How can we simulate the difference in forest fire spread with different species of trees in a real-time environment.

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Graduation work 2021-2022
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ABSTRACT

This paper explains a way to simulate fires using different tree species. Forest fires are one of the natural disasters having impact on our climate. The idea came originally as a request from a Belgian university, KU Leuven. Forest fires can be compared to the electrical waves of a heart. After looking through different existing simulation software, the idea to simulate a fire using a tree's properties. A program was made using the Unity 3D engine and the simulation mostly involved around the Huygens principle for the spreading of the fire while using the density of the wood of a tree to change the pace of the spread and the moisture content to slow down the burning of the tree. The results of the spread were wanted but did not give a large impact. This had mainly to do with the moisture being used to increase the burn time for a tree and not the resistance to it.

INTRODUCTION

Many existing forest fire simulations use a fire model using Huygens principle. With the most recent model using the structure of a tree as base. The others use an area to determine the spread parameters. This gave the idea to use the Huygens principle with a tree as parameter instead of an area.

RELATED WORK

HUYGENS PRINCIPLE

Huygens principle originally described how light waves travel, where each point on the edge of a wavefront is an independent source of secondary wavelets that propagate the wave. These wavelets are represented as elliptical wavelets.

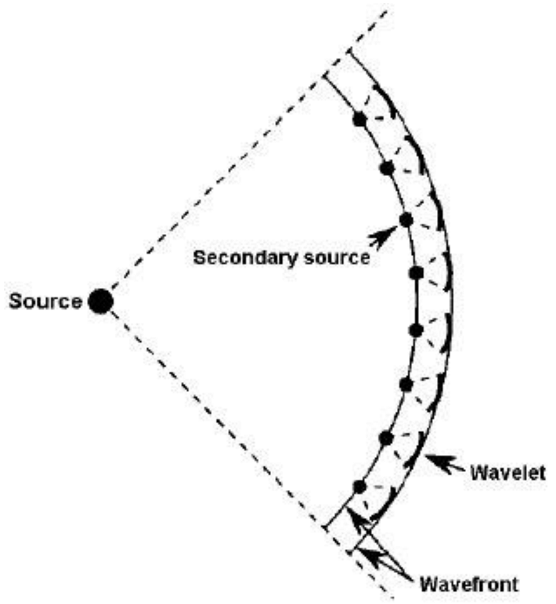

Figure 1

An ellipse can have different shapes and sizes. This is also what already existing fire models use. There, wind and slope parameter make a vector that determines the shape and the orientation of an ellipse, while the fuel determines the size or spread rate. [1]

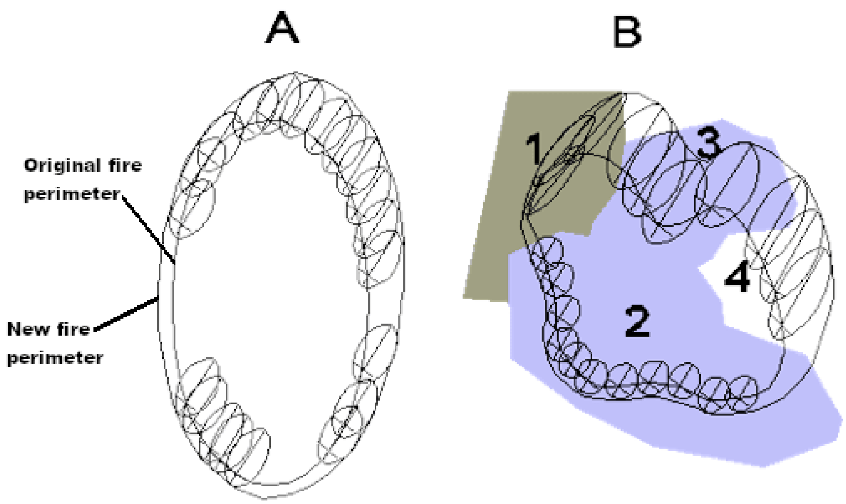

Figure 2 ((A), one type of fuel; (B), four types of fuel)

This method was developed by Richards[2] where he describes the expansion of an elliptical wavefront from a series of vertices that define the edge of a fire. This is useful for a 2D application where a calculation happens on an area instead of a tree. The ellipse can still be used to simulate the fire of one tree. Since a tree can also be seen as a new wavefront or new vertex.

