Impact of Clear-Cutting Strategies on Forest Fire Dynamics: A Cellular Automata Approach

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Introduction

Forest fires are becoming an increasingly widespread threat in today's world due to climate change. Increased frequencies of heat waves dry out the landscape and facilitate the spark and spread of these fires, and they are burning nearly twice as much tree cover today as they did twenty years ago (MacCarthy et al., 2023). While the only long-term solution involves reducing greenhouse gas emissions, there are still mitigating efforts that can be used to limit the frequency and spread of these fires, such as restoring wetlands and peatlands (United Nations Environment Programme, 2022). One of these methods is forest thinning. Previous studies have found thinning trees in forests to be an effective way to stop the spread of fires, especially when paired with a prescribed burn (Brodie et al., 2024). Thinning helps remove excess biomass and create firebreaks that contain the burn to one area, though too much thinning may overexpose the undergrowth to sunlight and exacerbate the problem (BCon Ltd, 2022). While the effects of different spatial thinning patterns have been examined from a forest health standpoint (Brown et al., 2019), it is still unclear how these patterns affect the spread of forest fires.

In this research, the effect of different thinning strategies on the spread of fire in a forest fire will be investigated using the forest fire cellular automaton model. This model will use active cells to represent trees, then simulate the spread of fire with three different spatial distributions. The first will be entirely randomly generated. The second will clump trees together to simulate cleared areas. The third will divide the forest into long strips. By investigating the effects that these thinning techniques have on the spread of our simulated wildfire, we can gain new insights about what strategies should be implemented to mitigate fires in life.

Material & Methods

We begin by modifying the forest fire model provided by Mesa. The original model is described in the following terms "The forest fire model is a simple, cellular automaton simulation of a fire spreading through a forest. The forest is a grid of cells, each of which can either be empty or contain a tree. Trees can be unburned, on fire, or burned. The fire spreads from every on-fire tree to unburned neighbors; the on-fire tree then becomes burned. This continues until the fire dies out" (Mesa, 2024). To make this model fit our needs, we make three essential changes:

1. We change the probability of the neighbors of on fire trees catching fire themselves from 100% to 80%. In real life, trees are not always guaranteed to catch on fire. Different species of trees, like old redwoods, may limit the fire's spread. (Abbany, 2020)
2. We add a 5% probability that the 16 cells surrounding the neighborhood of a burning cell will also catch on fire. This allows the fire to "jump" as it sometimes does in life due to wind conditions or the presence of undergrowth.
3. We add options to distribute the spatial pattern completely randomly (fig. 1), in random clumps (fig. 2) and random rows (fig. 3) as described above.
4. We adapt the *repeatedExperiments()* function from lab seven to run the forest fire code repeatedly and output the total percentage of area burned after a certain number of time steps.

Figure 1: "Random"

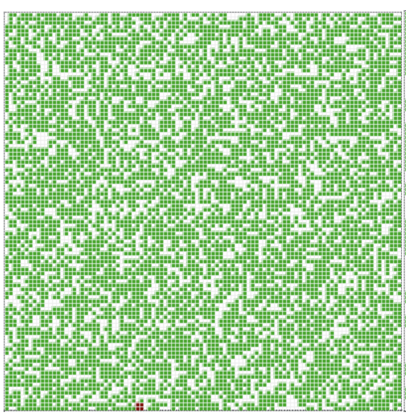


Figure 2: "Clustered"

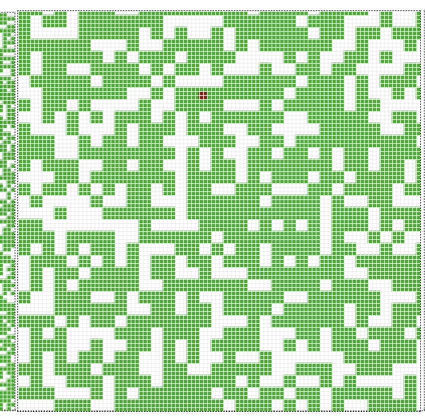
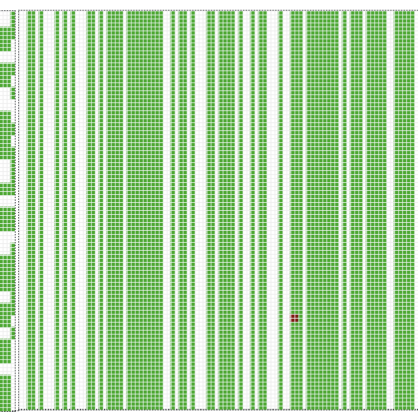


