Modeling the Mountain Pine Beetle Population's Response to Temperature Fluctuations

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Introduction

This simulation models the growth and spread of populations of the Mountain Pine Beetle (MPB) through stands of trees in a forest. It is a modified SIR (susceptible, infected, recovered) model cellular automata because it does not have a recovered state since the simulation is meant to be short term and pine trees do not grow back quickly enough to be included in the model (National Resources Canada, 2018). I want to be able to measure the health of a section of forest defined by the number of normal, infested, or dead tree stands after a set number of years. I also want to be able to analyze the spread of MPB populations through a forest. I use Colorado temperature data from the National Oceanic and Atmospheric Administration (NOAA) (Diamond, H., Karl, T., et al., 2013). The model consists of a CA with cells in a grid. These cells can have states of empty, tree, infested, and dead. The time step unit is one day. “Tree” and “tree stand” will be used interchangeably throughout this paper, but in the simulation cells are supposed to represent tree stands, which contain many trees.

Rules

The rules of my simulation are based on a model blueprint that Mason Noteboom, a 2020 student, wrote last year. A more fleshed out description and research on the topic matter can be found in her paper (Noteboom, 2017). The following rules and assumptions govern the agent-based model:

- Temperature is the only changing parameter.
- MPB can only move in the summer.

- The summer is defined as anytime the temperature is over 20 ºC.
- Consecutive summer months increase the probability of both movement of the MPB to other tree stands and probability of successful infestation once moved. Over 120 days there is a 70% chance of movement and 100% chance of successful infestation, from 75 to 119 days, 40% and 50% respectively, from 30 to 74 days, 20% probability for both movement and infestation success, and under 30 days 5% probability for movement and infestation success.
- Droughts increase the probability of successful attacks by MPB on tree stands because trees are water stressed and can't fight off MPB with resin they usually would be able to produce. MPB have a 10% higher infestation success probability and a 20% higher movement probability when in drought.
- Cold snaps reduce the beetle population by 90% and occur when the temperature is below -40 ºC in the winter and -20 ºC in other seasons.
- To introduce randomness into the system coming directly from humans I include a probability of someone transporting infected wood to a tree stand in the forest which can spread the MPB infestation beyond dead tree stand clusters. I discuss its value later.

Assumptions

- This simulation is synchronous to reflect the synchronous nature of time. I wanted to capture the days going by for every cell in the forest.

- I use Moore neighborhoods within one cell to represent the capability of the beetle to fly to the nearest healthy tree. In reality this distance may be variable, and would greatly affect the results from my simulation (I will show this later).
- Droughts weaken the trees due to them being water stressed. Trees produce resin to fight off MPB and other insects but when water-stressed they are unable to defend as successfully. This is an externally and internally valid assumption.
- MPB and trees do not evolve or adapt in the simulation. Research has shown MPB have evolved to ingest the resin produced by trees and convert it to a pheromone that attracts other beetles to the tree. This decreases the validity of the model.

Values of Interest

After a certain period of time we are interested in the proportion of infested, dead, and healthy trees. For example, we can see that after one year, our 100 x 100 cell forest CA has 3830 empty cells, 5178 healthy tree stands (untouched by MPB), 643 infested tree stands, and 349 dead tree stands. Totaling 6,170 trees we can calculate 84% healthy tree population after an abnormally hot year in Cortez, Colorado, USA.

Results

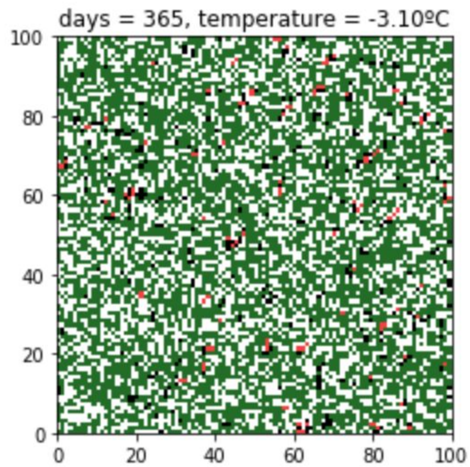

Fig. 1: Cortez, CO 2017, regular temperatures

Figure one shows a forest infested sparsely by MPB after a regular temperature year. There is a 95% (91%, 97%) remaining healthy population. While 5% of the healthy tree stand population being wiped out is bad, the following figure shows what happens with abnormally hot and long summers in Cortez, CO (10 ºC above normal temperatures).