How an ellipse is represented is by looking at its foci (plural for focus). Foci exist on the longest axis and are equally spaced from each other. They can be used as anchor points for drawing an ellipse by hand.

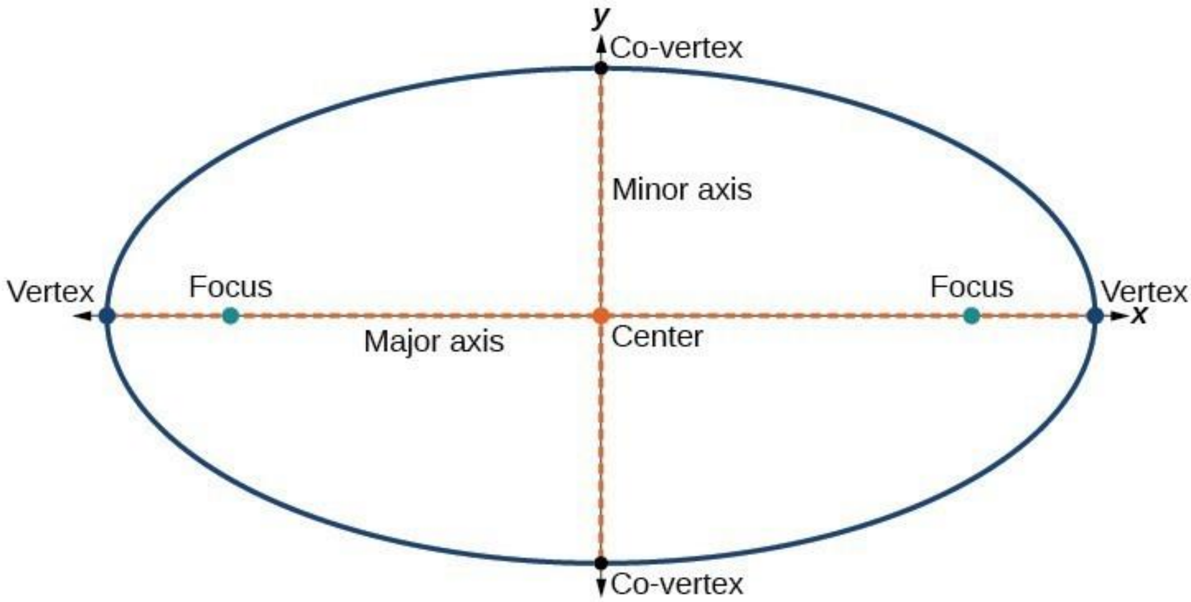

Figure 3 https://courses.lumenlearning.com/waymakercollegealgebra/chapter/equations-of-ellipses/

The further the one focus lies from the centre the sharper and longer the ellipse becomes.

The equation of an ellipse is:

$$\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} = 1$$

x,y: the location on the ellipse

h: the horizontal displacement

k: the vertical displacement

a: the horizontal radius

b: the vertical radius

CELULAR AUTOMATA

Another technique that can be used, is cellular automata. An algorithm used on a grid where a cell is a rectangular, hexagonal, or other topology. Each cell can be in a certain state and has a defined neighbourhood.

There are two commonly used neighbourhoods for the rectangular topology, the (von Neumann neighbourhood) where the neighbourhood consist of its centre, north, east, south and west neighbour, and the (Moore neighbourhood) where also the north-east, south-east, south-west and north-west neighbours are included.[3].

It requires less performance but is also less realistic because of the non-organic representation and is wildly used for simple representation of fires in games, where performance is important.

