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Modeling Maine's Rockweed Harvest

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Abstract
Currently, Maine is in a political struggle over the best way to manage the harvesting of Rockweed, or *Ascophyllum nodosum*. As the dominant macro algae along the state's rocky intertidal zone it supports over 150 different species, meaning its loss could impact food web stability, protection of endangered species, and support of economically viable harvests. This work takes parameters found in the literature to create a Stella model, which is then manipulated to explore the relative impact of possible management strategies. It is found that a strictly accurate model is not possible to create given the current biological knowledge and complexity of the species involvement in the overall system. Despite this, a rough model indicates banning mechanical harvesting tools, which decrease the species' recruitment rate, is unlikely to be as effective a management tool as placing limits on the harvest-able area.

Keywords
Rockweed, Harvest, Management Plan, Stella

Cover Page Footnote
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1. Introduction

If you have ever been to Maine's rocky coast and slipped on the seaweed, odds are Rockweed (*Ascophyllum nodosum*) was to blame. Not only is it the dominant macro algae in Maine's intertidal zone, it is referred to as an ecological engineer due to its impact on other species. During low tide it protects biota such as periwinkles or barnacles from heat stress, it slows currents at high tide, facilitating settlement of pelagic larvae (such as barnacles and mussels), and it creates habitat in death floating in the open ocean or washed up on the shore (Seeley and Schlesinger 2012).

Rockweed has also supported humans for at least three centuries, providing fertilizer for gardening or farming. Not until 1985 were mechanical harvesters introduced to the process, significantly increasing harvest levels (Sharp *et al*, 1994). In fact, not until 2000 did the Maine Department of Marine Resources begin requiring seaweed landing numbers to be reported (Maine Sea Grant Maine Department of Marine Resources, 2013). In 2009 the Cobscook Bay Management Area was established by Maine law, and in 2012 an act to require a statewide management plan was passed (Office of Legislative Information, 2013).

The harvest today does not appear to be unsustainable, but that does not mean a well-thought out statewide management plan is not advisable. During 2012, 15 million pounds were harvest in Maine alone, which represented less than 1% of Maine's resource (Maine Sea Grant and Maine Department of Marine Resources, 2013). However, this industry has a very low barrier to entry; only a $58 licensing fee and a sharp knife, meaning the potential to overexploit the resource is very real. Thankfully, the Maine Legislature and Maine Department of Marine Resources are currently working to develop a statewide management plan for this species (LD 585, 2013; LD 1830, 2014).

Using values from the literature and some educated assumptions a simple model of the *Ascophyllum nodosum* (*A.nodosum*) harvesting industry in Maine was created using the software program Stella. While the goal of the exercise was to determine the potential policy choices that could be expected to have the greatest impact on the sustainability of the harvest, it should be recognized there are many important aspects of the system that were beyond the scope of this paper. Therefore, this paper presents an approximate analysis.

2. Methods

In order to determine the policy actions which could make the greatest impact on the sustainability of the harvest an unbiased comparison had to be made, in this case using the program Stella. Essentially, Stella is used to create a mathematical model of a system (in this case, the harvest) by specifying the stocks, flows, and convertors (factors that influence the first two) and how they are connected. The model can then be 'run' for a number of periods, and the resulting value for any stock or flow can be recorded in graphical or table form. The parameters of the model can then be altered and the model can be run again to see how the system would change.

In order to create the Stella model, a conceptual model of the important dynamics of the harvest was first created. As seen in Figure 1, this included both ecological factors, such as the recruitment rate, and economic or otherwise anthropogenic factors, such as the harvesting tool used. Where anthropogenic factors influence a flow, such as the harvesting tool used, a management policy could be introduced to influence this relationship.