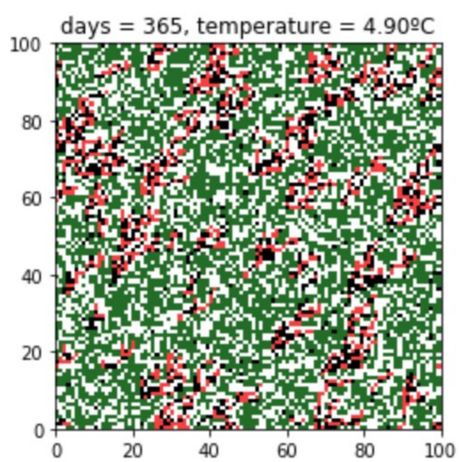

Fig. 2: Cortez, CO 2017, abnormally hot temperatures

In figure two we see an 85% (80%, 91%) healthy tree rate. It is obvious that there has been a MPB breakout in the forest and it appears to be a bit out of control. Figure three shows us what an obscenely hot and long summer would do to a forest.

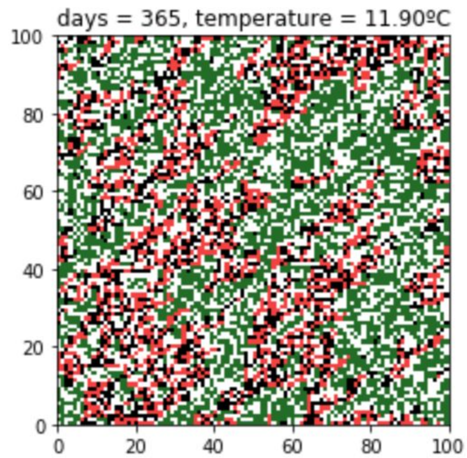

Fig. 3: Cortez, CO 2017, super hot temperatures

Figure three has temperatures 15 degrees celsius above normal temperatures, which is not unheard of but extremely improbable. We can use data from Boulder, CO for the same year, a colder place, as a comparison.

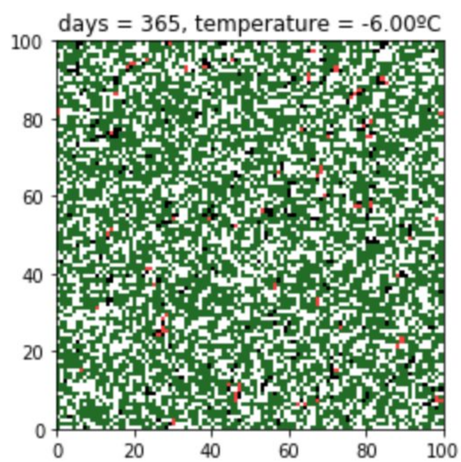

Fig 4: Boulder, CO 2017 regular temperatures, 95% (89%, 97.1%) healthy trees

There isn't much of a difference between the forests in Boulder and Cortez in my simulation. Figure five shows the forest simulation after the 2017 year for Cortez, CO.

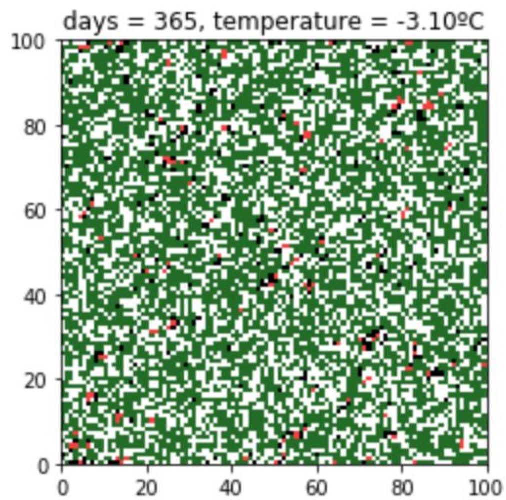

Fig 5: Cortez, CO 2017 regular temperatures, 94% (88.2%, 96%) healthy trees

Observing the simulation run for another year shows the lasting effects of the MPB population on the forest, and shows how devastating the MPB can be if left alone. In figure six below I show a forest at warmer temperatures in Cortez, CO after three years.

