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Impacts of Forest Thinning on Wildland Fire Behavior

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Abstract: Key message: We have explored the impacts of forest thinning on wildland fire behavior using a process based model. Simulating different degrees of thinning, we found out that forest thinning should be conducted cautiously as there could be a wide range of outcomes depending upon the post-thinning states of fuel availability, fuel connectivity, fuel moisture and micrometeorological features such as wind speed. **Context**: There are conflicting reports in the literature regarding the effectiveness of forest thinning. Some studies have found that thinning reduces fire severity, while some studies have found that thinning might lead to enhanced fire severity. **Aims**: Our goal was to evaluate if both of these outcomes are possible post thinning operations and what are the limiting conditions for post thinning fire behavior. **Methods**: We used a process based model to simulate different degrees of thinning systematically, under two different conditions, where the canopy fuel moisture was unchanged and when the canopy fuel moisture was also depleted post thinning. Both of these scenarios are reported in the literature. **Results**: We found out that a low degree of thinning can indeed increase fire intensity, especially if the canopy fuel moisture is low. A high degree of thinning was effective in reducing fire intensity. However, thinning also increased rate of spread under some conditions. Interestingly, both intensity and rate of spread were dependent on the competing effects of increased wind speed, fuel loading and canopy fuel moisture. **Conclusion**: We were able to find the limits of fire behavior post thinning and actual fire behavior is likely to be somewhere in the middle of the theoretical extremes explored in this work. The actual fire behavior post thinning should depend on the site specific conditions which would determine the outcome of the interplay among the aforementioned conditions. The work also highlights that policymakers should be careful about fine scale canopy architectural attributes and micrometeorological aspects when planning fuel treatment operations.

Keywords: forest thinning; wildland fire behavior; fuel moisture; crown fire; fire behavior modeling; canopy turbulence; wildfire modeling; prescribed fire

1. Introduction

Forest thinning is an important management tool to prevent high intensity crown fires [1]. A century of successful fire suppression in the western United States has resulted in a massive fuel accumulation, increasing fire danger in many parts of the country [2]. More than 95% of the wildland fires in western ecosystems are suppressed successfully in the phase of initial attack, where their sizes cannot grow more than two acres. However, less then 4% percent of fires that cannot be suppressed in the early stage result in more than 95% of the burnt area and cause the majority of life and property damage [3]. This has generated a strong support for fuel treatments, either conducted alone through thinning operations or thinning combined with prescribed fires. In general, the objective of fuel treatment is to reduce fuel loading and sometimes return the forests to their historical low intensity fire regimes that characterized the pre fire suppression era [4]. Additionally, thinning operations are also deemed useful to increase resilience of the forest against future disturbances [5–7].

The objective of thinning operations is primarily to reduce the potential of high intensity crown fires, by reducing fuel amount and connectivity. However, there are several short and long term consequences to forest thinning. As a discernible first order effect, thinning changes the stand structure and connectivity pattern of the fuel bed immediately after the operation. This alters the micrometeorology of the forest canopy. The opening of the canopy can entrain more wind [8] and solar radiation which might result in the reduction of fine fuel and canopy fuel moisture. Moreover, if the resultant additional surface fuel accumulation is not removed, it might increase surface loading of fuel. All of these effects could result in enhanced surface fire behavior and increase in crowning potential [1,9]. There could also be long term consequences such as altered regimes of carbon storage [10] which changes the future fuel loading and altered hydrologic regimes [11] which changes future water stress and fuel moisture. Moreover, the effectiveness of thinning treatments start to reduce with time [12] and therefore the timing of such operations is also crucial. The age and composition of the forest stand are important as well because older fine canopy fuels usually contain less moisture than newer fuel elements. Consequently, whether a thinning operation will lead to a reduction of high intensity crown fire is not a trivial questions and depending on the fuel and micrometeorological conditions, it is possible to have a range of outcomes.

Perhaps these uncertainties associated with thinning operations have led to controversies and counter arguments regarding the effectiveness of thinning operations in the context of fire behavior [3]. A few studies have been conducted over the years to study the effect on forest microclimate and fire behavior following thinning operations. A comprehensive study by [3] concluded that thinning operations can either increase or decrease fire intensity and associated fire severity. This result was found to be strongly dependent on the type and degree of thinning operation. Thinning from below, crown thinning, changing of crown height and operations that change the vertical canopy architecture were found to be important in changing fire behavior and crown fire intensity was found to be only reduced after a significant reduction of canopy density. Whitehead et al. [13] and Whitehead et al. [1] found that a thinning level which cleared about half of the basal area of a mature lodgepole pine stand resulted in enhanced in-canopy solar radiation, wind speed and near surface air temperature. Moisture content of fine surface fuels were found to be lower under low to moderate fire danger conditions. These studies declared the requirement for future studies to examine changes in microclimate and fire behavior under different levels of stand densities. Agee and Lolley [2] found that thinning increased surface fire flame lengths under a range of weather conditions. At the same time, thinning also increased crowning index—open wind speed needed to maintain active crown fire and thus reduced crown fire hazard. These two effects are evidently opposite to each other and the competition between these effects should determine the outcome of the operation. Stephens and Moghaddas [14] reported results from stand level experiments conducted in mixed conifer forests in North Central Sierra Nevada, where fire behavior were recorded after thinning and prescribed fire operations. Thinning from below and the crown increased 1000 h (thick fuels of 3–8 inches diameter) surface fuel loads and reduced bulk crown density by 13%. This was not sufficient to alter fire behavior unless mastication was introduced, which reduced ladder fuel and increased the surface to crown height.

