Optimizing Invasive Plant Removal Efforts

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May 6, 2022

1 Introduction

Red mangroves are a hardy species of shoreline trees, dwelling in brackish water. Their primary form of reproduction are seed-like structures called propagules, that are able to float on the water for about 40 days [3] before sinking into the mud and forming roots. Propagules are essentially seeds that germinate while still attached to their parent plant. Red mangrove propagules are also capable of growing on land as well, although the tree prefers to be quite close to a body of water.

What makes red mangroves so perseverant in the natural world also makes them an enemy of some ecosystems. On Kaua'i, aerial analysis has shown red mangroves make up as much as 95% of plants in regions of Nawiliwili bay [2]. In Hawai'i, their presence disrupts the growth of native plants, the chemical composition of some specially balanced ecosystems residing in shallow pools, the habitat of endemic wetland birds, and historic architecture found around fish ponds and kalo lo'i (taro patches) [1, 2].

Nawiliwili bay on Kaua'i has been the focus of a 2015 restoration effort that was completed as of 2021 [4]. I was inspired to model this scenario when I learned the amount of thought that went into what would become a successful attempt to clear 26 acres of mangroves. The removal of each mangrove is time intensive and arduous, as the trees primarily reside in shallow wetlands and must be physically cut down to be removed. As such, efficiency is of utmost importance. Furthermore, access to the land is not always a total guarantee, as the non profit leading the initiative, Mālama Hulēʻia, needed to ask land owners for permission to operate on their land [4]. Thus the total time of the restoration project is also of importance. With these two metrics in mind, I designed a simulation to model the plant growth and possible removal strategies that may have been employed.

2 Simulation

I created a simulation in NetLogo to test out different methods of removing a population of invasive plants.

2.1 Map

I based the world map off of the red mangrove invasion in Nawiliwili bay.

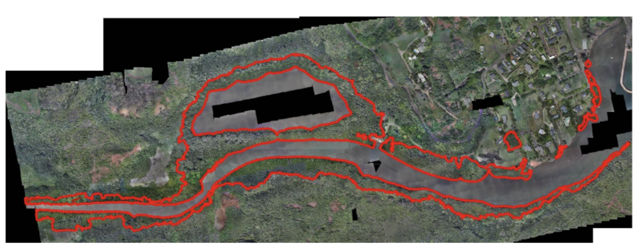
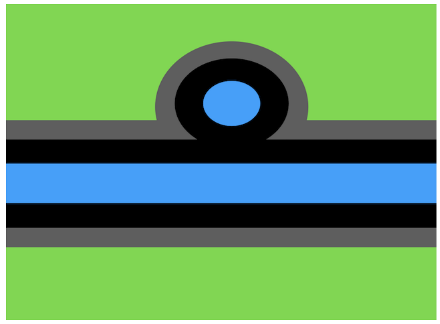


Figure 1: In red are outlined areas where aerial photographs found red mangroves.

The picture above shows the inner part of the bay, with the historic Alakoko fish pond also pictured. I simplified this to just include a stream and a fish pond.



In the simulation's map, there are four regions: green denotes land that is unfit to support red mangroves, grey denotes land that red mangroves may be supported on, black denotes areas of the bay that red mangroves may live in, and blue denotes areas where the water is too deep in the bay for red mangroves to survive in.

Using this color pallete, more maps could potentially be made with similar behavior.

2.2 Plants

In this section we detail the way in which we simulated the nature of a red mangrove forest without human intervention.

2.2.1 Growth

The general life cycle of the red mangrove is as follows:

1. Propagule drops from tree
   - Propagule in water: 40 days to root [3]
   - Propagule on land: 10 - 14 days to root [3]
2. Tree matures and begins flowering in 4 years if under ideal conditions [6]
3. Flowers become fertilized 1-2 months after bud appearance [5]
4. Fruits mature after 4-7 months [5]
5. Propagule germinates and matures while on tree after 4-6 months [5]

In reality, the average tree begins flowering after four years, after which it starts to put out propagules throughout the entire year. Something we don't consider in this project but could certainly factor into an ideal strategy is the time of year, which affects the average rate of propagule production [1].

