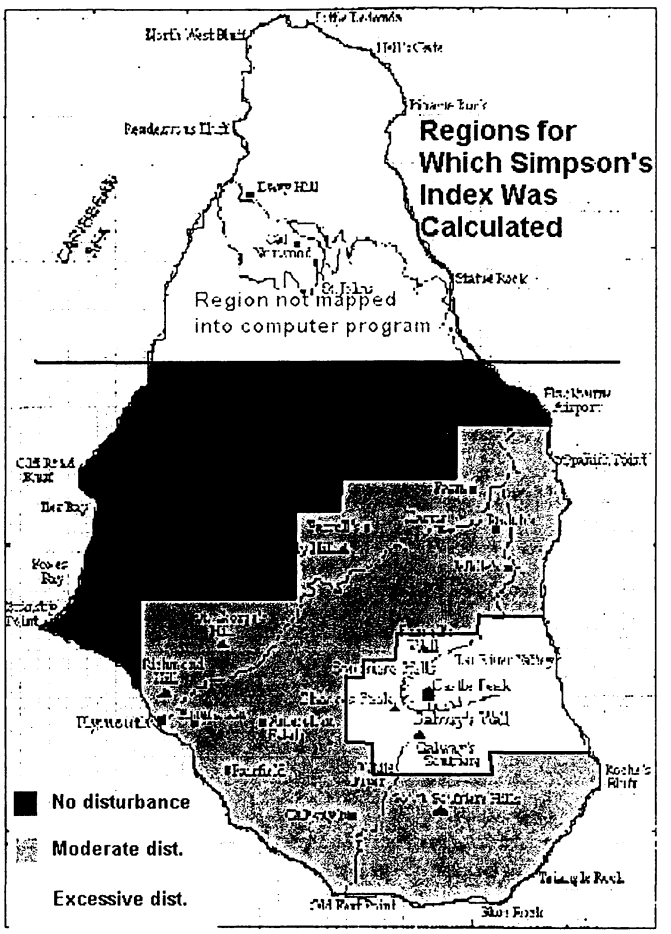
Figure 5.1 Color codes used in *MatLab* program.

5.2 Necessary Alterations to Model

The design of the program required that we slightly alter the transition matrix for the model. It was necessary to append states corresponding to the ocean (O) and the volcanic crater (C). For simplicity, we also rearranged the order of the states. The revised matrix can be given as

$$P = \begin{array}{c} \\ O \\ C \\ HP \\ LP \\ R \\ B \\ P \\ S \\ HO \end{array} \begin{array}{c} \begin{array}{ccccccccc} O & C & HP & LP & R & B & P & S & HO \end{array} \\ \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.9904 & 0.0096 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.9746 & 0.019 & 0.0064 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.9904 & 0 & 0 & 0.0096 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.981 & 0.019 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.9904 & 0.0096 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9962 & 0.0038 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0096 & 0.9904 \end{pmatrix} \end{array} \tag{6}$$

The occurrence of an eruption is strictly controlled by the matrix for volcanic activity. It is not affected by the succession transition matrix. Therefore, an eruption occurs independent of the process of regrowth. After an eruption, low pollution is programmed to cover the entire affected region determined by the magnitude of the eruption. The program changes each square in the entire risk area (consisting of regions A, B, and C) to low pollution with the probability of 60%. This is "destruction" due to the theoretical low pollution. High pollution then affects a smaller portion of the risk area. The squares in area B change to high pollution with the probability of 75%. Due to the algorithm of the program, 60% of the remaining 25% squares unaffected by high pollution are still low pollution. As a result, 90%



5.4 Alterations to the Program

Due to time constraints, the simulations using week-by-week calculations had to be adjusted. A new variable, n, had to introduced to calculate the P^n distribution of species after n time steps. The eruptive activity during the n weeks was also condensed into one cumulative eruption. This second method of determining succession allowed us to perform numerous simulations, whereas the first method required an 8 hour simulation time.

of land in region B is affected by pollution, 75% high and 15% low. The last portion of land affected by an eruption (region A) turns to 100% high pollution. After an eruption occurs, the decay of pollution and regrowth of plant life continues according to the transition matrix.