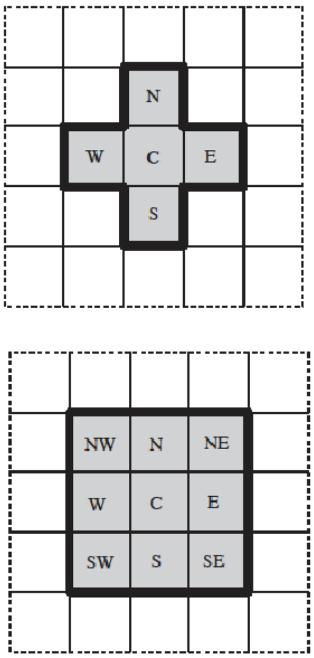

Figure 4 Top: von Neumann neighbour; Bottom: Moore neighbour

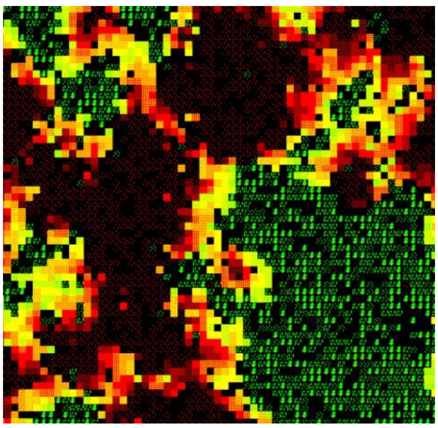

Figure 5

WIND

Wind is an extremely important factor when dealing with a wildfire. It is very unpredictable and has many uses to spread a wildfire.

SUPPLY OF OXYGEN

Plants do photosynthesis, a process where sugar is being made by using sunlight, water and carbon dioxide. This sugar carries the needed carbon and hydrogen that are responsible for a fire. After the process, oxygen is being released as a leftover from the process. Thanks to this we can have fresh oxygen.

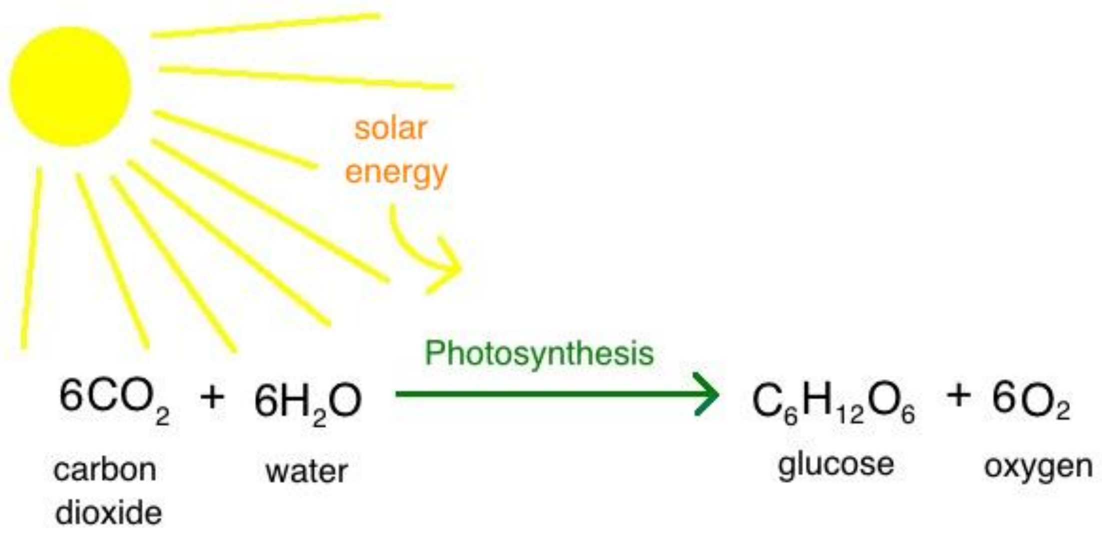

Figure 6

This shows us why a plant can catch on fire so quickly, but to start a fire, there needs to be a combustion. A combustion is a chemical process in which a substance reacts rapidly with oxygen and gives off heat[4]. In case of a plant, oxygen reacts with the carbon and the hydrogen that is present in sugar. Wind carries oxygen, the stronger the wind is, the more oxygen there will be. So, when there is more oxygen, there will be more combustion, creating more heat. But to start a combustion, there needs to be something that can release these substances first.