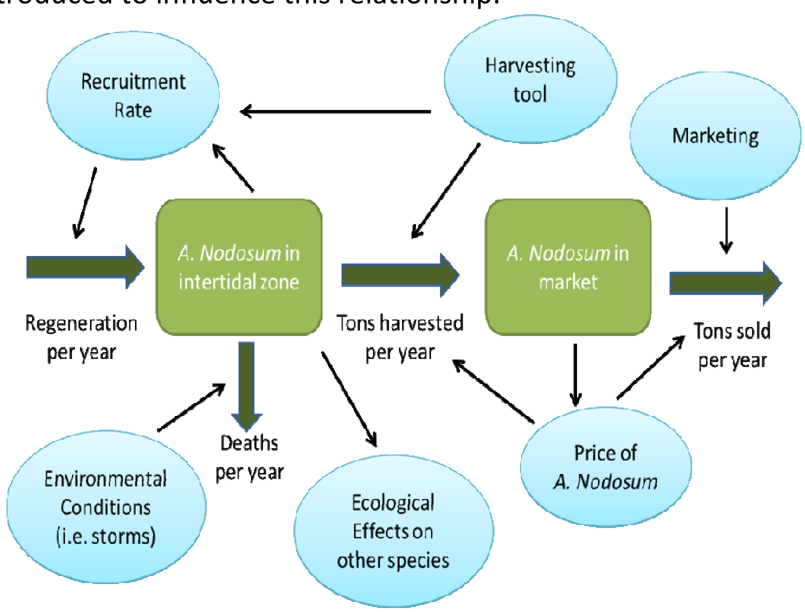

Figure 1: Conceptual model of the stocks and flows relevant to the harvesting of Ascophyllum nodosum in Maine. Stocks are represented by squares, flows by arrows from squares, factors by circles, and small arrows from factors indicate where an impact is made.

To begin creating the mathematical (Stella) model, the conceptual model was created using the Stella program, but there were issues with this approach.

For example, how does one measure the "ecological effects on other species," especially when the 'other species' includes potentially over 150 species, all being supported in different ways? Although a very important component of the system in reality, it was decided to remove this aspect from the model.

The model was then parameterized mainly according to estimates in the literature, with some support by educated assumptions by the author. For example, it is known that of the 2010 Maine landings, 48% were taken using hand rakes, and so this figure was used as the seed for the hand rake parameter. Since it can be expected this percentage does not hold true every year, 10% ± was allowed, an assumption by the author. For another example, Maine currently limits the harvest to 17% of the harvestable stock, a constraint that was included in this model by using an IF statement. Figure 2 shows a summary of the values used in the model and their source, while Appendix 1 shows the full model used as the 'current conditions' (baseline) model in equation form. Finally, and Figure 3 illustrates how the stocks and flows of the harvest are connected in the Stella model.

Selected Variables	Baseline Value	Source Leading to Value Used
Recruitment Rate	9% without harvesting, 6% if Hand Rakes used, 4% if Mechanical Harvestors used	Ugarte, 2001; Seeley and Schelesinger, 2012
Carrying Capactiy	1,500,500,000	Assumed
A. Nodosum in intertidal zone	1,500,000,000	Maine Sea Grant and Maine Department of Marine Resources, 2013
Deaths per year	1% of intertidal zone stock + Environmental Conditions*stock in intertidal zone	Assumed
Environmental Conditions	Random: 2-5%	Assumed
Hand Rake (percentage of harvest taken by)	Random: 58-38%, seed 48%	Maine Sea Grant and Maine Department of Marine Resources, 2013
Mechanical Harvester (percentage of harvest taken by)	1- Hand Rake	Inverse of Hand Rake use
Tons harvested per year	17% of intertidal stock, or Random Harvest	Maine Sea Grant and Maine Department of Marine Resources, 2013
Random Harvest	Hand Rakes take 4-15% of intertidal stock, Mechanical tools 20-36%	Seeley and Schlesinger, 2012
Area Harvest Allowed	0.01	Maine Sea Grant and Maine Department of Marine Resources, 2013

Figure 2: Values assigned to selected variables in the baseline model, and the source leading to this value.