The plants in the simulation had a generally simplified life cycle. Where each tick represents one day, each plant went through four years of growth, during which they were red. Then they went through a flowering and propagule incubation stage for 10.5 months, during which they were white. Finally, each plant turned pink for the rest of it's life, signifying it's full maturity and ability to put out young plants.

During the pink phase each plant put out propagules daily with probability $\frac{\text{size}*3}{365}$. Most plants were able to reach the maximum size which was arbitrarily chosen to be 30, thus the probability of putting out a propagule each day was $\approx 25\%$, resulting in an average of ≈ 90 propagules a year per tree.

In my research I was unable to find any information on the number of propagules produced yearly by a red mangrove so I approximated this figure using the yearly fruit count of the average mango tree. Mango fruit tends to take 3 - 5 months to drop which is similar to propagules growth period of

4 - 6 months. Both trees thrive in tropical environments making them comparable. Finally, mango trees tend to be bigger than red mangroves and they appear to have more fruits on average at any given time. Knowing that mango trees produce 200 - 300 fruits a year, I roughly estimated that red mangroves produce about 100 propagules yearly.

Figure 2: A red mangrove with a relatively large number of propagules (circle).

Figure 3: A mango tree

2.2.2 Natural Limitations

Naturally, the growth of a plant is limited based on the amount of sun it can get as well as by the physical space it can take up. Furthermore, young plants which start growing from inopportune locations will die if they don't get enough sunlight. Both of these features of plant growth were factored into the simulation.

Important to the simulation is the use of the "size" characteristic. Each new plant is created with an initial size of 5, with the plant growing each tick under the proper conditions which we describe in the next section. Furthermore, plants are able to start flowering only when their size meets or surpasses 15. Finally, the size of plants was capped at 30.

I defined "density" to measure the livability of an area, with a higher density corresponding to more packed in mangrove trees and thus lower livability.

```
to-report density
  let init 0
  ask plants in-radius 40 with [size >= 10] [
    set init (init + size)
  ]
  report init
end
```

Density is simply the sum of the sizes of plants who are both within a radius of 40 of this patch and larger than 10 units. I chose to have there be a minimum plant size because relatively small plants typically don't block much sun from other plants, making them not have much of an effect on the final result.

Deprivation from sun typically doesn't kill a plant over night. Furthermore, some plants are able to curtail branches to survive low amount of sun. The following function, which runs every tick, is meant to reflect this behavior.

```
to choke-small-plants
  ask plants with [size <= max-size / 4] [
    if (density >= 68)[
      set size (size - .5)
    ]
    if size <= 2 [die]
  ]
end
```

To summarize, the function only operates on relatively small plants, and has them shrink if the density of the area is quite large. When they become small enough, they simply die.

Finally, plants are only able to grow if the density of their area is less than a constant:

```
if density <= 70 [
  set size (size + (0.5))
]
```

This code chunk runs on all plants smaller than the maximum size every tick.

2.3 Propagules

To simulate the migrant nature of propagules, I simply had to allow propagules to float throughout the bay. Since propagules drop to the estuary floor after 40 days and the flow in this body of water shifts frequently, each propagule randomly travelled throughout the map until sinking. Only propagules that sank in areas that were shallow enough to support them survived.

2.4 Human Intervention

There are various ways a community might go about removing red mangroves. I decided to examine two methods, a continual daily effort to remove the red mangroves and a less frequent sporadic but strong effort to remove the plants. This is meant to model the difference between hiring a small team of people long term to address the issue, versus gathering a huge group of people rather few times.

2.4.1 Daily Effort

In this method NetLogo tests out the effects of a continuous, regular effort to remove red mangrove trees. The thought process behind this method is that it may be more realistic to hire a few people to remove the invasive species daily than it would be to gather a bunch of untrained people to help. Additionally, removing a bunch of red mangroves at once runs the risk of "tilling the soil" by opening up ideal real estate for any floating propagules to take root in.