DIRECTION

Wind travels in a certain direction and pushes everything that can be pushed in that direction. It carries oxygen, but also heat and small object, all important parts of a fire. The stronger the wind is, the more oxygen passes or an object getting dragged further.

Wind is not linear and changes its path depending on the obstacle it encounters. An obstacle with a high resistance shape, will slow down the wind, reducing the impact on obstacles behind it. Similar object like cubes give a high resistance towards incoming wind. While the shape of a rain droplet or golf ball give less resistance.

This is widely used for aerodynamics to make vehicles faster by giving them a shape that has less resistance to this impact. It is what makes us able to travel faster with less power required.

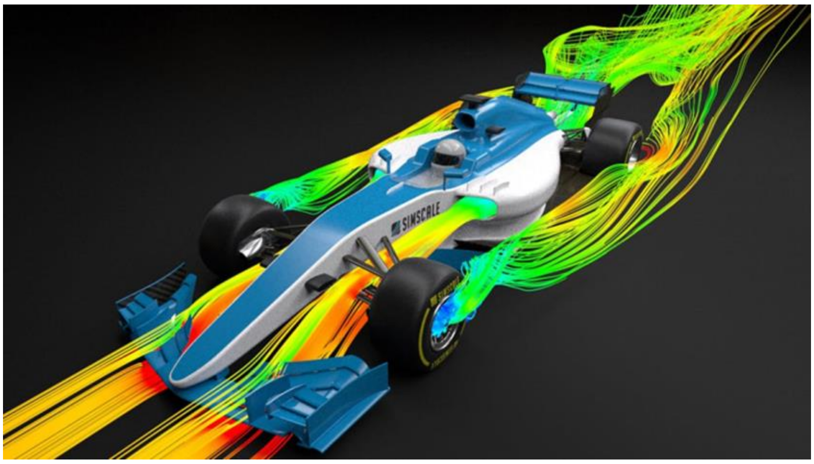

Figure 7

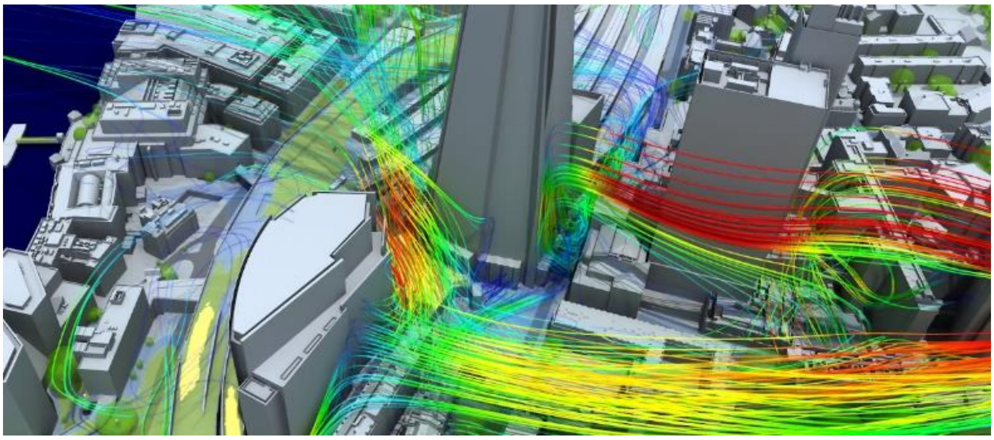

Figure 8 SimScale simulation 3D London

REDUCING FUEL MOISTURE

When combustion happens, water also gets vaporized, making a fuel having a lesser amount of moist, since increased wind force creates faster combustion. More water gets vaporized, but also carries that vaporized water away from the plant. The vaporized water keeps the moisture around the plant, when there is stronger wind, this vaporized water is being dragged with it at a higher rate, this causes the area around the tree being drier, making it easier to burn fuel.