5.3 Additions to Model

Using Simpson's index, we measure the diversity of species regrowth that has occurred after a period of time. This is programmed to be calculated at the end of 45 years to give a numerical estimate of the distribution of plant life on Montserrat when there is our assumed amount of periodic volcanic activity. Simpson's index is calculated for four different regions: the entire mapped portion of the island, the region with no disturbance, moderate disturbance, and excessive disturbance. These regions are mapped on the following page. Our program is designed to run based on the number of weeks and number of simulations entered. Every simulation was run for 45 years. Each simulation yielded the four index values and displayed a color-coded map of the island showing the distribution of plant species at the end of 45 years.

6 Assumptions

6.1 Succession and Diversity Assumptions

- Barren land is considered empty of all plant life and subject to seeding due to wind-blown plant species from the intact northern ecosystem of Montserrat.

- All four species in our model are present in northern Montserrat, providing an unlimited amount of seeds that can be spread to the South. The diversity in the northern part of the island exists due to other natural disturbances, such as hurricanes, that are outside the scope of our model.

- There exists a "seed bank" deep in the soil that constantly exists and is not disturbed since the lava penetration is shallow, allowing certain species to pioneer disturbed areas.

- Estimations of pollution decay and plant recovery were done based on observations found on the *Montserrat Volcano Observatory* web page. Information was given to indicate that in 1997 plant life had started to grow in less polluted areas following the 1995 eruption. We assumed this 2 year time period would represent the time for our theoretical high pollution to decay to low pollution and the time required for a resistant plant species to begin to grow. We then extrapolated the additional estimations needed for decay and succession times from this general information available. Our estimations were verified as accurate by the *EcoBeaker* simulation done in section 4.0.

- Montserrat has different forest type regions according to heights below the volcanic vents: xeric woodlands on coastal areas and lower slopes, rain forest on higher slopes. We assume that our theoretical species can grow on all parts of Montserrat and are not restricted to this distribution of different forest types.

6.2 Disturbance Assumptions

- The predetermined regions for which we calculated the Simpson's index were decided upon based on the amount of disturbance. Moderate disturbance was considered to be the area that was mainly affected by

low pollution of large eruptions. Excessive disturbance was considered to be the area that was covered by high pollution of small eruptions or lava flow and was constantly being destroyed.

- Soufriere Hills will be the only destructive force on Montserrat and Castle's Peak remain the only active vent.

- The destruction of an area due to lava flow is considered to be 100% high pollution, based on the idea that lava kills everything in its path and will require the same amount of time to decay as high pollution.

- We do not take into consideration how wind, weather, or the topography of the region will affect the distribution of volcanic debris in future eruptions.

- Future eruptive phases of the Soufriere Hills volcano are assumed to last an average of 5 years. This was because the average length o f activity of 167 volcanic domes like those on Montserrat was found to be 5 years.

- Previous periods of volcanic activity on Montserrat were separated by periods of inactivity of about 30 years (1897, 1933, 1966, 1995). Most volcanoes tend to have fairly constant lengths of intervening periods of inactivity. Accordingly, in our model, we have assumed an approximate 30 year span of inactivity between active periods.

- Any increased volcanic activity observed in our model would be a result of the stochastic process governed by our transition matrix.

6.3 Program Assumptions

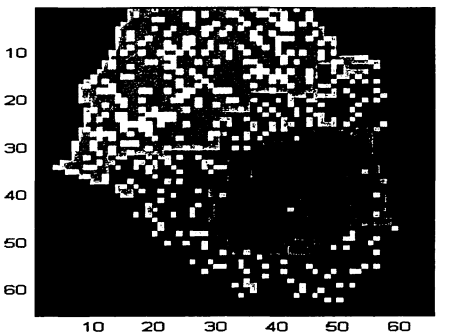
- Due to the algorithm of the *MatLab* program, it did not incorporate the cumulative effects of pollution from successive eruptions. It was necessary to assume that once a new eruption occurs, all areas of high pollution (or low pollution) are equally affected by the degree of new high (or low) pollution, regardless of the amount of pollution that may have already been present in that area at the time of the eruption. However, this program *did* take into account that a new eruption spreading low pollution in an area already affected by high pollution would not take precedence over the high pollution. That is,

a high pollution square in the simulation map would not change to low pollution due to an eruption, it would only change due to pollution decay.

