EXERCISE ONE

TREE PLANTING, GROWTH, AND HARVEST

Prepared for Systems Dynamics SYSC 514 (Winter 2016)
Prepared on 1/29/16
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Problem Formulation

The primary goal of this effort was to model silvicultural operations for a woodlot containing a mixture of mature and immature trees. Harvesting mature trees decreases the available resources and need to be replaced with new, immature trees. The system being modeled is similar to current silvicultural practices in Oregon as mandated by the Forest Practices Act (FPA). Key elements of the FPA include the following:

- Landowners must complete replanting of harvested ground within two years of a harvest.
- Within six years of harvest, the young trees must be "free-to-grow", meaning they are vigorous, well-distributed, and ready to grow into successfully into a young forest.
- Depending on site productivity, a minimum of 100 to 200 trees per acre must survive following replanting.
- A landowner may be required to replant additional seedlings to ensure a sufficient number of trees per acre following selective harvest or thinning.

For this modeling effort, the system has been simplified to exclude consideration of key factors influencing timber harvest such as tree mortality, thinning, spray, and density dependence of time to maturity. Early consideration of including mortality was rejected to avoid the risk of overcomplicating the model and/or straying too far beyond the bounds of the prescribed assignment guidelines. Future steps aimed at improving the model to address these issues are discussed at the close of this document.

One additional component was added to the model outside the bounds of the course specifications: harvested trees. Addition of this factor provides insight into the results relative to the purpose of the system in the real world, which is to extract natural resources in a sustainable fashion. An early version of the model (discussed below) was developed without including harvested trees that connected mature and immature trees in a loop. Although it is possible to generate quantitatively accurate results this way, it does not accurately reflect the real world reality that new trees are continuously being added to the system while mature trees are continuously leaving it rather than the same trees endlessly cycling through the system. This observation highlights the dual purposes of developing a formal systems dynamics model, 1) to illustrate the underlying structure the feedback loops that drive the systems behavior and 2) to generate quantitatively accurate estimates of system behavior under varying assumptions and parameters.

Model Development

Model development began with the development of a Stock and Flow Diagram (SFD). As has been discussed in course lectures, in situations where the modeling effort begins with a clear understanding of the system (including equations and starting values), it is often easiest to begin with a SFD rather than a Closed Loop Diagram (CLD).

Stock variables include the following:

- Harvested Trees = INTEG(Harvesting) [*units = trees; initial value = 0*]
- Mature Trees = INTEG(Maturing-Harvesting) [*units = trees; initial value = 100*]]
- Immature Trees = INTEG(Planting-Maturing) [*units = trees; initial value = 100*]

Flow variables include the following:

- Harvesting = Harvesting Rate*Mature Trees [*units* = *trees/year*]
- Maturing = Immature Trees/Years to Maturity [*units* = *trees/year*]
- Planting = Harvesting [*units* = *trees/year]*

Auxiliary variables include the following:

- Harvesting Rate = constant *[units = 1/years]*
- Years to Maturity = constant [*units* = *years*]
- Replant Rate = constant [*dimensionless*]

As one can see above, the model variables exhibit dimensional consistency in their units (i.e. all stocks and flows use 'trees' as their base unit).

The units of time were set as years, the time step was set to one, and the model was set to run for 100 years (with one exception discussed in the results section of this document). The choice of time step is justified by the real world discrete nature of harvesting and planting operations.

As discussed above, a preliminary SFD model was developed that did not include an output to harvested trees. As can be seen in the figure below, the model gives the impression that trees flow continuously in a cycle through the system. Because the initial problem is specified such that planting and harvesting are done at equivalent rates, this configuration is capable of generating accurate results under many scenarios. However it is conceptually incorrect, and cannot capture the behavior of the system when those rates diverge. Although replanting is now a legal requirement in the State of Oregon, this was not always the case, not is it true in many other parts of the world. This observation illustrates that although a conceptually incorrect model may be capable of solving an initial problem, it is preferable to accurately model the system processes to maximize the applicability and flexibility of the tool.