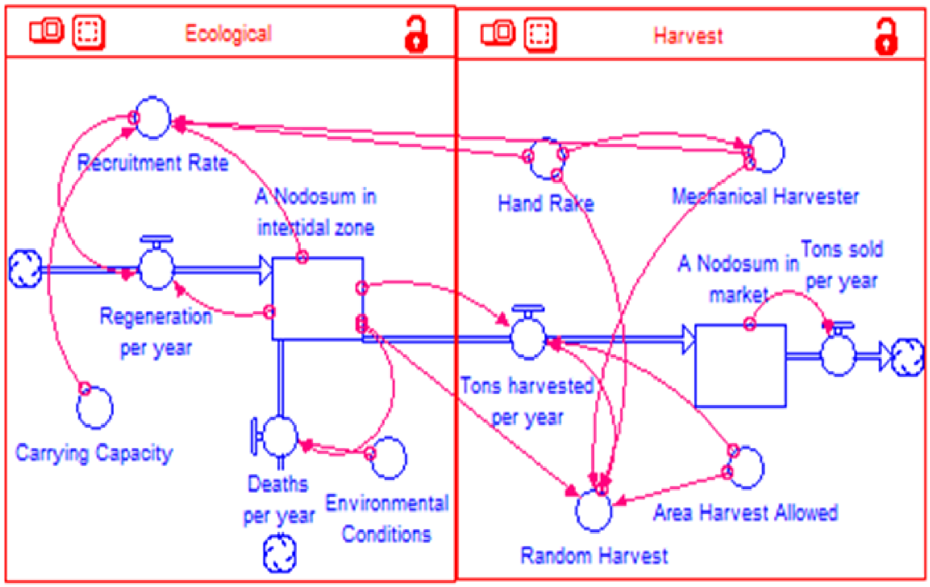

Figure 3: The final Stella model used in this study. Stocks are represented by squares, flows by circles with arrows, and 'converters' by stand-alone circles. The red arrows are 'actions,' meaning they represent a connection between what they are rooted on and what they point to.

Once the baseline model was established the model was run and the resulting volume of *A. nodosum* in the intertidal zone and in the market was recorded in graphical form. This generated the baseline result, or what the model would predict as an outcome if the current harvest conditions were not altered. Key areas for policy intervention, such as the harvesting tool allowed or the area open to harvesting, were then analyzed by changing the relevant model parameters and rerunning the model, again recording the results graphically. Finally, key values such as the regeneration rate were modified as a check on the sensitivity of the model to these uncertain values, even though they are not a point for policy intervention.

3. Results

The baseline model, representing the expected outcome given no policy interventions to the current harvesting industry, shows a decrease in the quantity of *A. nodosum* in the intertidal zone from 1.5 billion pounds to approximately 451 million pounds after 150 years (Figure 4). This is a significant decrease, but also leaves a significant amount in the intertidal zone, although it is unknown what quantity of *A. nodosum* is needed to continue supporting the diverse array of species depending on the various functions *A. nodosum* provides. The result of this baseline model will be used to compare the results of policy interventions.

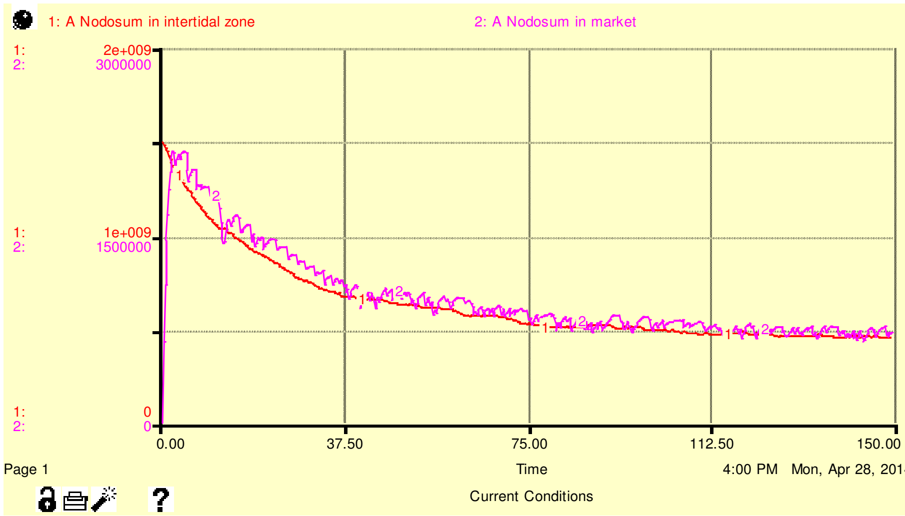

Figure 4: Results of the baseline model, representing current harvest conditions. Approximately 451 million pounds of Ascophyllum nodosum are expected to remain in the intertidal zone after 150 years.

The first potential policy action explored was gear restrictions. Because the use of mechanical harvesting tools reduces the recruitment rate of *A. nodosum*, restricting their use could be biologically justified. Indeed, as seen in Figure 5, if mechanical harvesting tools are banned the stock of *A. nodosum* remaining in the intertidal zone after 150 years increases compared to the baseline result, from approximately 415 million to a fairly stable 620.5 million pounds. However, if only mechanical harvesting tools are used, an extreme and improbable comparison, 282 million pounds still remain after 150 years, albeit on a decreasing trend (Figure 5). While banning the use of mechanical harvesting tools is expected to increase the quantity of the resource remaining by 205.5 million pounds compared to the baseline result, only 133 million pounds are lost by only using mechanical harvesting tools compared to the baseline result. When the stock of the resource was originally 1.5 billion pounds these may not be meaningful differences.