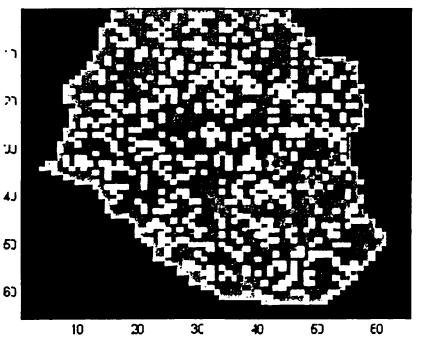
7 Results

7.1 Simulated Maps

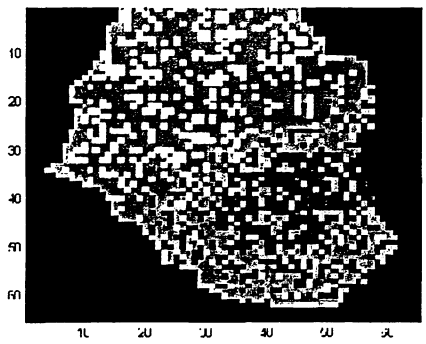
The following maps are the end results for some simulation runs of 45 years, with Simpson's index values for the high, moderate, and no disturbance, and for the entire island, respectively.



Simpson's indices: 0.00 2.6255 1.6752 2.3301



Simpson's indices: 1.9292 1.7048 1.6596 1.7085



Simpson's indices: 2.6445 2.494 1.6902 2.2202

7.2 Data

Figure 7.1: Simpson's Index Results

Simulation	High Dist	Mod Dist	No Dist	Island
1*	**2.7607**	**2.2002**	**1.6678**	**2.0288**
2*	**1.5077**	**2.7212**	**1.7046**	**2.2777**
3*	**2.1964**	**2.6426**	**1.6904**	**2.2647**
4*	**1.9756**	**1.9048**	**1.7278**	**1.807**
5	2.278	1.8014	1.6747	1.7975
6	2.7016	3.0717	2.0328	2.6981
7	2.0331	2.0672	2.0868	2.0731
8	2.4864	3.0679	2.0549	3.0683
9	2.5909	2.0627	1.6265	1.934
10	2.2629	2.0977	2.0368	2.0924

[table continued in Data Appendix]

***Some figures were calculated at a time step of 1 week.**

The majority of the figures were calculated with the time step of 25 weeks due to time constraints of the simulation process.

The following histograms are representative of the number of simulations with the specified Simpson's index for each level of disturbance.