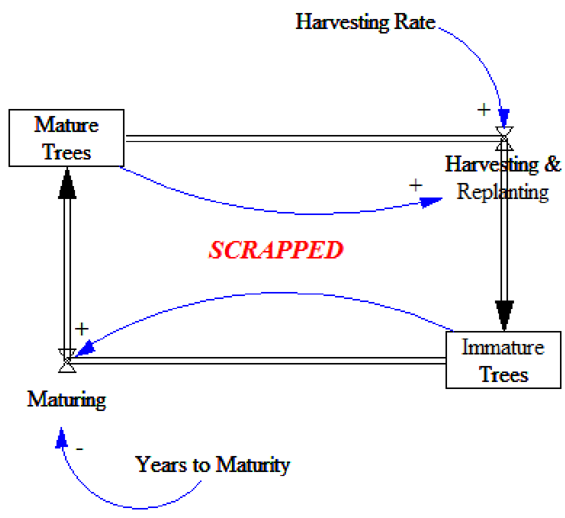

Figure 1. Preliminary (scrapped) SFD

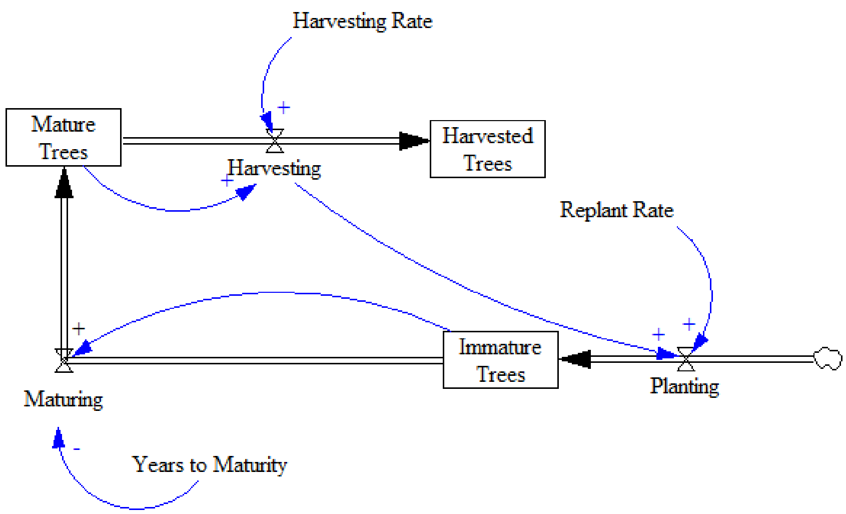

Figure 2. Final SFD

Although a Stock & Flow Diagram was built first, a CLD was also developed to help provide a high level, conceptual understanding of the feedback loops that control the system. Key variables were the same as those used in the SFD (with the exception of replant rate which is simply a dimensionless ratio). As one can see, there are two key balancing loops (the mature and immature loops) which serve to stabilize the number of trees in each stock. Finally, the output to harvested trees is purely positive and lacks any kind of feedback. As such, it is clear that the number of harvested trees should increase monotonically (when harvesting is greater than zero).

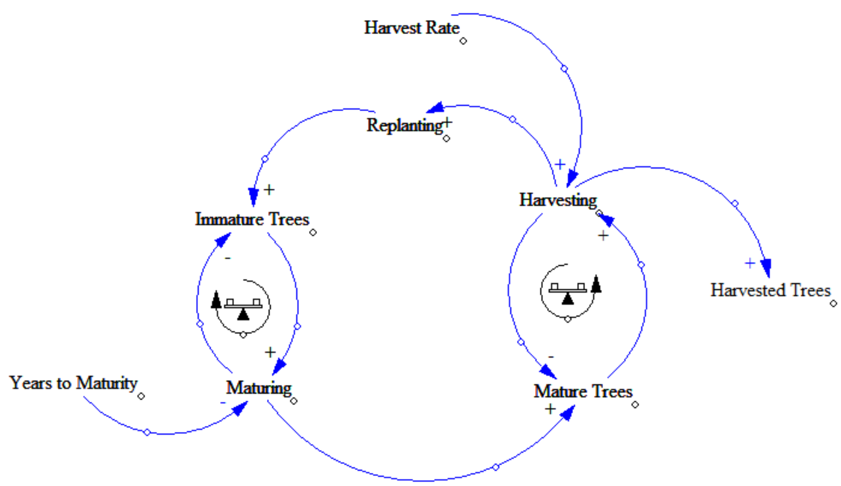

Figure 3. Final CLD

Model Testing

Reference Behavior Patterns (RBP) refers to the actual behavior of the system in the real world. In this case the model reflects silvicultural practices similar to those utilized in the Oregon under the existing Forest Practices Act (FPA). Due to the very simple nature of the model, extensive testing was not required to ensure correspondence with the RBP. The following basic tests/requirements were evaluated by using the Synthesim tool available in Vensim to systematically permute the auxiliary variables to explore model behavior. Key features of the RBP (in italics) to be tested and the model responses to these tests are described below.