Parsons et al. [7] suggested that while fuel treatment effects are often successful in attaining their ecohydrological objectives, their success depend on the tradeoff among several factors [15]. Another relatively recent review by Kalies and Kent [16] points out that there is a significant shortage of data to assess fuel treatment effectiveness. The current literature reports mixed results on the effectiveness of fuel treatment alone and in general fuel thinning combined with prescribed burns were found to reduce fire severity, although not in all cases. The interested reader is referred to Kalies and Kent [16] for a compilation of results pertaining to canopy structure, soil, carbon, wildlife and human values from previous fuel treatment operations. As summarized by Kalies and Kent [16], a large number of studies reported lower fire intensity and fire severity in thinned only forests compared to untreated forests, although thinning combined with prescribed burns were found most effective [17–30].

At the same time, some of the studies did not find any changes in crown fire behavior after thinning and sometimes found a more intense fire behavior [31–38].

The emergent understanding from this literature review points out to the fact that our understanding of the effect of fuel thinning effects on fire behavior is still limited. It is partly attributed to uncertainties associated with micrometeorological response following thinning, especially pertaining to canopy fuel moisture. Nevertheless, it is well understood that thinning of the forest canopy will lead to an increase of wind speed [8] and solar radiation. Bigelow and North [39] conducted a study in the mixed conifer forests in the Sierras to examine whether the microclimate effects could counteract the original goal of curtailing fire severity by reducing fuel through silvicultural practices. They concluded that some microclimate effects could cancel out each other. For example, an increase of wind speed would increase turbulence driven mixing of the air above and below the canopy sub layer, thereby not allowing air temperature to increase or fuel moisture to decrease. Therefore, Bigelow and North [39] did not find any appreciable difference between the microclimate of denser and thinned canopies, as well as the dead fuel moisture. However, they recognized that these microclimate effects might vary with different degrees of thinning and called for more modeling studies to this effect. It is worth noting here that the terms micrometeorology and microclimate are used interchangeably to be consistent with the literature.

Whitehead et al. [1] found that fuel thinning increased solar radiation, wind speed and near surface temperature but almost no differences were observed in relative humidity or surface fuel moisture when fire danger was high. Faiella and Bailey [40] studied season variations of fuel moisture post fuel treatments in semi-arid ponderosa pines of northern Arizona. They found no conclusive evidence of depletion of live or dead fuel moisture in treated forests and declared that concerns of amplified fire behavior due to fuel moisture depletion is unwarranted, at least for semi arid ponderosa pine forests of the American southwest. Estes et al. [41] found that the 10 and 1000 h fine dead fuel moisture was not significantly different between thinned and unthinned forests and fuel moisture effects resulting from thinning is not expected to exacerbate fire behavior in the period of high fire danger in the mixed conifer forests of northern Sierras. However, they did find some differences post precipitation events which might be important for planning prescribed fire operations.

On the other hand, Pook and Gill [42] concluded that fine fuel moisture in thinned stands were lower than untreated stands for both surface and aerial fuels (Figure 5 in Pook and Gill [42]). Weatherspoon and Skinner [43] concluded that stand thinning leads to reduced fuel moisture and increased flammability during periods of high fire danger [44]. Additionally, Weatherspoon and Skinner [43] stated that removing large trees from the stand and leaving the understory in place and doing little or no slash treatment would inevitably lead to increased fire danger by increasing surface fuel depth and creating a warmer, dryer and windier sub canopy environment. Whereas, thinning from below and removing whole trees and removing the slash by a prescribed burn would lead to lower wildfire hazard. This is an example of how the effects of micrometeorological changes can compete with the effects of lower amounts of fuel and the final outcome in terms of fire behavior would be a function of the outcome of this competition.

Therefore we can state that the science of microclimate shifts and changes in fire behavior is far from settled and there is a requirement of a systematic evaluation of the effects of fuel reduction along with changes in micrometeorological changes. The lack of conclusive evidence from previous research in this area motivates us to further investigate such changes in fire behaviour. Note that some studies conclude that there could be possible changes in the surface or dead fuel moisture post thinning, while some studies find no evidence of such changes. Thinning operations could also lead to increase of surface fuel loading, unless this additional accumulation is removed manually or by prescribed fires. While the post thinning response of surface and dead fuels is an important research question, there seems to be even less amount of data on the state of canopy fuel post thinning. Henceforth, we use a process based model HIGRAD/FIRETEC to investigate possible changes after canopy fuel reduction and canopy fuel moisture variations only, while keeping surface and dead fuel properties unchanged. It is also interesting to note that while a number of studies have addressed this topic using field experiments, only a handful of modeling studies can be found. Parson et al. [7] and Marshall et al. [45] are examples of process based models being used to investigate such changes; however, they are mostly focused on other types of fuel structures such as fuel strips or patchiness or changes due to tree mortality. In this study, our objective is to answer the following two questions:

- What changes in fire behavior are observed following thinning effects?
- Can we observe the signatures of this competition between changes in wind speed and reduction of fuels following fuel treatments? If this competition exists, what the thresholds for competing effects to dominate the other?