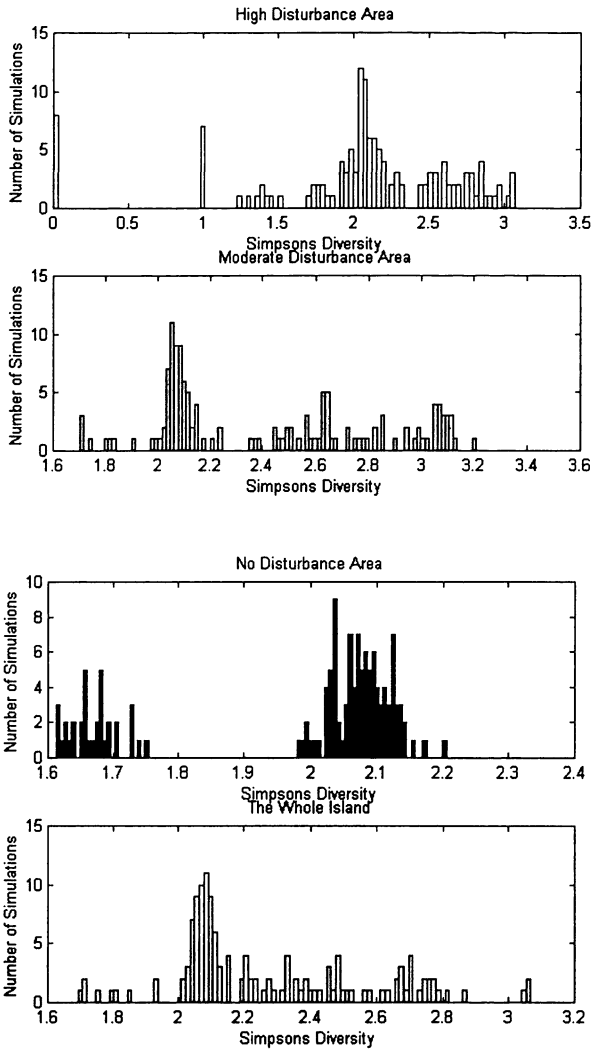


Figure 7.2: Histograms for Different Levels of Disturbance

8 Analysis and Conclusions

We ran 138 simulations of plant succession using the two different methods described in program building. 20 sets of Simpson's indices came from the method 1 long simulation. Because method 1 took 6 hours per simulation, we decided to speed up the simulation process by using mainly method 2. In

order to better analyze the long-term distribution of plant life on Montserrat, we combined the data from method 1 and method 2.

8.1 High Disturbance Area

The average diversity index value obtained for this area is approximately 2.0358 with a very high standard deviation of about 0.6929. The index ranges from 0 to values as high as 3.0252. This wide variation is an indication of the extremes of plant diversities that this area experiences, as shown on the graph in fig 7.2. Zero (0) diversity indices describe time periods soon after an eruption when the area is totally devastated by volcanic hazards and is still covered with pollution. From fig 7.2 , it can be seen that this scenario of no regrowth is an outlier - an extreme result.

If this scenario was not considered in finding the average Simpson index for this region, a higher average index of 2.1792 would be obtained. Disregarding this outlier for analysis purposes can be interpreted as assuming that plants will have enough time for some recovery. The lower standard deviation of 0.4683 (resulting from disregarding the outliers) would also imply a more stable diversity level consisting of an average of two species. In our simulations, we observed two scenarios that gave a Simpson's index of about 2. One involves the resistant and pervasive species sparsely populating the high disturbance area in fairly equal proportions. This distribution is typical of the first few years following an eruption. The other scenario is found in later years after an eruption. It is characterized by an abundance of the pervasive and higher order species with very sparse populations of the pioneering and resistant species, which at this point have declined.

The highest indices obtained for this area, such as 3.0252, are given by distributions of mainly pioneering, pervasive and resistant species. At this point, the pervasive species is beginning to dominate the area. There is also the possibility of seeing a few high order plants if there has been a long enough time lapse after an eruption. The high disturbance area can therefore experience periods of high species diversity. However, this periods are often followed by eruptions which totally devastate the land, resulting in zero (0) diversity index. The species composition of the area therefore fluctuates wildly, as indicated by the high standard deviation, depending on the frequency of eruptions. There is no permanent extinction of plants from this area since inactive periods allow for regrowth. However, the plant populations are generally very sparse.

8.2 Moderate Disturbance Area

The average Simpson's index for the moderately disturbed areas is 2.4149, the highest value obtained for the four areas modeled. Fig 7.2 also confirms that the area experiences high diversity. The graph for this area gives the highest concentration of data. Also, all indices are quite high, implying that there is usually a high level of diversity. The standard deviation for this average, 0.41465, is smaller than that for the region of high disturbance. This implies there is a more stable plant distribution than in the high disturbance areas. This is what is expected, since the area experiences less frequent periods of devastation than the high disturbance region.