In the code, this strategy was implemented by removing a constant number of big trees (size ≥ 15), and a near constant number of little trees (size < 15), which probabilistically adjusted to reflect how small plants might be overlooked.

```
let cut-down 0
ask plants with [size >= 15][
  while [cut-down <= daily] [
    set cut-down (cut-down + 1)
    die
  ]
]
set cut-down 0
ask plants with [size < 15][
  while [cut-down <= daily] [
    set cut-down (cut-down + 1)
    if random 100 <= count plants with [size < 15]  [
      die ]
  ]
]
```

2.4.2 Strong but Fewer Visits

This was modelled similarly to the daily effort simulation. In this case the simulation removes the same number of plants per time as the daily simulation, but instead it removes them all at once. Defining period as the number of days between restoration days, the simulation "cut down" (period)*(daily average) big plants and little plants whenever the simulation reached a day for plant removal.

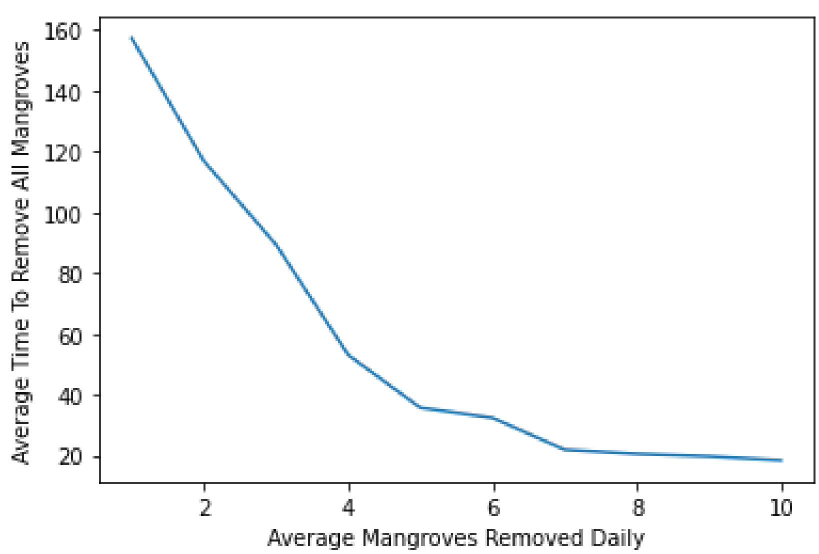
3 Results

For the results we look at two quantities that would be of concern for conservation groups: number of days to complete mangrove removal, and total work done, where the work is defined as the (daily goal / daily average)*(total days). For each test I ran 10 simulations and graphed the results against desired average number of plants picked daily.

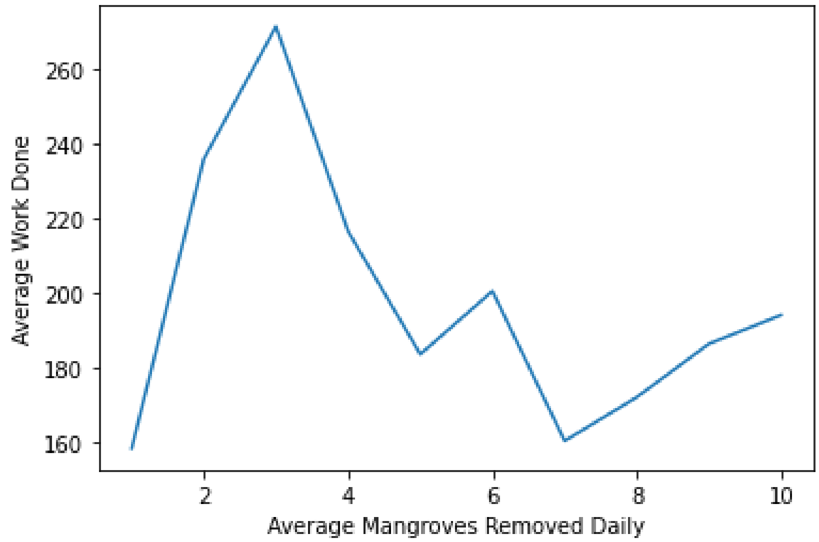
We primarily want to minimize the work done and the total time.