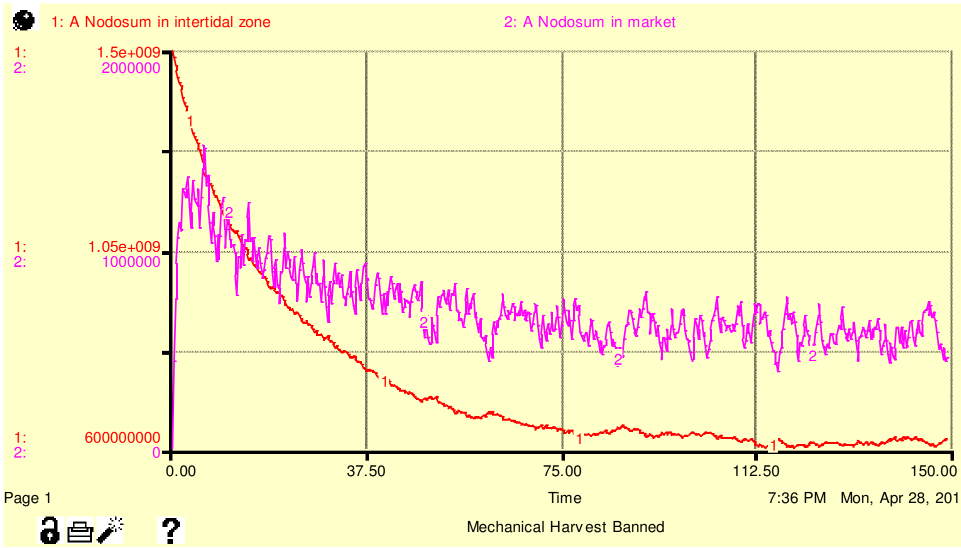

Figure 5: Results if only hand rakes are used, mechanical harvesting tools having been banned. Approximately 620.5 million pounds of Ascophyllum nodosum are expected to remain in the intertidal zone after 150 years.

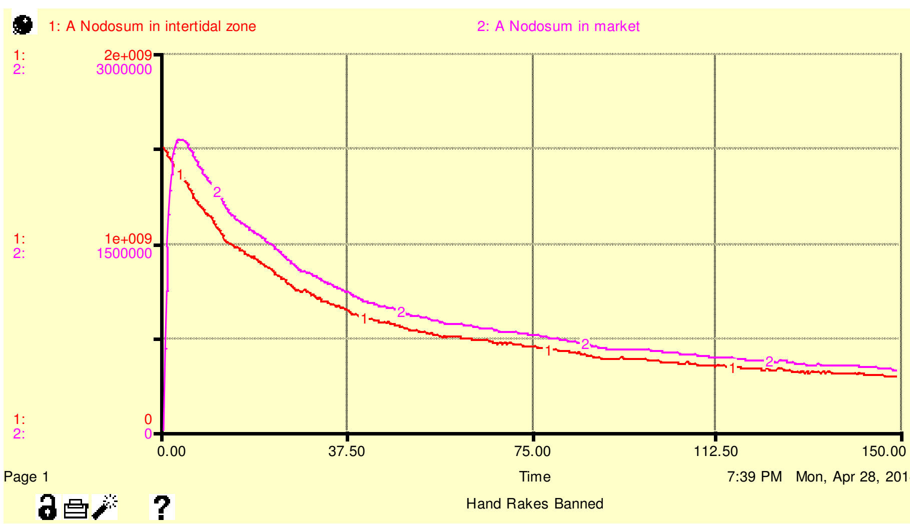

Figure 6: Results if only mechanical harvesting tools are used, hand rakes having been banned. Approximately 282 million pounds of Ascophyllum nodosum are expected to remain in the intertidal zone after 150 years.

The quantity of area being harvested is another potential key policy to examine. Since only about 1% of the resource is actually being harvested currently, it seems unlikely a smaller area will be harvested in the future. Given this, the expected results from just 5% of the resource being harvested, with a limit of 17% of the harvestable resource being taken in any harvested area was first examined. In this case (Figure 7), approximately 275.8 million pounds would remain after 150 years, which appears to be an equilibrium quantity. For an increase in area harvested of just 4%, an additional 139.2 million pounds of *A. nodosum* are removed from the intertidal zone.