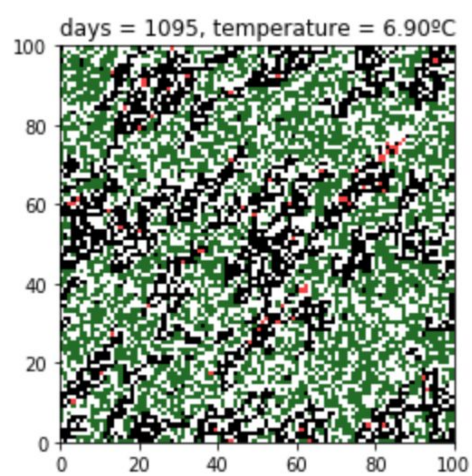

Fig 6: Cortez, CO 2017 super hot temperatures after three years, 51.6% (47%, 58%) healthy trees

Figure six shows the destruction a MPB population can cause after a longer period of time. The percentage of healthy trees dropped from 83.3% (80.1%, 86%) the first year, to 72.45% (66.8%, 75%) the second year, and finally 51.6% (47%, 58%) the third year with extremely hot temperatures. The spread of the MPB starts to slow as cold snaps and other natural death occurs, and as trees around clusters of MPB die off, but the damage is still widespread and impactful.

Moore Neighborhood Radius Modification

Earlier in the assumptions section I discussed the implications of a larger flying range for the beetle to infest other tree stands more than one cell away using Moore neighborhoods.

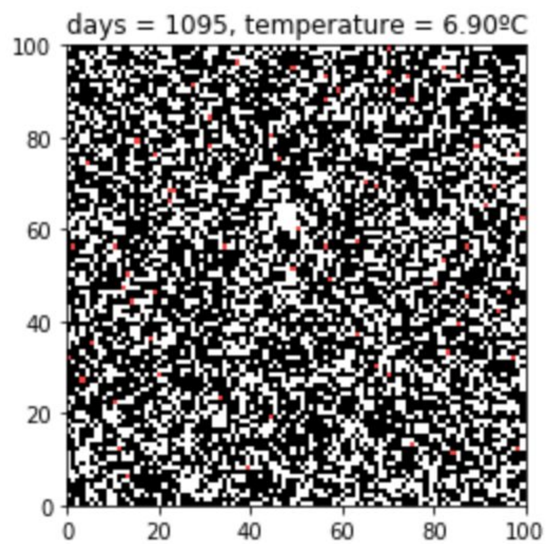

Fig. 7: Cortez, CO 2017, super hot temperatures, Moore neighborhood with radius of two

Figure seven shows the obliteration of the tree stand population by the MPB when using Moore neighborhoods with a radius of two instead of one. There is no short term recovery in sight for this forest and the healthy tree rate is 0% (0%, 0%). Using larger neighborhoods may improve the external validity of this model when applied to specific scenarios but for the sake of simplicity and lack of understanding of the underlying biological systems and their reactions to certain parameters I will stick with simple Moore neighborhoods with a radius of one.

Tree and MPB Density

The density definitely plays a role in the spread of MPB populations, but not at lower risk (regular) temperatures. Figure eight shows a forest with a density of 0.8 after three years. The health only dropped to 96% (95.2%, 97.5%).

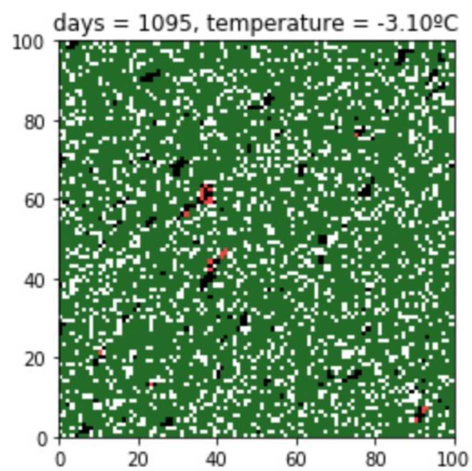

Fig. 8: Cortez, CO 2017 regular temperatures after three years, 0.8 tree density

However, if we have abnormally warm summer, the high density is detrimental to the health of the forest in similar ways to how the Moore neighborhood being extended was detrimental. The more trees or the easier it is to reach a tree for MPB, the more destructive the MPB becomes.

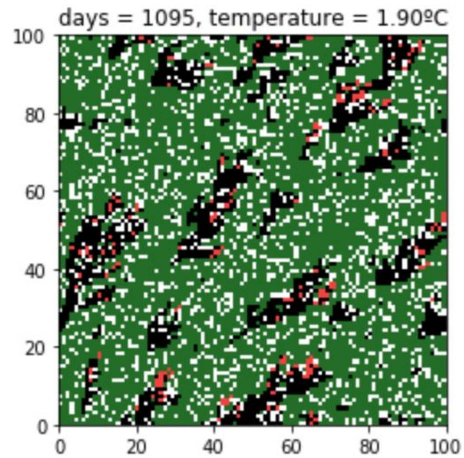

Fig. 9: Cortez, CO 2017 warmer temperatures after three years, 0.8 tree density

In figure nine we see the effect of a 5 ºC increase on temperatures. Instead of the 97% (95.67%, 98.4%) forest health we saw with regular temperatures we see a reduction to 91% (89.9%, 92.9%) forest health after three years. Clearly, the temperature plays a bigger role than any other parameter, because high temperatures trigger breeding and flying for the MPB.