TEMPERATURE

Most wildfires start in the summer when it’s warm. This is because when it is warmer, less heat is required for ignition. This does not only apply for plants, but also for the air. Both contain a certain amount of moisture and when it is warmer, that moister is being evaporated quicker.

Not only has temperature effect on moister, but also the travel direction of air. Wind blows air into a certain direction, but the temperature of air also changes its direction. Heat creates lower pressure, and air travels to higher pressure areas or lower temperature places to balance the difference. Which causes fires to also spread in the height.

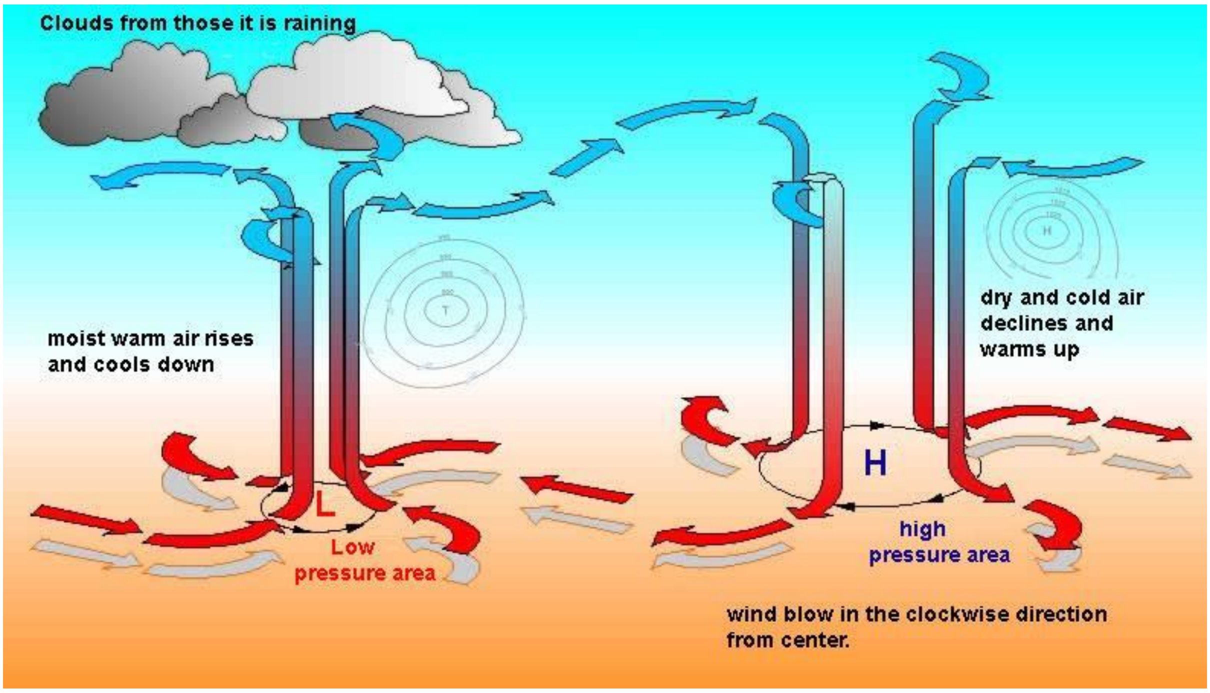

Figure 9

SLOPE

Because warm air travels upwards, when there is a fire on a slope, a mountain for instance. This will spread the fire upwards at a faster rate than downwards. The steeper the slope the faster the fire will spread.