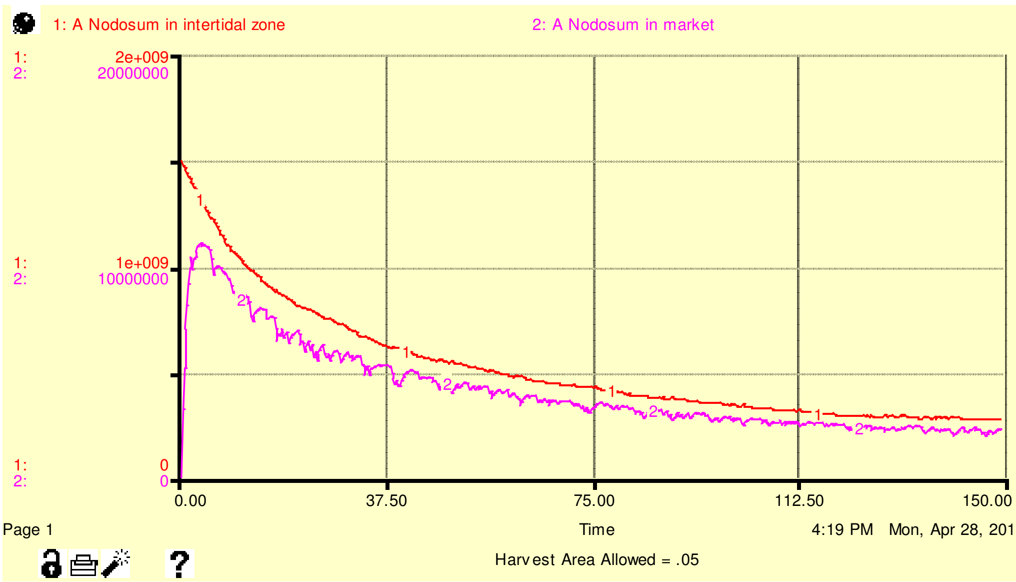

Figure 7: Results if 5% of the area is harvested. Approximately 275.8 million pounds of Ascophyllum nodosum are expected to remain in the intertidal zone after 150 years.

If instead 20% of the area was harvested, only 31.6 million pounds would remain (decreasing at a rate of about 1 thousand pounds a year), and if 50% of the area was harvested only 40 thousand pounds would remain (again, decreasing at a rate of about 1 thousand pounds per year). See figures 8 and 9, respectively. Again, these results should be compared to a baseline outcome of 415 million pounds remaining, meaning an additional 383.4 million pounds are taken if a quarter of the area is harvested and an additional 414.96 million pounds are taken if half of the area is harvested.

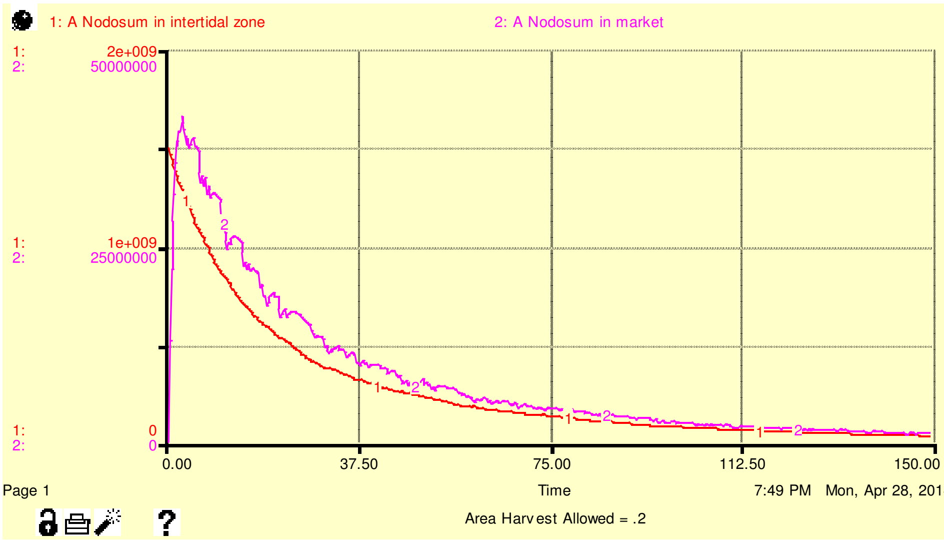

Figure 8: Results if 20% of the area is harvested. Approximately 31.6 million pounds of Ascophyllum nodosum are expected to remain in the intertidal zone after 150 years.