Figure 3: "Lines"



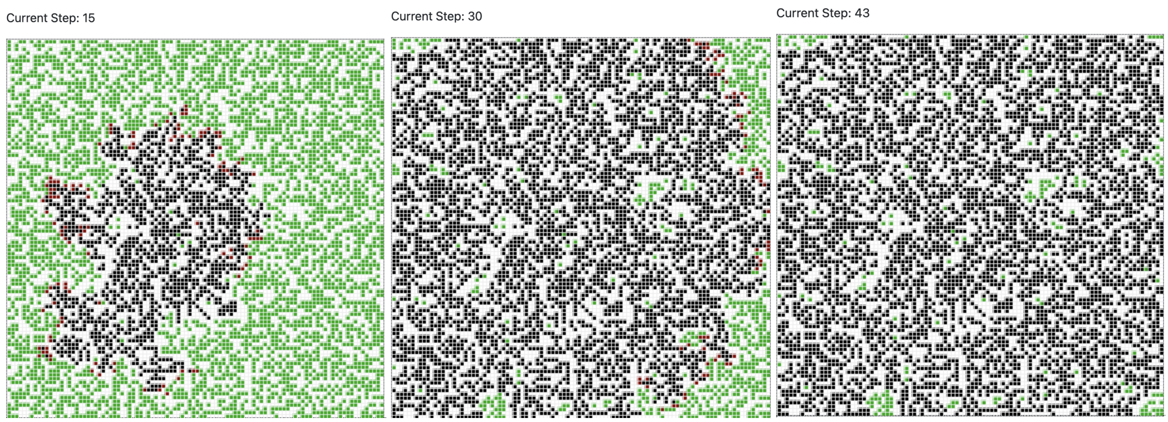
We will run each pattern for three different densities: 50%, 65%, and 80%. These densities allow us to consider the effects on both denser forests, such as the Taiga, and sparser forests found in more arid landscapes. For each pattern and density, we will use the Mesa framework to model and visualize the spread of fire. Additionally, we will employ the *repeatedExperiments()* function to run the model 100 times for each scenario. The resulting average from these trials will help us determine which strategies best minimize the spread of the blaze.

Results

To observe the general patterns of the forest fire, we run each distribution once, looking at the percentage burnt and the time stamp when the fire stops (no more red cells).

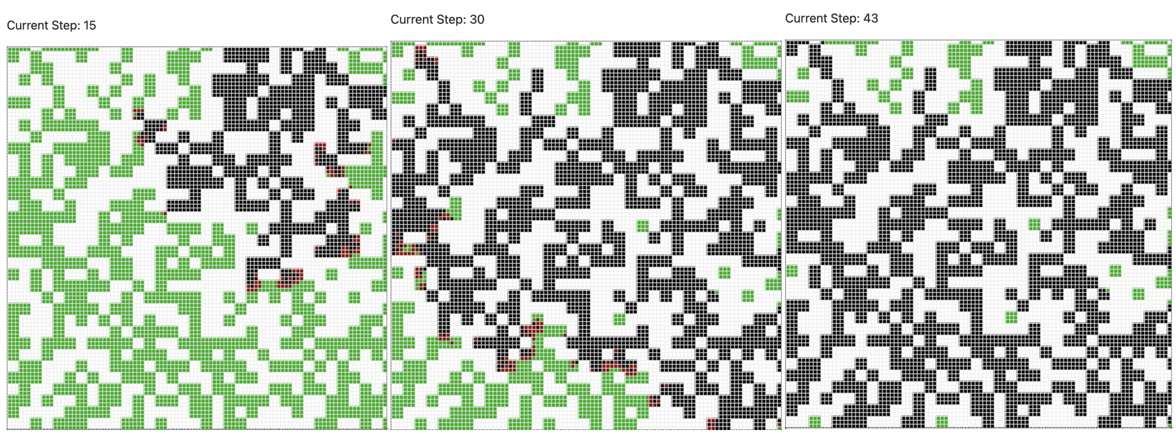
Density 0.5

Figure 4: Random



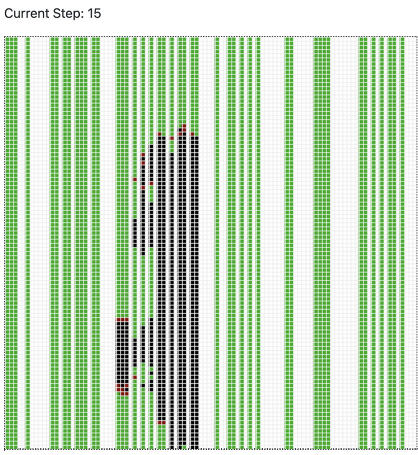
Step 15: 24.19% Burned   Step 30: 86.17% Burned   Step 43: 96.17% Burned