2. Methods

2.1. Model Description

Use use the model HIGRAD/FIRETEC, which is a high resolution computational fluid dynamics (CFD) tool developed at Los Alamos National Laboratory with the aid of the US Forest Service. FIRETEC is useful in simulating the micrometeorology and fire—vegetation—atmosphere interaction for a landscape in three dimensions. It uses a large eddy simulation (LES) framework that can resolve atmospheric turbulence interactions with three-dimensional heterogeneous fuel structures at the meter scale and can capture the spread, intensity and extent of burnt area under different ignition conditions at 1–2 m resolution [46]. This is deemed to be an ideal tool to simulate different fuel treatment and ignition scenarios before planning a prescribed fire. It solves the compressible Navier—Stokes mass, momentum, energy and species balance equations in three dimensions to solve for the evolution of the coupled fire-atmosphere behavior on flat or complex topography. It uses the same vegetation drag parameterizations employed in other state-of-the-art LES simulations. Wind runs in HIGRAD/FIRETEC have been validated [47] against other canopy LES studies such as Shaw and Schumann [48] which modeled a horizontal homogeneous canopy and studies involving edges and gaps such as Raupach et al. [49]. HIGRAD/FIRETEC has also been validated against historical fires [50] and field experiments with controlled burns [51–54]. Detailed model descriptions can be found in Linn [55] and Dupuy et al. [56]. HIGRAD/FIRETEC can account for both the turbulent and convective heat transfer as well as the radiative heat transfer. The finest scale above which heterogeneities can be resolved is in the order of 2 m. Processes occurring below this resolution are parameterized as sub grid scale (SGS) processes.

It is important to note that since HIGRAD/FIRETEC is a physics based and therefore can be described as 'self determining' [57]. The implication is that unlike operational models, one does not need to prescribe separate empirical models for surface fires or crown fires. A fuel bed is built inside the model in its entirety, including both surface fuels and canopy fuels as well as dead fuels. The fire is allowed to burn based on the prescribed environmental conditions and whether it spreads as a surface fire or a crown fire or a mix of both is an emergent phenomenon.

2.2. Simulations

We conducted a suite of simulations under different degrees of fuel thinning and canopy fuel moisture scenarios. Thinning was conducted by a percentage, starting from an unthinned forest and then systematically thinning the forest by 25%, 50% and 75%. For example, a 25% thinning implies that 25% of the trees are removed at random, chosen at random locations using a random number generator. After the thinning, the total fuel loading if reduced by the same percentage of thinning. Note that HIGRAD/FIRETEC uses the full three-dimensional fuel structure data as an input and calculates the total fuel loading based on this three dimensional structure, as opposed to a single fuel loading value (which are used in empirical operational models). A sample simulation with 25% thinning is shown in Figure 1, where the three-dimensional structure of the fuel and the flame front is visible. It is also important to note that selective thinning is not simulated in this study, as all trees are assumed to be of the same species and same height.