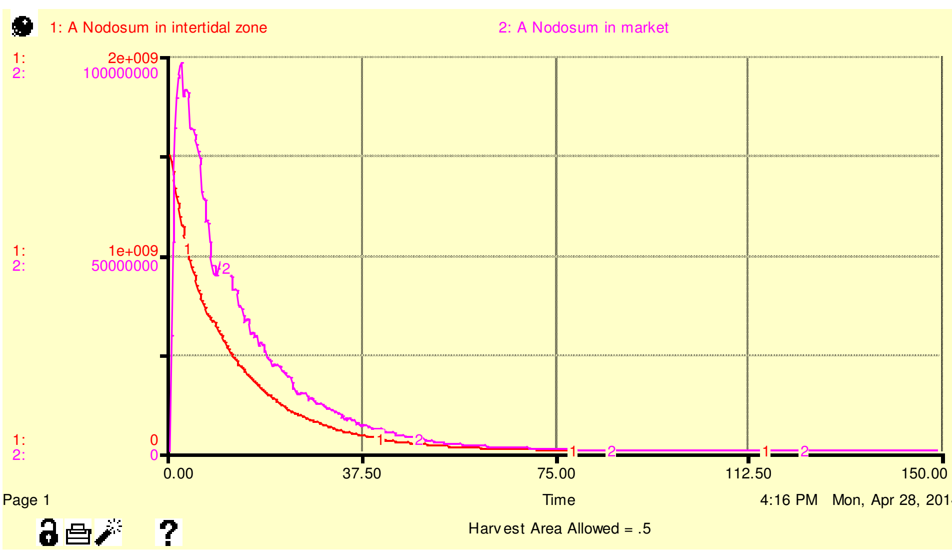

Figure 9: Results if 50% of the area is harvested. Approximately 40 thousand pounds of Ascophyllum nodosum are expected to remain in the intertidal zone after 150 years.

Finally, since some of the ecological parameters are uncertain or vary depending on location, the sensitivity of the model to these values was explored. Specifically, the effect of changes in the recruitment rate without any harvesting allowed was of concern since estimates of the recruitment rate vary in the literature and are known to depend on factors such as exposure to wave action, a spatial factor which varies significantly along the Maine coast and was beyond the scope of this model. Recall a 9% recruitment rate (without harvest) was used in this model, but the actual recruitment rate may be lower than this. Rates lower than 9% caused a crash in the stock of *A. nodosum,* even without harvesting allowed, and so were not used.

In the somewhat unlikely case the recruitment rate should actually been higher than what was used in this model, a 2% increase in the recruitment rate was modeled (Figure 10). In this case, approximately 717 million pounds of *A. nodosum* remained in the intertidal after 150 years, a 302 million pound increase compared to the result of the baseline model. In the more likely case that the recruitment rate was set to high, a 2% decrease in the recruitment rate was modeled (Figure 11). In this case 140 million pounds remained, continuing to decrease at a rate of a few thousand per year, 275 million pounds less than remained in the baseline case. These differences are fairly approximate to the differences seen from banning mechanical harvesters or hand rakes, indicating the model was sensitive to the uncertainty of this parameter.