The most common scenario observed was a decline of pioneering and resistant species with the pervasive species peaking in abundance. The higher order plants had also started to appear. Therefore, all four species were generally found in this moderate disturbance area. This is what is expected for an intermediate level of disturbance since it produces the greatest diversity according to the intermediate disturbance theorem (see section 1.1). Note that although the pioneering, resistant and higher order populations appear in other areas, they are found in greater numbers in the moderately disturbed areas. The moderately disturbed area therefore enjoys both abundance and diversity - the optimum distribution for any ecosystem.

8.3 No Disturbance Area

The graph for the undisturbed areas show two distinct distributions of data, one ranging from about 1.61 to 1.76 and the other from 1.98 to 2.2. These two distributions were obtained because the data was generated using the two methods mentioned in 8.0. These methods used different transition matrices for pollution decay and succession. Method 1 simulations were run with the matrix $P(6)$, section 5.2, which changes the squares in the map of our island with a one week time step; method 2 used the matrix P^{25} which changes the squares with a 25 week time step. (See "Program Building", section 5, describing these two methods). These two different matrix powers give different results in some scenarios. This is particularly seen in this no disturbance area.

P gives the smaller index values ranging from 1.61 to 1.76 and P^{25} gives the larger values. P was considered to give a more accurate representation of what occurs in the 45 year period in this scenario because, looking at the map of the final plant distribution, the P^{25} matrix gives a considerable pop-

ulation of pioneering species in the no disturbance area. This is a scenario that should not be at all common in an area that has experienced no disturbance in 45 years. The pioneering species should have long been taken over by the pervasive second order species. The P matrix, on the other hand, gave a distribution that consisted of only the pervasive and higher order species. This we took to be more accurate since after such a long period of no disturbance, it is expected that ecological succession has progressed far enough such that no pioneering species would be seen. It also matches some historical descriptions of plant life on Montserrat. Using this data, it is seen that the no disturbance area has a fairly constant plant diversity, consisting of the high order species and the second order species. Such low diversity is unhealthy for an ecosystem. However this may not be an entirely accurate representation of diversity in this area on Montserrat, due to other disturbances that may occur. These disturbances are outside the scope of our model.

8.4 The Whole Island

The graphical distribution for this area is an average of the data obtained from the three areas of disturbance. The average Simpson's index is 2.2653. This number should probably be lower since we assume that the P^{25} matrix used produces inaccurately high indices for the no disturbance area. As it is, this average is still lower than those for high and moderate disturbance areas. Therefore, the island as a whole experiences less diversity than areas which are affected by volcanic activity. The average is higher than that for the no disturbance region. This confirms the theory that disturbance is necessary for an ecosystem to have diversity.

8.5 Conclusion

The above data and analysis support the intermediate disturbance theorem. From the comparison of plant distribution in the disturbed and undisturbed areas, it can be seen that disturbance promotes species diversity. Although the highly disturbed area had sparse plant populations, there was no extinction of any plants in our model. Therefore, if the Soufriere Hills volcano erupts according to the eruption frequency used in this model, the ecology of the island of Montserrat does not face irreparable damage from volcanic activity. This conclusion is based on the assumptions used in this model. The increased diversity observed in the moderate disturbance region shows

that inhabitants of Montserrat who have fled the island can return to find an ecosystem that may be even healthier than when they left. With this level of volcanic activity, after sufficient recovery time, the plant life on Montserrat would probably be capable of supporting its dependents.

9 Improvements

• **Second Order Transition Matrix**

The 4x4 matrix (2), given in (section 3.12), predicts the probability of activity and its magnitude in any week based on the activity in the previous week only. In order to obtain a more accurate prediction of activity, we used the data in table 3.1 to construct the 16x16 second order transition matrix (7) on the following page. This predicts the activity in a given week, based on the activity in the preceding 2 weeks. Matrix (7) contains a lot of zero "0" probabilities. Thus, it does not give enough information to accurately portray the frequency of volcanic eruptions. In an improved model, enough data describing previous years of activity would give more non-zero entries. Such a second order matrix could more accurately predict volcanic activity.