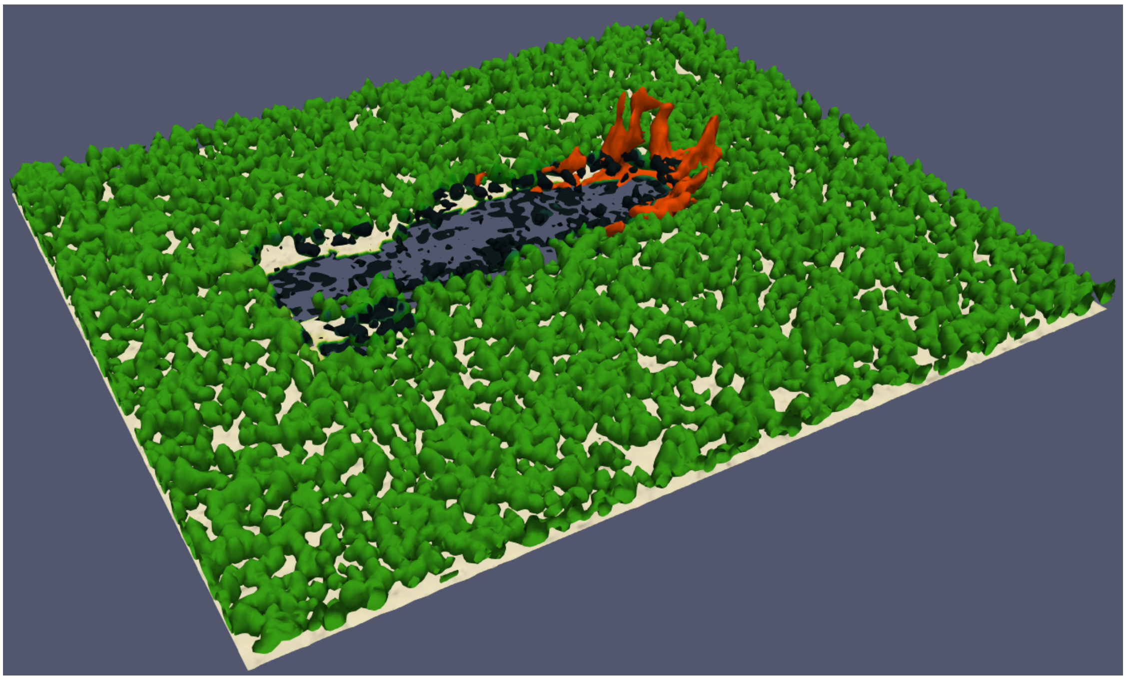

Figure 1. Sample simulation output showing the three-dimensional view of fire spread in the fuel continuum, using the 25% thinning fixed moisture case as an example. Green indicates unburnt canopy, and orange indicates the flame front.

In the first set of simulations, the canopy fuel fuel moisture was not changed as the forests were thinned. In the second set of simulations, canopy fuel moisture was reduced with the same percentage of thinning. These are the two theoretically extreme scenarios and given the lack of information and consensus on how canopy fuel moisture changes as forests are thinned, these two sets of simulations can be taken as the theoretical limits that bracket actual fire behavior in thinned forests soon after the thinning operation.

The simulation domain size is 400 m by 320 m by 600 m (x vs. y vs. z) for all cases. The grid resolution is 2 m by 2 m by 12 m in x, y and z directions respectively. The vertical grid is much finer close to the ground surface and is stretched towards the top so the canopy is resolved in high resolution. The average grid size in the canopy layer is 1.8 m. The time step is 0.02 s. Thus the number of grid points in each direction is 200 by 160 by 50. The number of processors used in x and y direction are 10 and 8, overall 80, to parallelize the simulations with MPI (Message Passing Interface). All simulations were run until 30,000 iterations (600 s or 10 min). Each of the simulations were run for 3100 s to sufficiently develop the inlet turbulent wind fields. Periodic boundary conditions were used at the inlet and outlet of the domain. A wind profile with a value of 8 ms^{-1} at 30 m above ground level was prescribed, which adjusts to the presence of the vegetation during the up spin up simulations for the wind. The domain top was prescribed with a free slip boundary condition. The fire simulations were started after the wind runs with a 4 m wide and 80 m long ignition line, which was 80 m offset from the inlet domain. A target ignition temperature of 1000 K was reached with a ramp rate of 350 $\mathrm{K\,s}^{-1}$. The vegetation data used is real canopy structural data in three dimension collected by the US Forest Service (USFS) Rocky Mountain Research station (RMRS) for a 20 m by 50 m area for ponderosa pine. This tile of vegetation distribution is used in a random pattern as shown in Figure 2. The fraction of the tree canopy shape that is concave downwards is 0.8 (standard for ponderosa pine). This corresponds to the leaf area density shape, namely how high are the branches off of the ground. The average density for tree canopy (fine fuel) is 0.4 $\mathrm{kg\,m}^{-3}$ for ponderosa pine as suggested by the USFS [51]. The fuel loading values are representative of longleaf and loblolly pines in the US Southeast and ponderosa pines in the US southwest [58–60] and therefore the results should be applicable for a wind range of conditions in coniferous forests. Note that for all cases, a 40 m open space is left to allow the wind to equilibrate. The full domain is populated by grass and litter at the ground level, while the open grassland grass density is 0.4 kg m^{-3} and the open grassland grass height is 0.7 m. Below the canopy, grass density should be less because of canopy shading and this is accounted for by using an exponential attenuation factor of 5.0 [51]. The estimated maximum litter density within the fuel bed is 5.0 kg m^{-3} and estimated maximum litter height is 0.1 m. An exponential factor of 5.0 is used to enhance the litter density because of canopy shading. The nominal fuel moisture for canopy is 80% and 5% for grass and litter. The nominal fuel size scale is 0.5 mm. Maximum tree height in all cases is 19.9 m.