3.1 Daily Effort

These results reflect simulations in which a near constant number of plants is being picked daily. As is expected, increasing the number of plants removed daily decreases the total amount of time needed to remove all mangroves.



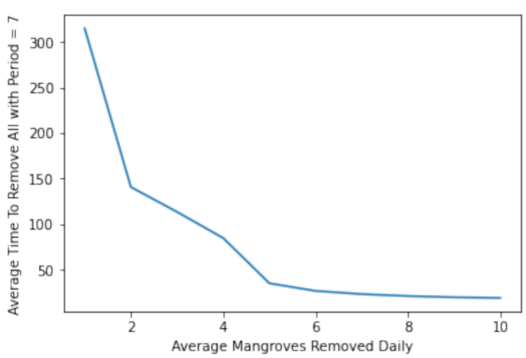
The second graph is less predictable. Notably, the work is minimized when the number of mangroves removed daily is 1, with a close runner up being 7 mangroves removed per day. What is interesting to note is how erratic this graph is, which demonstrates how simulating scenarios like these may offer unique benefits as opposed to numerically approximating the best strategy.

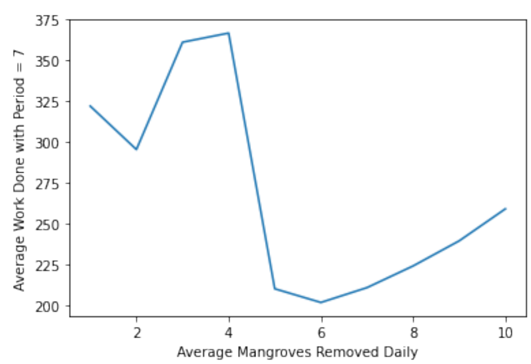


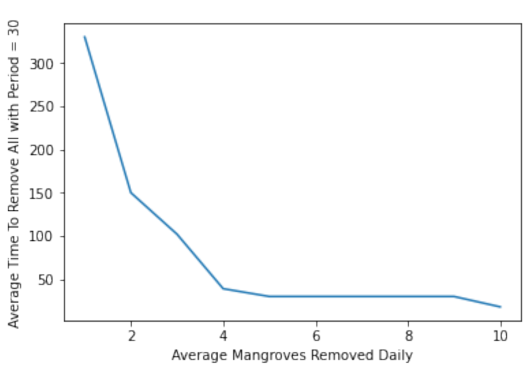
3.2 Stronger / Community Effort

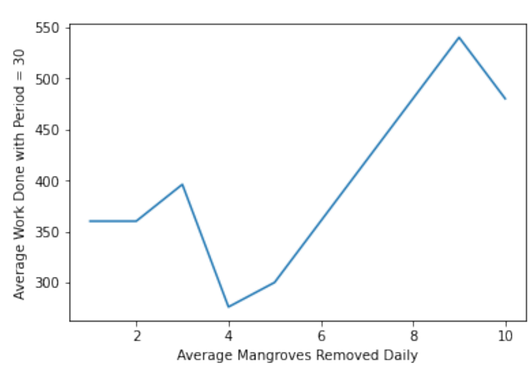
With this strategy, we simulate the effects of a restoration effort that involves picking many plants as once. Note that the x-axis represents the same thing on these graphs as on the graphs in Section 3.1.