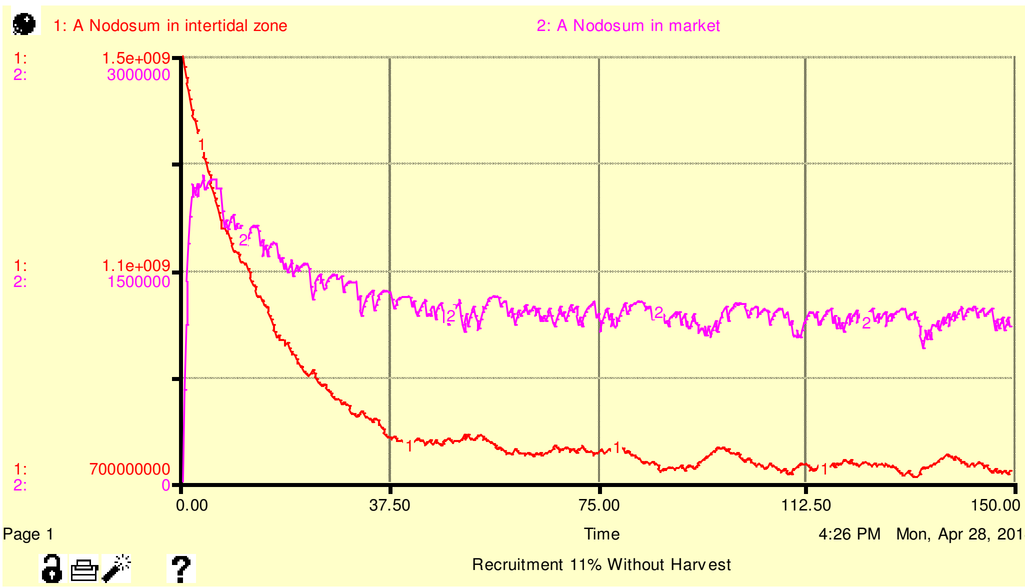

Figure 10: Results if recruitment rate is 11% without any harvesting. Approximately 717 million pounds of Ascophyllum nodosum are expected to remain in the intertidal zone after 150 years.

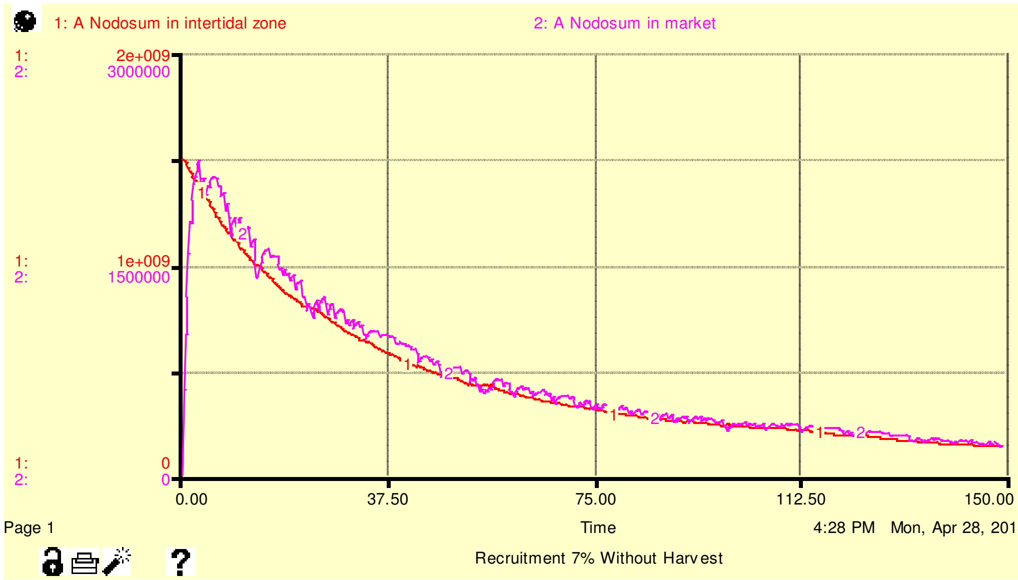

Figure 7: Results if recruitment rate is 7% without any harvesting. Approximately 141 million pounds of Ascophyllum nodosum are expected to remain in the intertidal zone after 150 years.

4. Conclusions

Although the effect of restricting the harvesting tool was expected to have the greatest impact on the stock of *A. nodosum* in the intertidal zone after 150 periods, it did not have as great an impact as that of the area harvested. This result is perhaps in part driven by the currently very low levels of harvesting occurring on a percentage level, although in absolute terms it is an impressive quantity. This result further indicates that Maine should be wary of the species being vulnerable to a tragedy of the commons problem, particularly with the currently low barriers to market entry, as the steps to adopt a comprehensive management plan indicates it is.

At the same time, the difficulties in creating an accurate model for this harvest indicate a need for an increased knowledge base and sophisticated consideration when creating a management plan. If estimates of the recruitment or growth rate were more widely agreed upon this would increase confidence in management decisions, for example. However, this and other factors, such as death rates, are known to depend heavily upon the spatial characteristics of the area the organisms are living in, such as exposure to wave action. This leads to a hypothesis that *Ascohyllum nodosum* beds on the open coast may not be able to withstand as intense a harvest as beds in sheltered coves, an idea which should be recognized when creating a management plan, perhaps through the creation of designated harvesting zones with specific regulations.