• **Topographical Risk Map**

A topographical risk map would more realistically simulate the behavior of the pollution. This map is more realistic in that the flows of many kinds of pollution are significantly affected by the valleys and channels surrounding the volcano. This map would allow for more specific, complex risk area designations. A version of this type of map for Montserrat can be found on the second following page.

10 APPENDIX: Key Words

10.1 Math Terms

m1.) **Discrete-time Markov chain** is a stochastic dynamical system in which the probability of arriving in a particular state at a particular time depends on the state at the previous time. (Adler 451)

m2.) **Limiting distribution**, $\lim_{n\to\infty} P^n$. This represents the long-run proportion of time that the process will be in the given states. Raising a matrix to a power n represents n time steps having occurred, and the resulting matrix gives the probabilities of arriving at any state from a given

initial state after n iterations of the transition matrix. As $n \rightarrow \infty$, this matrix reaches a limiting distribution where all the rows are equal. For an $m \times m$ matrix P, $P^n = 1'(I + P + J)^{-1}$, where 1' is an m size vector of 1's, P is the transition matrix, and J is an $m \times m$ matrix of 1's. This equation yields an m size vector containing the probabilities of reaching the states of P at any time. In this case, the initial state is no longer relevant and the limiting distribution is written as $P^n = [P_0 P_1 P_2 ...]$ for element P_i equal to the probability of stepping to state i. (Ross 172-174)

m3.) **Stochastic processes** $\{X(t), t \in T\}$ are a collection of random variables. For each $t \in T$, $X(t)$ is a random variable where the index t is the time and $X(t)$ is the state of the process at time t. Set T is the index set of the process. When T is a countable set the stochastic process is said to be a discrete-time process, as we are using in our model. (Ross 77)

m4.) **A transition matrix** is a mathematical matrix whose entries incorporate the rules of transition governing a **Markov chain**. For any two states k and j in the Markov chain, the fixed value P_{kj}represents the probability that when in state k, the Markov process will make a transition to state j in the next time step. (where $P_{kj} \geq 0$, k,j≥ 0, $\sum_{j=0}^{\infty} P_{kj} = 1$, for k=0,1,2,... These probabilities form the entries of the transition matrix. In a transition matrix, only certain states may "communicate" with each other. For example, in a matrix governing ecological succession, given that the current state of a piece of land is barren (state b), there is a certain probability, P_{bb}, that in the next time step, the land remains barren. There is also a probability P_{bi}, that the land is colonized by an invasive species. However, barren land cannot be directly colonized by a higher order plant (state h). Therefore, the states b and h do not communicate, and the probability of barren land becoming colonized by h, P_{bh}=0. If we further wish to define another species which is pervasive (state p), we need to state the rules of succession to complete the transition matrix. Suppose this plant also needs initial growth of an invasive species before settlement can occur, but it can take over (or succeed) the invasive species or the higher order species with certain probabilities. Then, the probability of the pervasive species settling barren land at the next time step would be P_{bp}=0, and we would have probability P_{ip} of the invasive species being taken over by the pervasive species and probability P_{hp} of the higher order plant being succeeded by the pervasive species. Our transition matrix, P, would be filled

with the appropriate probabilities where the rows and columns correspond to the four states. This transition matrix is given as

$$P = \begin{array}{c} \\ b \\ i \\ p \\ h \end{array} \begin{array}{c} \begin{array}{cccc} b & i & p & h \end{array} \\ \begin{pmatrix} P_{bb} & P_{bi} & 0 & 0 \\ 0 & P_{ii} & P_{ip} & P_{ih} \\ 0 & 0 & P_{pp} & P_{ph} \\ 0 & 0 & P_{hp} & P_{hh} \end{pmatrix} \end{array},$$

where we assume the death rate of any species is taken into account by the fact that once a species dies, that area will be taken over by another species and not remain barren land.