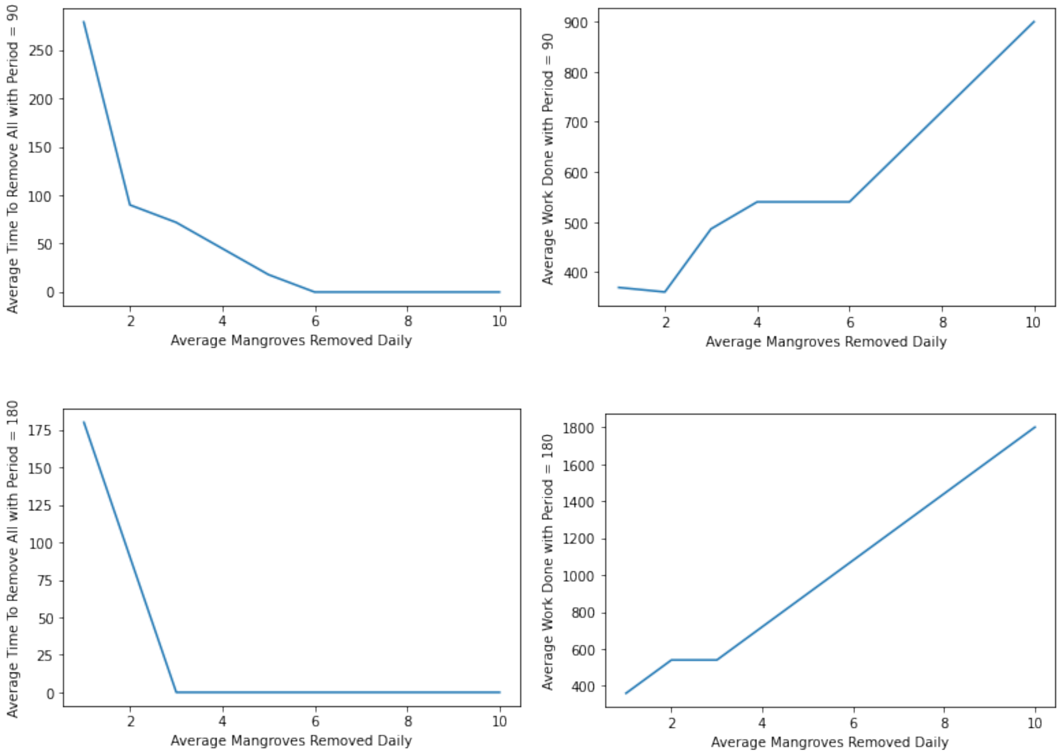
As we might expect, when the period is relatively small, the graphs appear quite similar to graphs showcasing daily effort.











In each of these graphs we see a similar trend with the average time to remove all mangroves. As the period and the average plants removed daily become quite large, the average time to remove all plants goes to 0 because all mangroves essentially get removed on day 0.

4 Analysis

In Section 3.2, we saw that removing all mangroves in a day doesn't result in a desirable amount of work done. In 3.1, the minimum work done was about 160 on average, whereas the simulations that entail only 1 day of removal efforts all result in an average value of above 500 for work done. We find that modest daily efforts are much preferable to massive bursts of labor as these simulations resulted in a lower average measurement of work at the expense of taking slightly longer to complete removal efforts.

Again considering the simulations in section 3.2 with period 90 and 180, as the period becomes larger, the average work done throughout the simulation enters into a nearly linear relationship with the average number of mangroves removed daily. This is likely because when both values are large, the simulation lasts a shorter amount of time. Furthermore, my formulation of work is directly dependent on the average mangroves removed daily.

It can be argued, that the values for work in the last two sets of simulations overestimate the amount of work actually done. Because of the way the algorithm is written, the amount of work done is the same even if the job were to theoretically get done early. It could be interesting to look into the efficiency of "flash" restoration efforts that do the bare minimum work to complete the job in one day.

5 Conclusion

In this project, I simulated various invasive species removal techniques, taking inspiration from the 2015 restoration effort in Nawiliwili Bay. I found that relatively small daily efforts to remove the plants in my simulation were preferable to big pushes of invasive plant removal, although it is possible that editing the simulation and fine tuning the restoration strategy could yield better results for the non-daily strong effort strategy.

Throughout the building of this project, it became clear to me how highly complex ecosystem simulations have the potential to be. Due to the massive number of factors that go into an ecosystem, other analytical methods are necessary to build a truly accurate simulation.

References

[1] James A. Allen. Mangroves as alien species: The case of hawaii. *Global Ecology and Biogeography Letters*, 7(1):61–71, 1998.

[2] Carl Berg, Mason Chock, Luke Evslin, Alberto Genovia, Mark Hubbard, Pomai Kane, Debbie Lee-Jackson, Pepe Trask, Steve Yee, Ruby Pap, and et al. *Red Mangrove Invasive Species Action Plan for the Hulē'ia*, Oct 2015.

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[6] Paul Marek. Mangroves - faq.