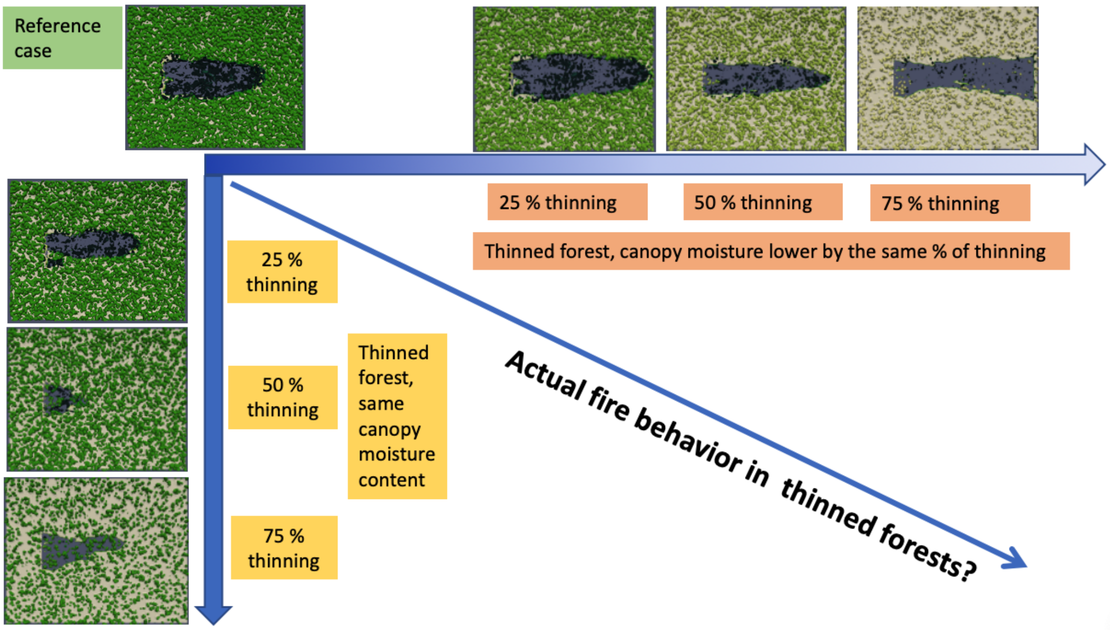

Figure 2. Burnt patterns for the different simulation cases after 400 s. Horizontal axis shows burnt areas for 25%, 50% and 75% thinning cases where canopy fuel moisture is lowered after thinning. Vertical axis shows the three thinning levels, but the moisture content is same as the reference case.

It is again important to note that although in the model setup, all parameters including surface, canopy and dead fuel attributes are included, we only focus on the possible changes in the live fuel moisture regimes post thinning to isolate its effect. The surface and dead fuel properties are held fixed in all simulations, while the canopy fuel moisture amounts are either held fixed or systematically varied across the simulation cases. Nevertheless, the simulations do differentiate between canopy fuel moisture and surface as well as dead fuel moisture encoded in the canopy, grass and litter parameters discussed earlier. At the same time, it is also acknowledged that thinning operations might lead to changes in surface and dead fuel properties. However, given the lack of data and contrasting experimental evidence, these properties are held fixed in this study and the focus is constrained on the variations associated with canopy fuel and live fuel moisture only.

3. Results

3.1. Burnt Area

Figure 2 shows the burnt area for the seven different simulation cases. The reference case is the untreated forest at the top left corner of the figure. On the vertical axis, the burnt areas for the three thinning cases (25%, 50% and 75%) are depicted where the moisture contact of the canopy or surface fuel has not been changed. Note that unburnt trees are shown in the color green and in some cases, they are also visible in the burn scar, such as the 75% thinning case with fixed moisture content. This highlights the fact that various degrees of of crown damage are observed in these different scenarios. On the horizontal axis, the three thinning cases are depicted where the canopy fuel moisture is lowered by the same proportion of applied thinning. It is hypothesized that these two axes represent the theoretical envelop of fire behavior under different degrees of thinning and the actual observed fire behavior in an actual experiment would be bound by these two axes. If canopy fuel moisture is unaltered by fuel treatment, the actual fire behavior would be close to the vertical axis. If canopy fuel moisture is reduced due to thinning, fire behavior would be close to the horizontal axis, although it is unlikely that actual canopy fuel moisture would be reduced in proportion to the thinning level. This behavior should strictly be taken as a theoretical limit. However, given the uncertainty in the literature and lack of any such information available in the literature, we are interested to explore the phase space of actual potential fire behavior. Nevertheless, some interesting observations can be made from Figure 2. Increasing the degree of thinning without changing canopy fuel moisture reduces the burnt area up to 50% thinning level. At 75% thinning, the burnt area increases again. On the other hand, 25% thinning with 25% additional fuel dryness increases the burnt area. The burnt area decreases slightly at 50% thinning and 50% less canopy fuel moisture and then increases significantly again at 75% thinning and 75% less canopy fuel moisture. This wide range of behavior points to complex nonlinear interactions between wind effects and fuel availability.

3.2. Wind Speed

Figure 3 shows the instantaneous wind speeds at canopy top at the reference case and three different thinning levels before fire propagation using a colormap. The flow fields are highly turbulent and red and yellow streaks show zones of higher gustiness, whereas green and blue streaks show lower magnitudes of wind speeds. Evidently, the proportions of yellow and red streaks increase with higher degrees of thinning. This indicates that wind speeds are indeed higher at thinned forests which is consistent with several studies discussed earlier.