10.2 Succession Terms

s1.) **Disturbance** can be defined as any event or process which destroys or disrupts the natural growth in an area. This disturbance can change the entire composition species of the ecosystem.

s2.) **Pioneering species** are the first to appear, starting re-growth after a land disturbance.

s3.) **Higher order plants** are a type of secondary growth that succeed some type of previous settlement.

s4.) **Simpson Index** calculates diversity by taking into account the abundance and richness of a species. Simpson's index is given by the following formula

$$D = \frac{1}{\sum_{i=1}^{s} (p_i)2}$$

such that D increases as diversity in the ecosystem increases. This representative D displays numbers in a bounded region determined by the number of species, s. Simpson's index says that D_{max} is obtained as S_{max} is approached. Where p_i is the proportion of species i to the total population.

10.3 Volcanic Terms

p1.) **Lava** is the term for magma that has reached the surface of the earth. Lava flows are primarily controlled by topography. They flow downhill, becoming channeled into river valleys if they extend far enough. Thus, lava flow affects mainly terrain that is down slope from the vent. Lava flows are destructive to any vegetation in the path of the flow. (Blong 14-21)

p2.) **Tephra fall** is a mixture of hot volcanic gas and tephra. Tephra is a term for all fragmented volcanic materials, including blocks of rock and pumice; which is bubbly frozen magma and volcanic ash. This mixture is ejected rapidly into the air from volcanic vents. The major hazards of tephra are: impact of falling fragments, suspension of abrasive fine dust in the air and water, burial of structures, and vegetation. (Blong 21)

p3.) **Pyroclastic flows** are avalanches of hot (300-800 °C), dry, volcanic rock fragments and gases that descend the volcano's flanks at speeds ranging from 10 to more than 100 meters per second. Due to their mass, high temperature, high speed and great mobility, pyroclastic flows are destructive and pose lethal hazards from incineration, asphyxiation, burial, and impact. These tend to destroy topographically low areas and beyond the steep ridges of the volcano are channeled into valleys. (Blong 33-36)

p4.) **Pyroclastic surges** are turbulent, relatively low density (denser than air), mixture of gas and rock that flow above the ground surface at high velocities similar to those of pyroclastic flows. Their behavior can be compared to a very severe hurricane. These can be formed above pyroclastic flows or directly by very violent explosions. Hazards resulting from pyroclastic surge include incineration, destruction by high-velocity ash laden winds, impact by rock fragments, burial by surge deposits, exposure to noxious gases, and asphyxiation. The combination of high temperature, high speed and high mobility makes this an extremely hazardous phenomenon (Blong 33-36).

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Acknowledgments

The research in this manuscript has been partially supported by grants given by the National Science Foundation (NSF Grant DMS-9600027), the National Security Agency (NSA Grant MDA 904-96-1-0032 and 9449710074), Presidential Faculty Fellowship Award (NSF Grant DEB 925370) given to Carlos Castillo-Chavez, Presidential Mentoring Award (NSF Grant HRD 9724850), Sloan Foundation Grant (97-3-11). We also thank INTEL corporation for providing the latest high performance computer and software. Substantial financial and moral support was also provided by the Office of the Provost of Cornell University. We also thank Cornell's College of Agricultural & Life Science (CALS) and its Biometrics Unit for aoolwing the use of CALS's facilities. The research in this report does not necessarily reflect the ideas and/or opinions of the funding agencies and/or Cornell University.

We would like to thank the following people for all the help, support, and motivation they gave us throughout this summer and especially during the final critical stages of our research project: Carlos Castillo-Chavez, Prof. Robert Kay, Carlos Hernadez-Suarez, Prof. Peter Marks, Steve Tennenbaum, Carlos Melgar, Sharon Lima, Carlitos, Julio Villarreal, Steve Wirkus, Jaime H. Barrera, Alex the Grad Student in Geology and to all persons that we have failed to mention but have not forgotten. We especially thank NSA, SACNAS, and the Mathematical & Theoretical Biology Institute (MTBI) for Undergraduate Research, Biometrics Unit at Cornell University for allowing us to participate in this research program.