Infested Wood Transport Rate

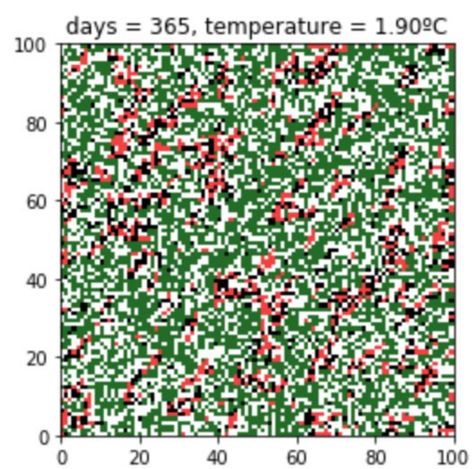

Fig. 10: Cortez, CO 2017 warmer temperatures, 0.1% transport rate, 86.1% health (83%, 90%)

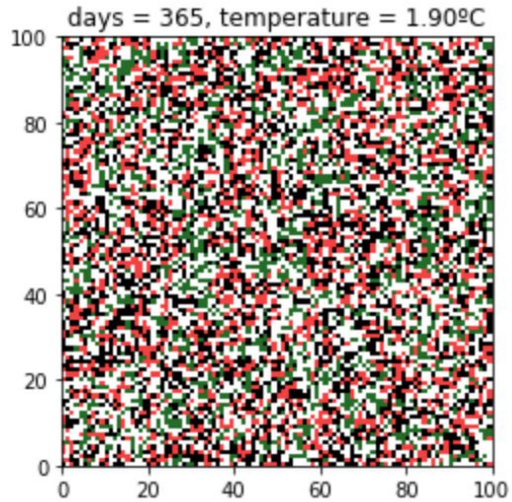

Fig. 11: Cortez, CO 2017 warmer temperatures, 10% transport rate, 43% health (40%, 53.8%)

Finally, taking a look at figures ten and eleven shows us the impact on reducing transport of felled wood infested by MPB. When there is not effective enforcement of laws cracking down on transporting firewood, lumber, or other wood infested with MPB we see a very obvious increase and spread of the MPB population to other previously untouched parts of the forest. The reduction from 10% to 1% transport rate improved health by 43%, from 86.1% to 43% health.

Suggestions

Besides the obvious and intractable treatment of trying to keep the atmosphere at a normal temperature, forestry services should enforce laws against transporting wood from MPB infested areas with road checkpoints, high fines, and high certainty of being caught. As evinced by the comparison between figures ten and eleven, reduction of transportation of MPB infested wood is critical to reduce the spread of MPB infestation. Also, forestry services should thin out forests, especially around MPB infested tree stands to limit the spread of MPB populations and increase control of the MPB population. Figures eight and nine show the dangers of neglecting to thin out forests. When the temperature increases, the density greatly affects how far the MPB can move. This practice should be thought of as analogous to thinning forests to avoid superfires, but is focused around concentrated areas of MPB. If there are key connection points in the forest where two large clusters of forest are linked, thinning out that connection enough to stop MPB may help stop the spread of the MPB from one cluster to another. A temporary solution could be directly killing the MPB, but that is just treating a symptom of the problem. Long term solutions should include enforcement of wood cleanliness and thinning key points in the forest as well as the forest as a whole to stop the spread of MPB.

Remaining Uncertainty

To demonstrate the consistency of my simulation I ran it for 100 separate years independently with the regular 2017 Cortez, CO temperature data and found a healthy tree stand rate of 94.895% (confidence interval: [93.909%, 95.785%]). There is little variance in the outcomes of the tree stand health. These confidence intervals are very narrow and reflect the consistent temperatures driving the consistent behavior in the system. The majority of the randomness in this model comes from the temperature data that is measured by the NOAA. Throughout the rest of the analysis I was bootstrapping 95% confidence intervals by running the simulation for ten independent years, which resulted in wide confidence intervals. If I had more time and computing power I would run the bootstrapping for 100 or 1000 independent years to get a more accurate interval.

Future Work

To extend this model and increase its external validity I would definitely include tree regeneration and a more accurate timing model for tree death. If I wanted to make the model more accurate I would include time for each cell state. I would also include evolution over time of MPB's resistance to cold snaps and attacking power during droughts. I would also try to incorporate real data from forest service law enforcement to get realistic data for transportation rates and how law enforcement affects transportation.

Work Cited

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