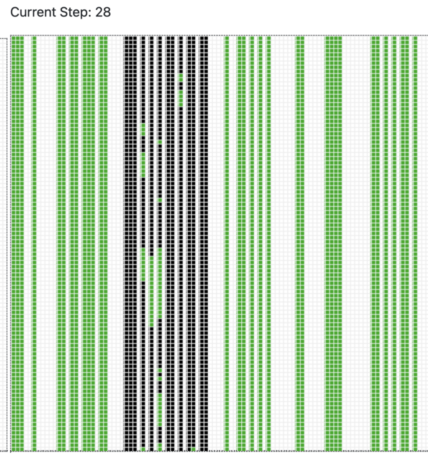
Figure 5: Clusters



Step 15: 27.29% Burned   Step 30: 74.82% Burned   Step 43: 92.57% Burned

Figure 6: Stripes





Step 15: 11.62% Burned   Step 28: 30.48% Burned

Upon analysis, we observe that both the random distributions (fig. 4) and clustered distributions (fig. 5) exhibit a similar burning rate, swiftly engulfing a considerable portion of the landscape. While they both leave small clusters of untouched trees, the majority of the area succumbs to the blaze. The final burn percentages for the random and clustered patterns are 96% and 93%, respectively.

In contrast, the striped forest demonstrates a significantly different outcome (fig. 6). Despite witnessing the fire leap over seven single-cell width trenches, its progression is curtailed at time step 28. The wider lines act as effective firebreaks, containing the blaze earlier than in the other two patterns. Consequently, the total burned area in the striped forest amounts to only 30.48%. Moreover, this controlled burn leaves extensive sections of the forest unscathed.

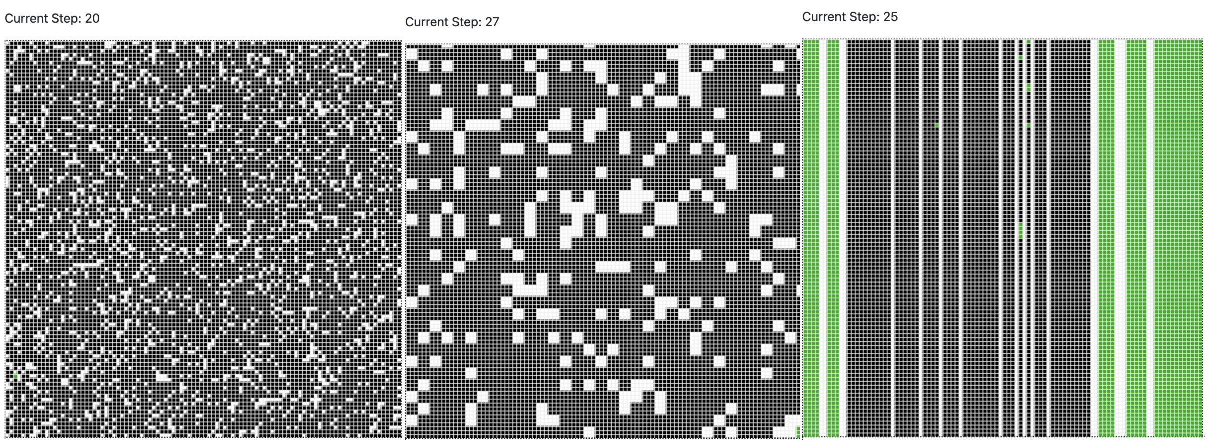
Density 0.65

Figure 6

Step 41: 99.77% Burned   Step 31: 99.70% Burned   Step 25: 44.82% Burned

Density 0.80

Figure 7



Step 20: 99.99% Burned   Step 27: 99.96% Burned   Step 25: 64.88% Burned

It is evident from the model runs at densities of 0.65 (fig. 6) and 0.80 (fig.7) that the denser the forest, the fewer time steps it takes to reach a final attractor, and the greater the proportion of trees are consumed by the blaze. Once more, we observe a near-total devastation of the random and clustered plots. However, the striped plot again demonstrates its ability to impede the fire's spread, successfully safeguarding half of its forested area. An interesting observation emerges regarding the trees on the edge of clearings in the striped pattern, particularly in the thinner stripes. Several of these trees survived the blaze despite being in direct contact with a burned tree.