1) *Harvested trees always increase (or at least do not become zero)*. Upon first testing this assumption, the author noted that minimum (and maximum) values had not been specified for harvest rate, which made it possible to violate this requirement. This error was corrected in the final version of the model.
2) *So long as planting and harvesting are equivalent, both mature and immature trees should find a state of dynamic steady state equilibrium*. Evaluation with Synthesim showed this to be true, although for very high values of years to maturity and very low harvest rates it can take a long time to reach equilibrium.
3) *Because planting lags harvesting in time, increases in immature and matures trees should lag in time in relation to harvest rate and harvested trees*. Evaluation with Sythesim also showed this to be the case. An example of this for a single step change is discussed in the Results section below.

Finally, the appropriateness of the time step (1 year) used in the initial model was tested by rerunning the model with the step set to a much lower value (0.0625) and comparing the output. No differences were observed thus validating the use of a value of 1 year as appropriate.

Model Application

The model as described provides a simplistic framework for evaluating the impact of changing harvest proportion (which is really just a surrogate for harvest frequency) and the time to maturity on the total number of trees harvested. However the absence of numerous key variables which impact timber production and growth substantially limit the applicability of this model. Potential improvements which could address these limitations are discussed at the close of this document.

Results & Conclusions

Note to the Reviewer

Results have been consistently presented in graphical form (as opposed to tabular presentation of numerical results). It is the author’s opinion that this is the most effective means of conveying the results of this modeling effort.

Initial Model

Under the initial model runs, harvest rate was set at 0.05/year and years to maturity was set at 20. This particular configuration obviously equalizes harvesting and maturation times at 20 years. Therefore one expects that the total number of mature and immature trees will remain constant at 100, while the number of harvested trees will increase in a linear fashion. Graphs of model output showing exactly these results are included below. Please note that there is a red and green line at the very top of the graph. In general the initial model run did not generate any findings of particular interest or surprise.

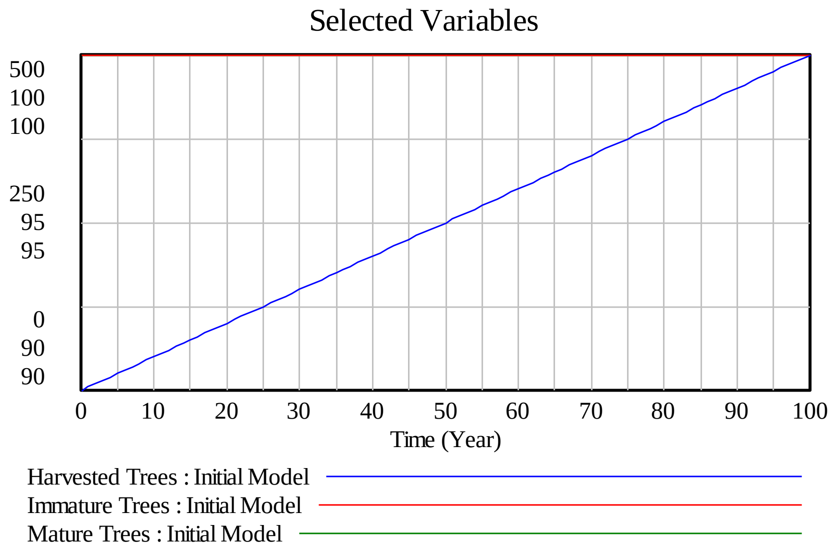

Fig 4. Stock Variables – Initial Model

Year Five Harvest Increase

Under the second scenario evaluated, harvest rate was increased from .05 (i.e. 5%) to 0.10 (i.e. 10%) at year 5 in the model. This was accomplished by modifying the equation for harvesting rate from a constant to a STEP function equal to [0.05+STEP(.05, 5)]. As you can see this has the effect of 1) increasing the number of trees harvested (with a change in slope at year five), 2) the number of immature trees rises exponentially (in the form of e^{-x}), and 3) the number of mature trees drops exponentially (in the form of $1-e^{x}$). The results show that system finds a new dynamic equilibrium at roughly 25 years. This kind of response driven by the two balancing loops described above, and illustrates the kind of exponential smoothing discussed by Sterman.