There are other ecological aspects of the industry are difficult to model but must be considered by policy makers. One, not all tools are equal in their effect on recruitment rate, or their efficiency of extraction. Some mechanical harvesting tools seem to rarely take holdfasts (the factor affecting recruitment rate) while other designs do so often, and the rate hand rakes remove holdfasts may also depend on the care taken by the harvester (Domizi, 2013; Ugarte, 2001).

Additionally, the ecological effects on other species resulting from the harvest are very unclear. It is known that harvested fronds tend to grow back in more of a ‘bush’ shape than ‘tree’ shape (Ugarte, Sharp, and Moore 2006), which is hypothesized to affect at least some species use of *A. nodosum.* It also may be important to ensure intertidal areas are not suddenly left as bare rock when moisture had been retained by *A. nodosum* fronds during low tide for the sake of species such as barnacles or snails, which may not be able to move at all or quickly enough to avoid desiccation. Lastly, the effect of removing the quantity of harvested biomass, both in terms of removing nutrients from the system and in reducing habitat creation, is worth investigating before harvest decisions are made.

One economic aspect of the industry that should be considered by policy makers, but is not explored in this work, is the large discrepancy between the ‘dock ‘price’ and the value-added price. In recent years the raw product has sold for somewhere around $0.02 to $0.03 per pound, meaning the raw value was $233,000 in 2012, while the value after processing is estimated at $20 million (Walsh, 2013). The difference in price is likely generated because the processed product is often used in vitamins or other expensive products (United Nations, 1987; Domizi, 2013). This discrepancy marks a huge opportunity to generate revenue for Maine companies, something that is currently being capitalized by some, but not all, Maine harvesters (Domizi, 2013).

Overall, the harvesting of *A. nodosum* in Maine is a complicated industry that a simple Stella model is unable to completely address, although the model does highlight potentially key areas for policy makers to explore. Thankfully, the State of Maine has recognized the industry is worthy of developing a statewide management plan, and is hopefully incorporating many of the issues discussed in this paper.

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6. Appendix

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A_Nodosum_in_intertidal_zone(t) = A_Nodosum_in_intertidal_zone(t - dt) +
(Regeneration__per_year - Deaths_per_year - Tons_harvested_per_year) * dt
INIT A_Nodosum_in_intertidal_zone = 1500000000
INFLOWS:
    Regeneration__per_year = Recruitment_Rate*A_Nodosum_in_intertidal_zone
OUTFLOWS:
    Deaths_per_year =
    (A_Nodosum_in_intertidal_zone*.01)+(A_Nodosum_in_intertidal_zone*Environmental__C
    onditions)
    Tons_harvested_per_year = (If Random_Harvest
    <(.17*A_Nodosum_in_intertidal_zone*Area_Harvest_Allowed) then Random_Harvest else
    (.17*A_Nodosum_in_intertidal_zone*Area_Harvest_Allowed))
A_Nodosum_in_market(t) = A_Nodosum_in_market(t - dt) + (Tons_harvested_per_year -
Tons_sold_per_year) * dt
INIT A_Nodosum_in_market = 0
INFLOWS:
    Tons_harvested_per_year = (If Random_Harvest
    <(.17*A_Nodosum_in_intertidal_zone*Area_Harvest_Allowed) then Random_Harvest else
    (.17*A_Nodosum_in_intertidal_zone*Area_Harvest_Allowed))
OUTFLOWS:
    Tons_sold_per_year = A_Nodosum_in_market
Area_Harvest_Allowed = 0.01
Carrying_Capacity = 1500500000
Environmental__Conditions = RANDOM(0,.05,.02)
Hand_Rake = RANDOM(.58,.38,.48)
Mechanical_Harvester = (1-Hand_Rake)
Random_Harvest =
((Hand_Rake*A_Nodosum_in_intertidal_zone*RANDOM(.04,.15,.095))+(Mechanical_Harvester*A_
Nodosum_in_intertidal_zone*RANDOM(.20,.36,.28)))*Area_Harvest_Allowed
Recruitment_Rate =
(.09-(.03*Hand_Rake+.05*Mechanical_Harvester))*(1-(A_Nodosum_in_intertidal_zone/Carrying_C
apacity))
```

Appendix: "Current Conditions" (baseline) model used, in equation form.