In the clustered pattern, characterized by thick clearings, the protective effect is limited. Despite the presence of substantial clearings, only a few trees are shielded from the advancing fire. This suggests that the clustered arrangement, while providing some level of protection, is not entirely effective in containing the blaze. Conversely, the striped clearing pattern exhibits a markedly different outcome. Here, a significantly higher proportion of trees are safeguarded against the fire's advance. This suggests that the strategic placement of wider clearings in a striped pattern serves as a more robust barrier, effectively impeding the fire's progression and preserving a larger portion of the forest.

To gain more insight into how the forest fire spreads across the different distributions, we ran the experiment 100 times, for various quantities of time steps. Here are the averaged results:

Percentage of “alive” trees at different densities and timesteps (average of 100 experiments)			
	Random	Clustered	Lines
Density 0.5, Timestep 15	79.54	75.23	88.57
Density 0.5, Timestep 30	34.67	37.24	85.33
Density 0.65, Timestep 15	54.24	49.94	84.18
Density 0.65, Timestep 30	3.26	3.59	76.68
Density 0.8, Timestep 15	34.60	31.99	66.48
Density 0.8, Timestep 30	0.04	0.08	54.71

We can see here that the larger the density, the less alive trees remain at the end (34.67%, 3.26%, 0.04% for the random model; 37.24%, 3.59%, 0.08% for the clusters; and 85.33%, 76.68%, and 54.71% for the lines). We can also observe that at any time step, for any density, the lines model does significantly better than the two other distributions and that the clustered distribution seems, on average, after 30 timesteps, to do better than the random model, even if the random does seem to do better than the clustered after 15 timesteps.

Discussion

Among the three patterns, the striped clearing pattern emerges as the most effective strategy, especially when the cleared areas are sufficiently wide to prevent fire spread. The random pattern consistently performed the worst. The fire easily spread through the entire grid each time, leaving only a few small clusters of trees untouched. The clustered pattern provided slightly better protection, but it was still limited; despite substantial clearings, only a few trees were shielded from the advancing fire.

Conversely, the striped clearing pattern demonstrated a markedly improved outcome, safeguarding a significantly higher proportion of trees. The strategic placement of wider clearings in a striped pattern created a robust barrier, effectively impeding the fire's progression and preserving a larger portion of the forest. Clearing in this manner not only helps contain the fire and protect large areas of the forest but also offers better odds of fire resistance for individual trees in narrow strips. These trees, situated in single-cell stripes, face risk from only two close neighboring cells and two to twelve far neighbors. This configuration allowed some trees to escape the fire in exposed areas.

The implications of this research suggest that thinning should not be done randomly. Instead, a strategy of clear-cutting strategic areas of the forest is preferable. Cutting patterns that cleanly separate areas of the forest are most effective, as appropriately wide clear-cut areas can contain the fire regardless of forest density. Additionally, we observe that lower forest density results in a higher percentage of surviving trees after the fire. This supports the argument for maintaining reasonably low tree density and biomass, provided it does not harm the ecosystem.

In the future, it would be beneficial to adjust the conditions of this model to fit specific forests and ecosystems. For example, changing the probability of each tree catching fire to reflect the actual fire resistance of local plants. Other conditions, such as wind direction, strength, and biomass density, could also be tailored to the environment. This would help determine the most effective patterns for specific scenarios. Future research should also focus on refining the striped pattern to find the ideal width and distribution of cleared stripes, achieving the best trade-off between forest density and fire safety.

Conclusion

In conclusion, the most effective tree culling strategy appears to be creating rows of trees with clearings in between. This approach significantly outperformed other strategies, sometimes by as much as 50% in terms of the percentage of surviving trees. Additionally, there is a strong inverse correlation between initial forest density and the percentage of surviving trees in the final state, further supporting the idea that forest thinning can effectively reduce wildfire damage. Implementing the accumulation of the undergrowth, the wind, different tree species, the health of the trees would add more information that could be used to aid in implementing these findings in the real world.

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