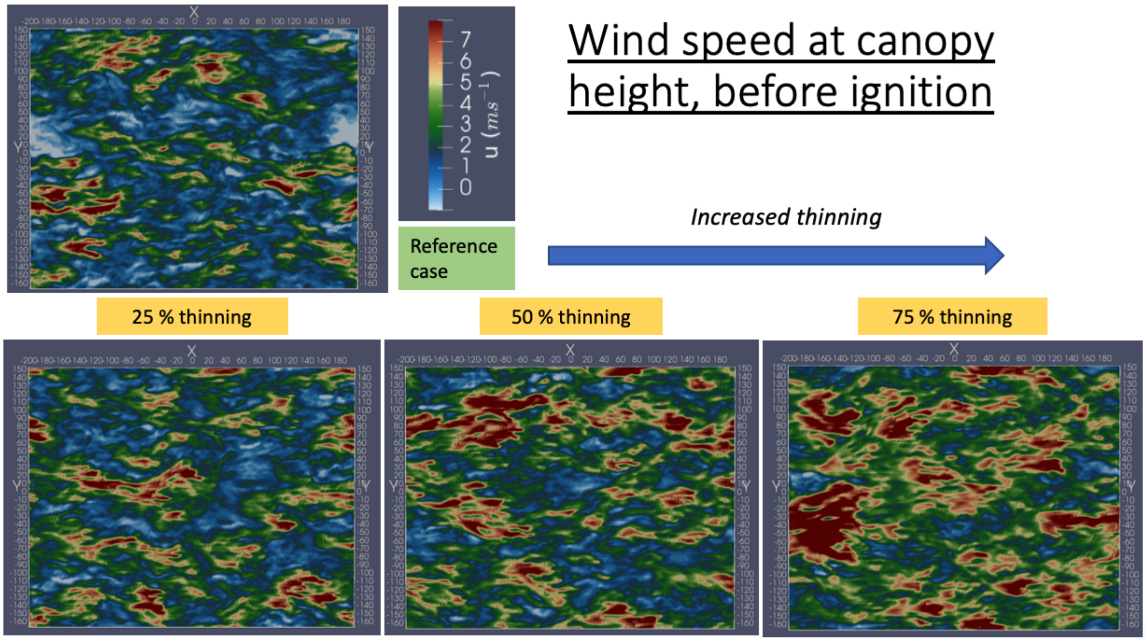

Figure 3. Wind speed at canopy height for the different simulation cases before ignition.

3.3. Rate of Spread

Figure 4 shows the location of the fire front with time. The top panel shows the rate of spread for the reference case with three thinning cases, where the canopy moisture content is fixed.

The bottom panel shows the same cases with lower canopy moisture content associated with thinning. Some interesting observations can be made from Figure 4. Without any changes in the canopy moisture content, the initial spread rate is almost same for the 25% thinned forest as the reference case and after 150 s, the rate of spread decreases slightly compared to the reference case. At 50% thinning, the initial rate of spread is higher than the reference and the 25% thinned case. However, after 175 s, this rate flattens and the fire does not proceed much in spite of higher wind speeds, probably due to lack of fuels. At 75% thinning, the rate of spread increases further from the very beginning of ignition. However, it also flattens after some time and does not increase with a strong rate.

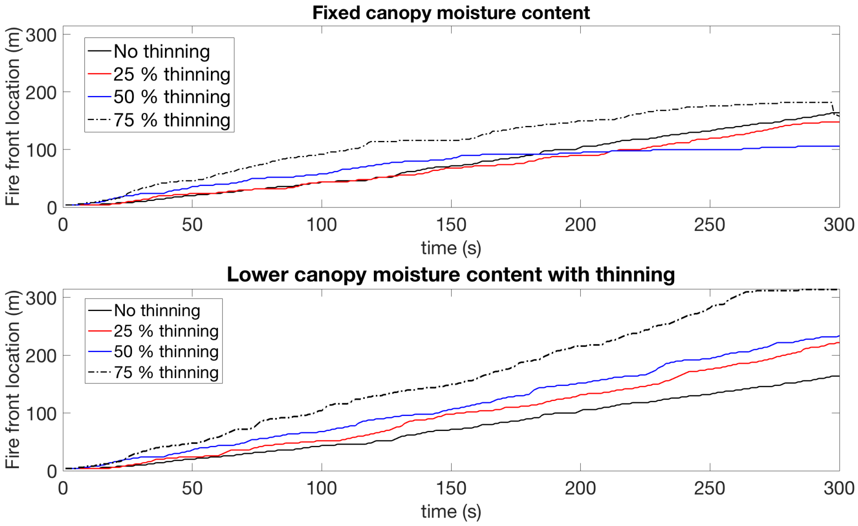

Figure 4. Fire rate of spread for the different simulation cases. Top panel shows the reference case and the three thinning cases with no change of canopy fuel moisture. Bottom panel shows the reference cases and the 3 thinning cases with lower canopy fuel moisture.

On the other hand, reduction of canopy fuel moisture along with thinning increases the rate of spread significantly compared to the reference case and the fire front progresses at a faster rate compared to the cases with no change of canopy moisture content. The difference between the spread rates at the different thinning levels are also more prominent when reducing canopy moisture with thinning.

3.4. Air Temperature

Figure 5 shows the time series of (potential) air temperature sensed by a virtual sensor placed at 15 m height at domain centre. Note that the location of the virtual sensor at 15 m is close to the canopy top. The left panel shows the cases with different degrees of thinning with no change in canopy moisture content, while the right panel shows the same with canopy moisture loss with increased thinning. The air temperature increases as the fire front comes close to the domain center. It is interesting to note that the air temperature almost reaches the same magnitude for the 25% thinning compared to the reference case, when there is no change in canopy moisture. The 50% and 75% thinning cases record a much smaller temperature increase without any canopy moisture change. When canopy moisture is reduced with thinning, the 25% thinning case actually records a higher temperature than the reference case. Moreover, even the 50% and 75% cases record a significantly increased air temperature when the moisture is reduced. This increase of air temperature at lower moisture contents is highlighted with a red arrow.