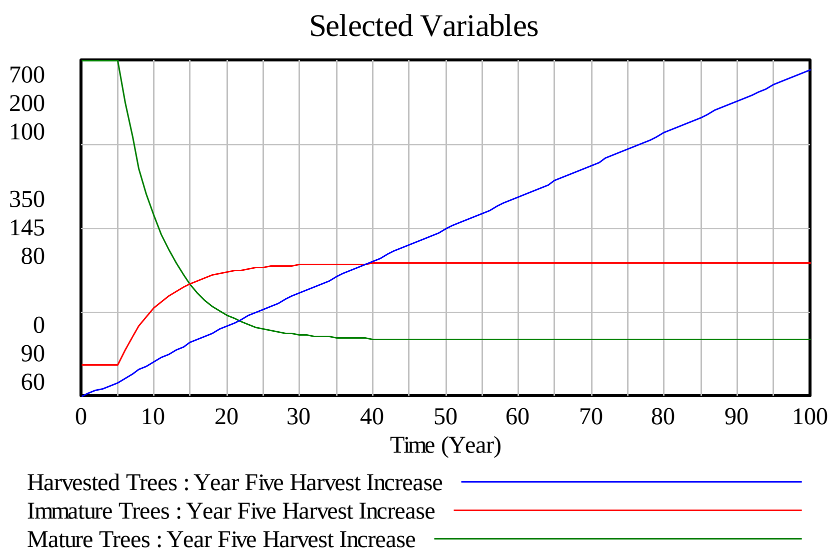

Fig 5. Stock Variables – Year Five Harvest Increase

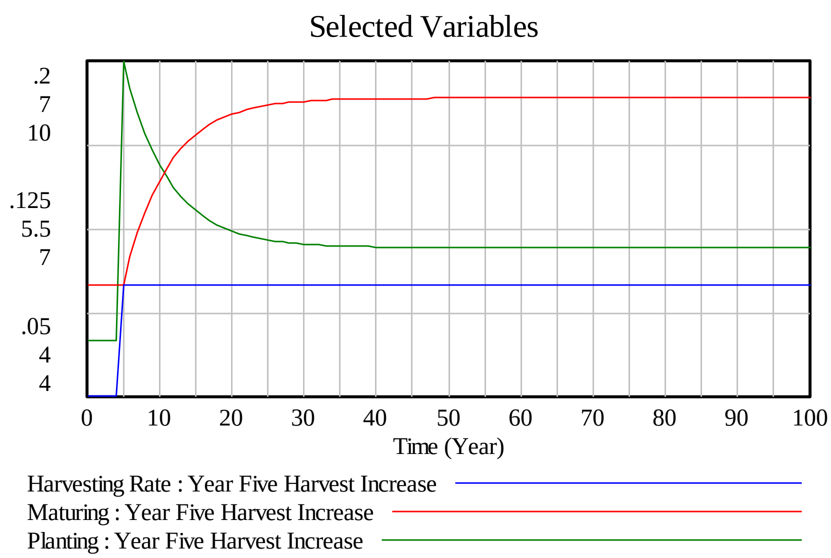

Fig 6. Flow & Rate Variables – Year Five Harvest Increase (note that the Harvesting flow is identical to that of the Planting flow and is not shown for clarity)

Exploring Strategies for Stand Preservation and Stability

Four primary explorations are described in in this section: 1) increasing the time to maturity from 20 to 40, 60, 80 and 100 with harvest rate held at 0.05 ; 2) increasing the harvest rate from 0.05 to 0.10, 0.40, and 0.80 with time to maturity held at 20 years; 3) adjusting the years to maturity to 100 ***and*** the harvest rate to 0.80 to test for interactions at the extremes; and 4) systematically decreasing the replant rate from 1.0 to 0.8, 0.6, 0.4 and 0.2. Note that for this final exploration the time scale was expanded to 1000 years to reflect the timescale of the response. No attempt was made to model increases in replant rate above one, as the model lacks key components (e.g.

density dependence and mortality factors) needed to generate meaningful. This issue and potential solutions are discussed at the close of this document.

Increasing Time to Maturity

With regards to the first exploration, the figures below show that increasing the time to maturity decreases the number of trees harvested, but that the decrease is non-linear with respect to years to maturity. This finding illustrates the impacts of the feedback loops that balance the output of the model. The real world consequences of this finding are that the return (in terms of number of trees or board feet) on increasing the harvest rate diminishes as one approaches 100% harvest rate.

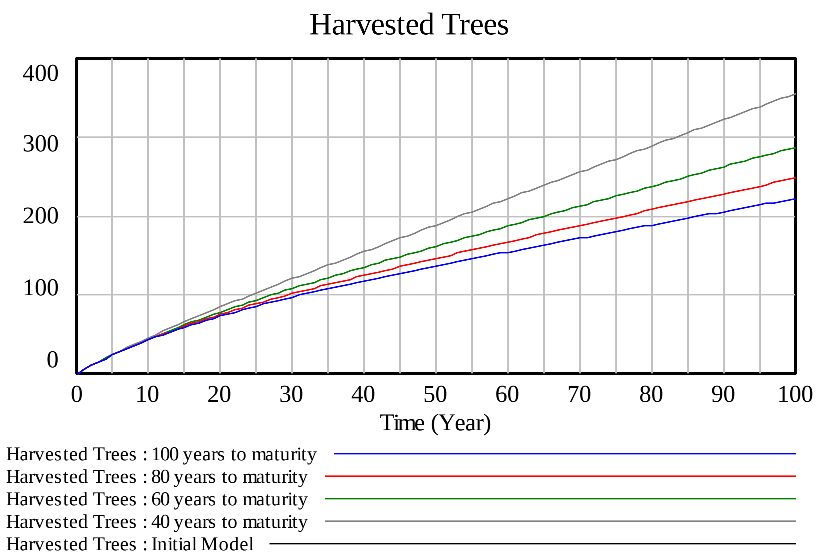

Fig 7. Harvested trees with varying times to maturity

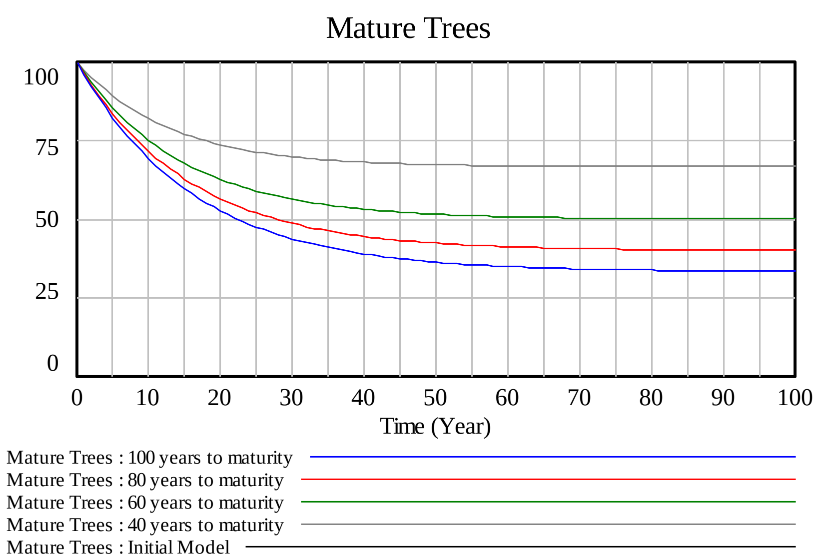

Fig 8. Mature trees with varying times to maturity

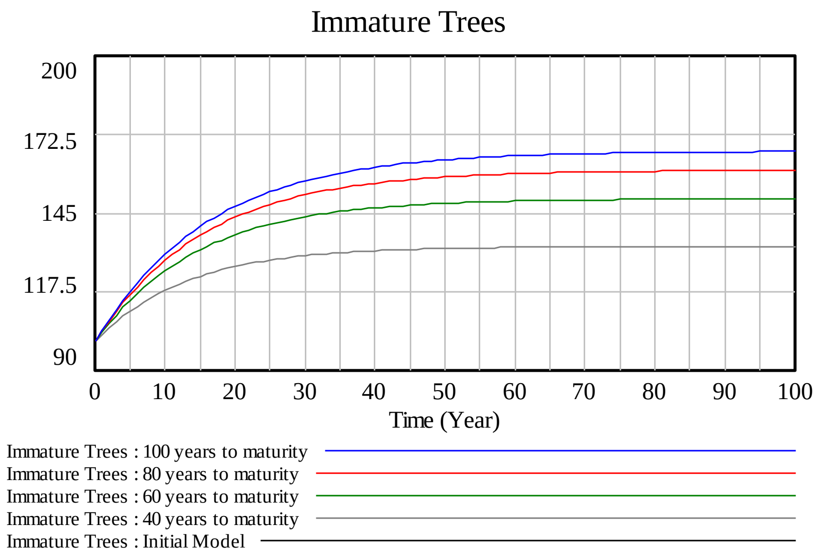

Fig 9. Immature trees with varying times to maturity

<u>Increasing Harvest Rate</u>

With regards to the second exploration, as harvest rates increase, unsurprisingly harvested and immature trees increase while mature trees decrease. Again the response is non-linear, reflecting the balancing feedback loops in the system.