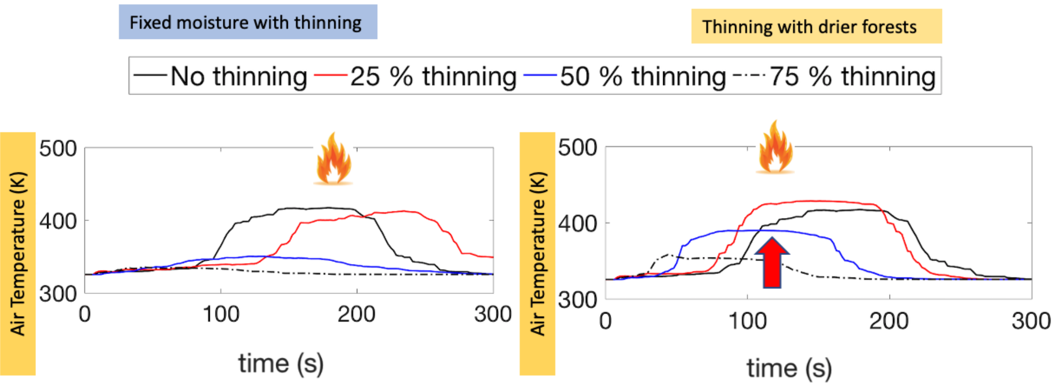

Figure 5. Air temperature recorded at 15 level at domain centre as the fire propagates. Left panel shows the reference case and the three thinning cases with no change of canopy fuel moisture. Right panel shows the reference cases and the 3 thinning cases with lower canopy fuel moisture. The arrival of the fire front is shown with a fire symbol.

3.5. *Sensible Heat Flux*

Figure 6 shows the turbulent sensible heat flux recorded at the same virtual sensor at 15 height at domain center for the different simulation scenarios. Similar to Figure 5, the left panel shows the cases where canopy fuel moisture is fixed and the right panel shows the cases where canopy moisture is reduced as well. The sensible heat flux is computed as the covariance of the turbulent vertical velocity fluctuations and the air temperature fluctuations. This can be taken as the heat pulse the canopy would experience from below as the fire propagates and thus a good indicator of crown damage. Moreover, the sensible heat flux contains the combined effects of wind speed and heat generated due to combustion. It turns out that at 25% thinning level without changing canopy moisture, the sensible heat flux is almost similar to that recorded by the reference case. The 50% and 75% cases record a low amount of sensible heat flux without canopy moisture change. When canopy fuel moisture is reduced along with thinning, the sensible heat flux at 25% thinning is significantly higher compared to the reference case. Even the 50% and 75% cases a significant increase of sensible heat flux when canopy fuel moisture is reduced with thinning. Note that the sensible heat flux can increase with higher turbulence demonstrated by stronger fluctuations in the vertical wind velocity as well as the increase of the potential temperature fluctuations. The augmentation of sensible heat flux due to fire front propagation is also indicated with an arrow in Figure 6.

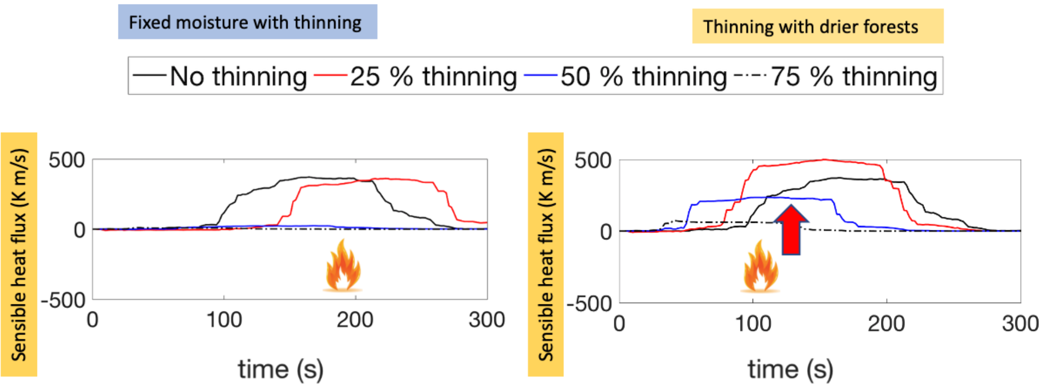

Figure 6. Sensible heat flux recorded at 15 level at domain centre as the fire propagates. Left panel shows the reference case and the three thinning cases with no change of canopy fuel moisture. Right panel shows the reference cases and the 3 thinning cases with lower canopy fuel moisture. The arrival of the fire front is shown with a fire symbol.