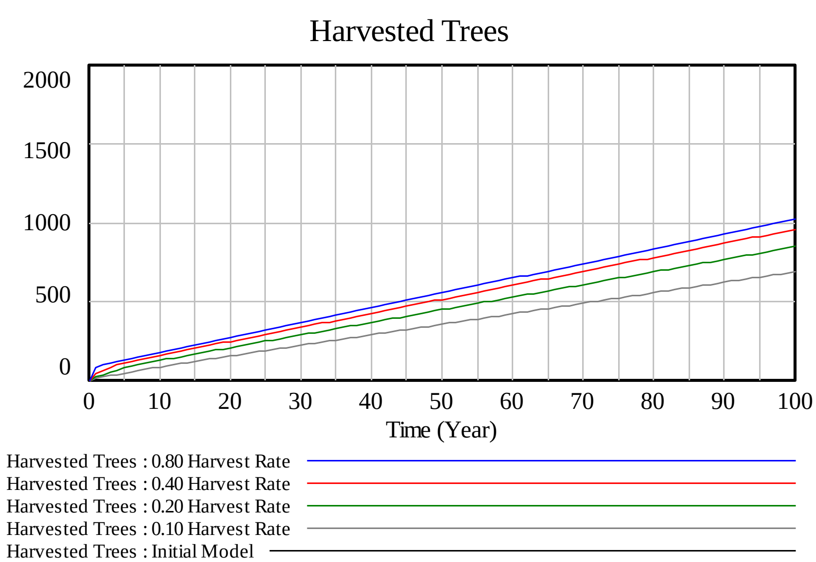

Fig 10. Harvested trees with varying harvest rates

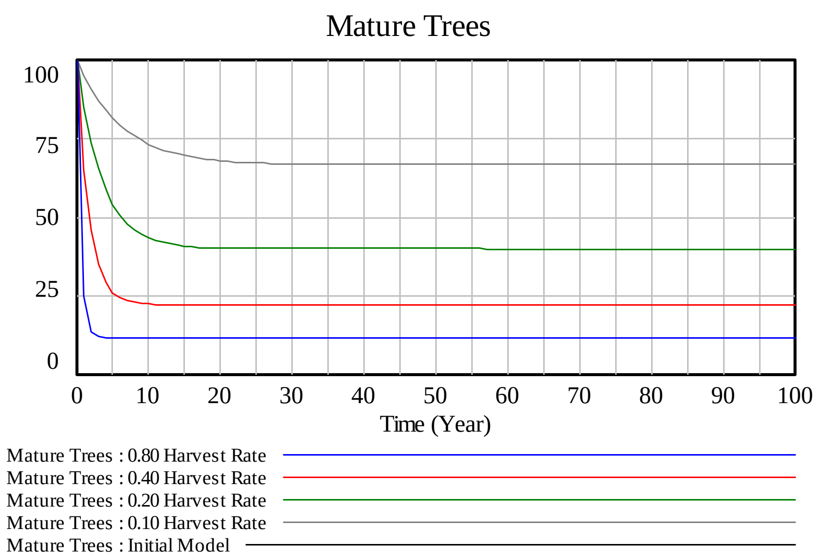

Fig 11. Mature trees with varying harvest rates

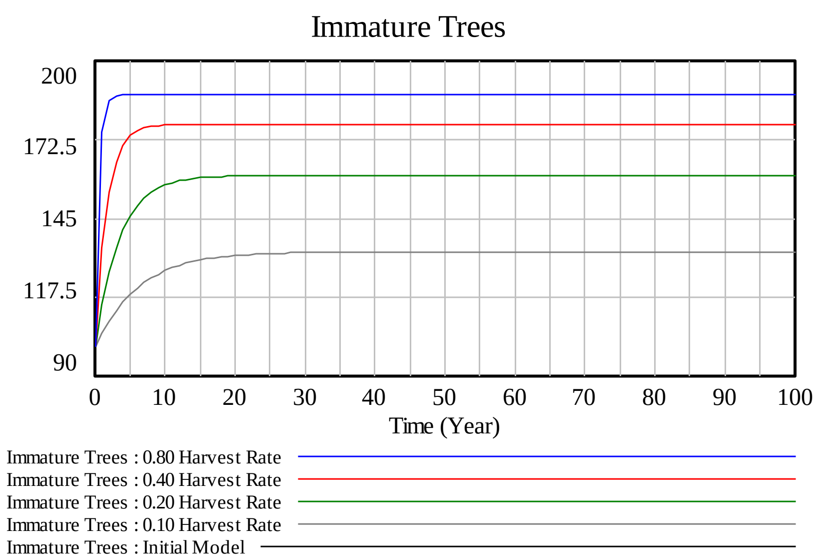

Fig 11. Immature trees with varying harvest rates

<u>Increasing Time to Maturity and Harvest Rate to Extremes</u>

With regards to the third exploration, when the harvest rate and years to maturity are pushed towards the extreme high end, the nonlinearity in the stock response is highlighted. As one can see below, there is a rapid and steep response to the very high harvest rate which immediately reduces the available mature trees by 80%. The stock variables rapidly come to equilibrium

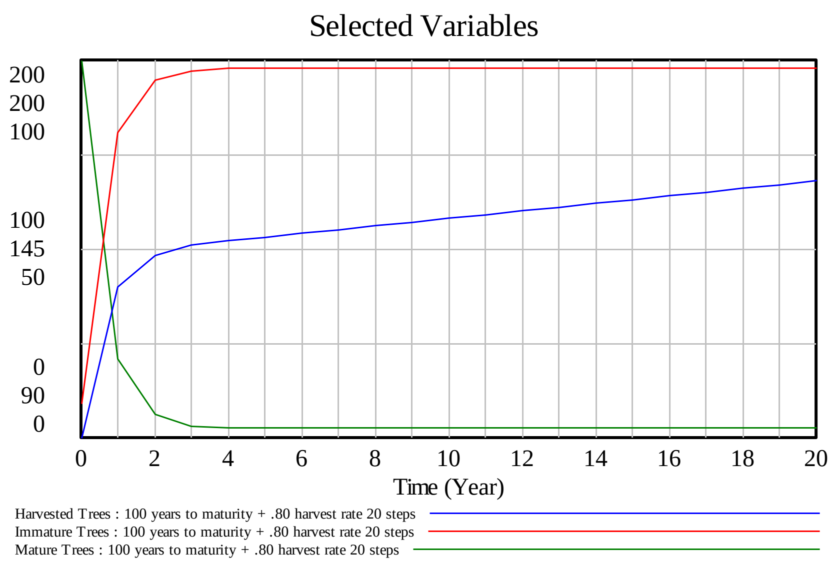

Fig 12. Stock variables with high end harvest rate and years to maturity

Decreasing the Replant Rate

With regards to the final exploration, decreasing the harvest rate below one forces the system out of steady state equilibrium, resulting in an eventual cessation of harvest as all of the mature trees are depleted. This intuitively logical result supports and justifies the mandates set forth in the FPA to replant timberland following harvest.