4. Discussions

The emergent understanding out of these simple simulations show a complex balance between micrometeorological changes and changes in fuel availability following thinning operations that influence fire behavior. There is no doubt that wind speed increases post thinning as the canopy is opened up after thinning. The opening up of the canopy reduces the fuel loading and fuel connectivity, thereby reducing fuel drag to wind, enhancing wind speed. At the same time, this increased space between trees increases the turbulence levels inside the canopy and augment the convective pre heating of the fuel elements downstream of the fire front, thereby facilitating fire front propagation. At a low level of thinning, there is some minimal loss of the heat generated due to burning of fuel. At this low level of thinning, the wind speeds also increases to some extent and possibly is enough to counteract this loss of heat generated due to burning and wind can maintain almost the same level of convective heating, which is a major mechanism for fire spread. If some canopy moisture is lost at this low level of thinning, the heat of combustion increases which compensates for the slight reduction of fuel. This, when combined with increasing wind speed leads to increased fireline intensity and fire severity compared to the untreated forest. This is potentially the reason, why some studies had reported increased fire behavior post thinning operations.

However, this effect cannot carry on at higher levels of thinning. At a higher degree of thinning, the loss of fuel is enough to generate a lower amount of heat of combustion and the increase of wind speed is not sufficient to compensate for this loss, so the convective heating starts to become lower than the untreated case. This change happens slower if the canopy fuel moisture reduces to some extent following thinning operations. In that case, the heat of combustion does increase by some amount and the increase of wind speed allows for a more significant fire severity, although less than the reference case. Perhaps this is the reason that most of the studies reported a lower fire intensity post thinning.

It is again important to note that it is hard to identify the exact parameters of this competition between fuel availability and wind effects and the exact threshold where fire severity increases first after some degree of thinning and then starts to decrease compared to the untreated case. Nevertheless, these simulations are able to point out the theoretical limiting scenarios of this behavior and actual fire behavior is likely to follow somewhere between these limits.

Another important factor apart from fire intensity (which is the energy released during fire propagation) is rate of spread. The trends of rate of spread does not follow the same trends of fire severity following thinning operations but is equally important from a management perspective. Rate of spread is dependent on wind but is also dependent to some extent on the intensity of combustion. A low degree of thinning can increase rate of spread to some extent. However, increase of wind speed can only increase rate of spread partially. Unless the intensity of burning is significant, the rate of spread does not increase prominently. Thus reduction of canopy fuel moisture leads to a higher rate of spread. It is only at a very high degree of thinning, that the energy of combustion does not contribute much to the rate of spread and is mostly driven by wind speed. Thus the rate of spread only increases significantly at much higher degrees of thinning and even then it is augmented due to loss of canopy fuel moisture and increased convective heating.

5. Conclusions

The impact of fuel treatment using mechanical thinning on fire behavior is a topic fraught with lack of consensus, although it is widely accepted as a major management tool. Thinning is either conducted alone or combined with prescribed fires. While thinning combined with prescribed fires is highly likely to reduce fire severity in coniferous forests, there are contrasting evidences in the literature on the effects of thinning alone. This motivated the current study and we wanted to explore the limits of possible fire behavior under different degrees of fuel treatment. We used simulations to systematically study different degrees of fuel thinning and were able to isolate the variables that are responsible for the wide range of fire behavior reported post thinning. We started with two questions—what changes were observed in fire behavior following thinning and what is the nature of the competition between contrasting factors such as enhanced wind speed and loss of fuel. To find out the answer to the first question, we conducted the simulations with three different degrees of thinning with two limiting conditions. In one set of simulations, the canopy fuel moisture was fixed and same as the reference unthinned forest. In the second set, the canopy fuel moisture was reduced by the same proportion of thinning. These are two theoretically extreme scenarios and we hypothesized that actual fire behavior would be bracketed between these limiting cases. The factors that would govern the actual fire behavior would at minimum be dependent on the post thinning states of wind speed and burning conditions, which answers our second question. We explored how the changes of wind speed, lack of fuel amount and lack of canopy fuel moisture can lead to increased fire intensity at some levels of thinning and how they could also lead to lowered fire severity at other combinations. This work demonstrates that fine scale modulations of micrometeorological characteristics and fuel architecture should be accounted for when planning for fuel treatment and prescribed fire operations. Moreover, fire rate of spread should also be incorporated apart from fire intensity when planning such operations. However, we were not able to precisely find out the exact trajectory of fire behavior given the uncertainty on how canopy moisture levels would change following forest thinning. This would be addressed in future research endeavours. Another important point to reiterate is that post thinning, there could be changes in the dead fuel moisture as well. However, in this study we did not consider potential changes in dead fuel moisture and held it fixed at a finite value for all cases. In future studies we will investigate the combined effects of changes in both dead and live fuel moisture in the context of thinning induced fire behavior. To conclude, while this study does not attempt to develop a 'unified theory of thinning effects' that could be a useful tool for forest managers, it does represent a step towards that goal. Process-based models enable us to perform the kinds of experiments that would be logistically impossible in the real world. While this work is not again the first to use a process based model to study fuel treatments and fire behavior, it is perhaps among the first to use a process-based model to simulate the effects of thinning on fire spread, and perhaps the first to decompose these effects into their component parts (e.g., fuel moisture vs. wind speed).

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