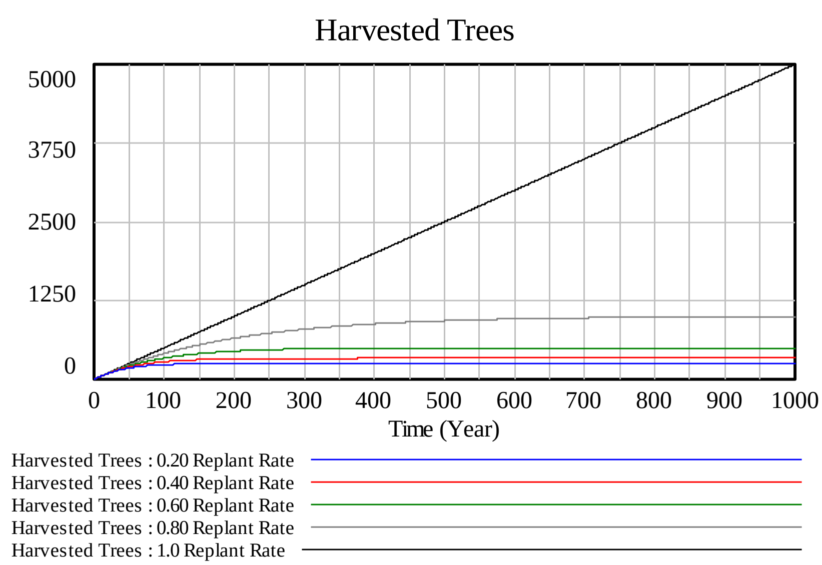

Fig 13. Harvested trees with decreasing replant rates

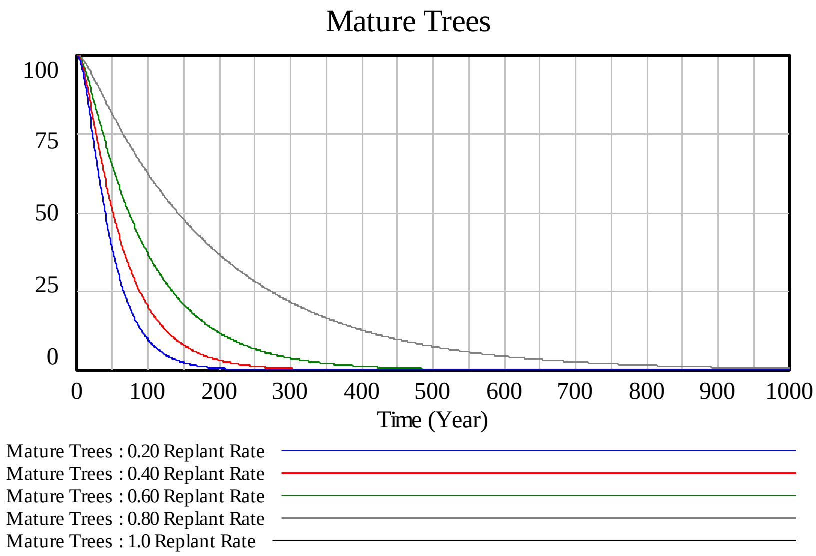

Fig 14. Mature trees with decreasing replant rates

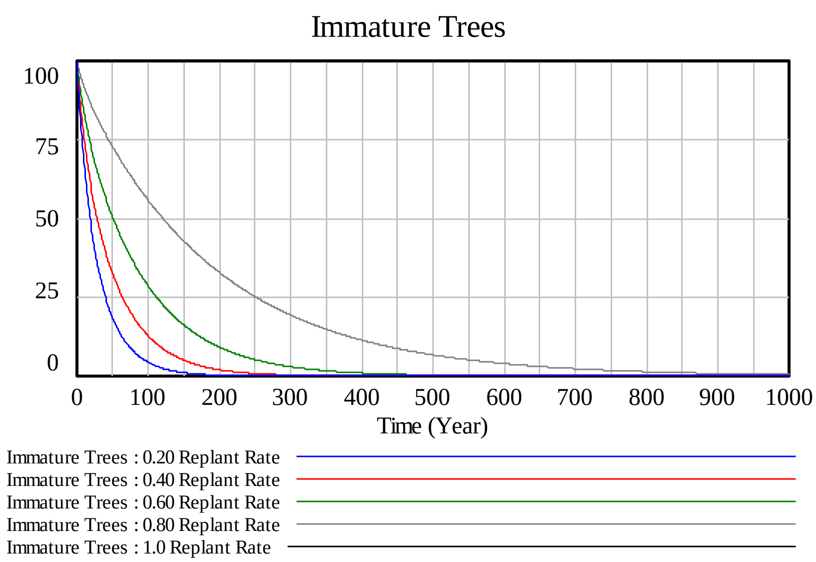

Fig 15. Immature trees with decreasing replant rates

Summary of Results

Overall the results of these manipulations show that regardless of the harvest rate or years to maturity, so long as the rate of replanting is yoked to the rate of harvest, the systems naturally self stabilizes through a process of exponential smoothing. Manipulation of these parameters primarily change the composition of the stand (increasing harvest rate by itself lowers the average age of the trees whereas increasing years to maturity alone raises the average age of the stand.). A more detailed and sophisticated model would be needed to identify parameters likely to maximize ecological (e.g. many very old trees) and/or economic (e.g. very high board feet of lumber) potential.

Potential Model Improvements

As discussed above, the model as currently implemented (based on the constraints of the exercise description), is missing key variables and feedback loops which influence tree growth and harvest. These omissions limit the model applicability substantially. Improvements and additions to the model are briefly discussed below.

- *Tree mortality* is a reality in timber operations, and can be due to weather, disease, pests, or ungulate browse. Furthermore, trees of differing ages and species are affected differentially by these causes. One obvious consequence of including this variable is that in order to maintain a steady state dynamic equilibrium, the number of trees planted must be greater than the number of trees harvested.
- *Density dependence* of tree growth reflects the trees need to for nutrients and solar input. Trees planted too closely together compete for resources and grow to maturity too slowly. Addition of this variable would balance the unrealistic increases in harvest output that comes with increasing planting numbers.
- *Precommercial thinning* is a silvicultural practice whereby trees are selectively removed to promote maximal growth of the most viable immature trees. It allows the silviculturalist to minimize mortality impacts at a young age while optimizing tree density as they grow.
- *Aerial spray* is a common and controversial practice used to minimize mortality among juvenile trees.
- *Tree size* is proportional to age, and determines the total number of board feet which can be obtained for a given number of trees harvested. Because trees, especially the conifers generally preferred for lumber, are so long lived, the term years to maturity is actually a bit misleading. Standard practice in industrial timber operations is to harvest at ~40 years of age to maximize the return per acre of timber.

References

1. **State of Oregon**. Forest Practices Act. http://www.oregon.gov/ODF/Working/Pages/FPA.aspx
2. **Sterman, J.D.** BUSINESS DYNAMICS: Systems Thinking and Modeling for a Complex World. Irwin McGraw-Hill (2000)
3. **Ventana Systems Inc**. Vensim 6.3E. Users Guide http://vensim.com/docs/ (2015)