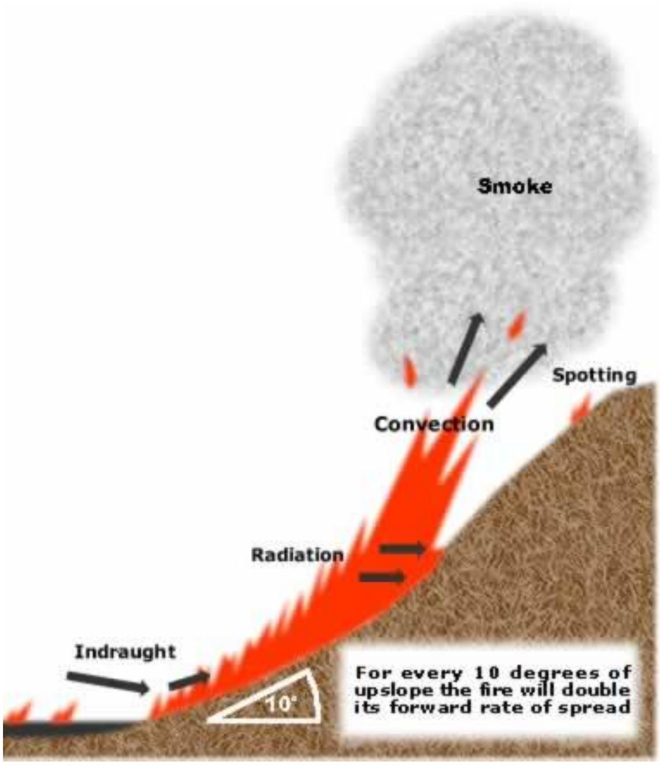

Figure 10

A different factor a slope has on a wildfire, is the direction it is facing. This has to do with the stand of the sun. When it faces the sun, it gets more heat. As mentioned in a previous part, dryer air and plants, make burning fuel or reaching a fuels ignition point easier.

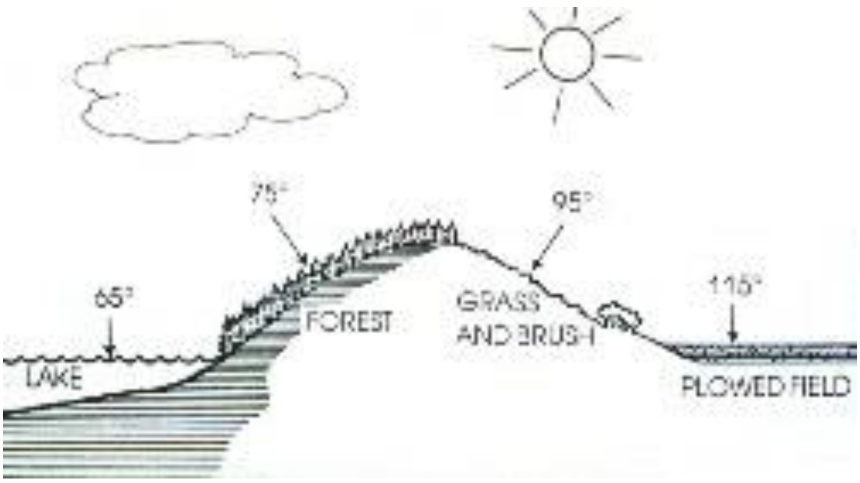

Figure 11

SURFACE FIRE

A forest fire mostly starts on the ground, where dead branches and leaves decompose, releasing carbon and causing combustion. When it gets very dry, the initial heat is already much higher causing the heat to reach their ignition point. This causes to reach the surface plants like grasses and bushes. The layer which is called the surface fire.

Figure 12 https://www.researchgate.net/figure/Prescribed-low-severity-surface-fire-carried-by-needles-cones-dried-grass-and-forbs_fig1_257931435

CROWN FIRE

A crown fire is a fire that happens in the crown of a tree or everything above the surface. Because of the shape of a tree, wind speed becomes slower when traveling through the trees at the crown layer. We know heat goes up and causes the fire from the surface to start on the higher layers of a forest.

Figure 13 https://commons.wikimedia.org/wiki/File:Crown_fire.jpg

FLAMMAGENITUS CLOUDS

Flammagenitus clouds are clouds created by burning wood. Burning wood vaporizes a lot of water and forms clouds. These clouds are a double-edged sword. When clouds get too heavy, it begins to rain, and rain can stop a fire. But the clouds can also make a thunderstorm. Lightning can be a new source of ignition of trees that have yet to catch fire.

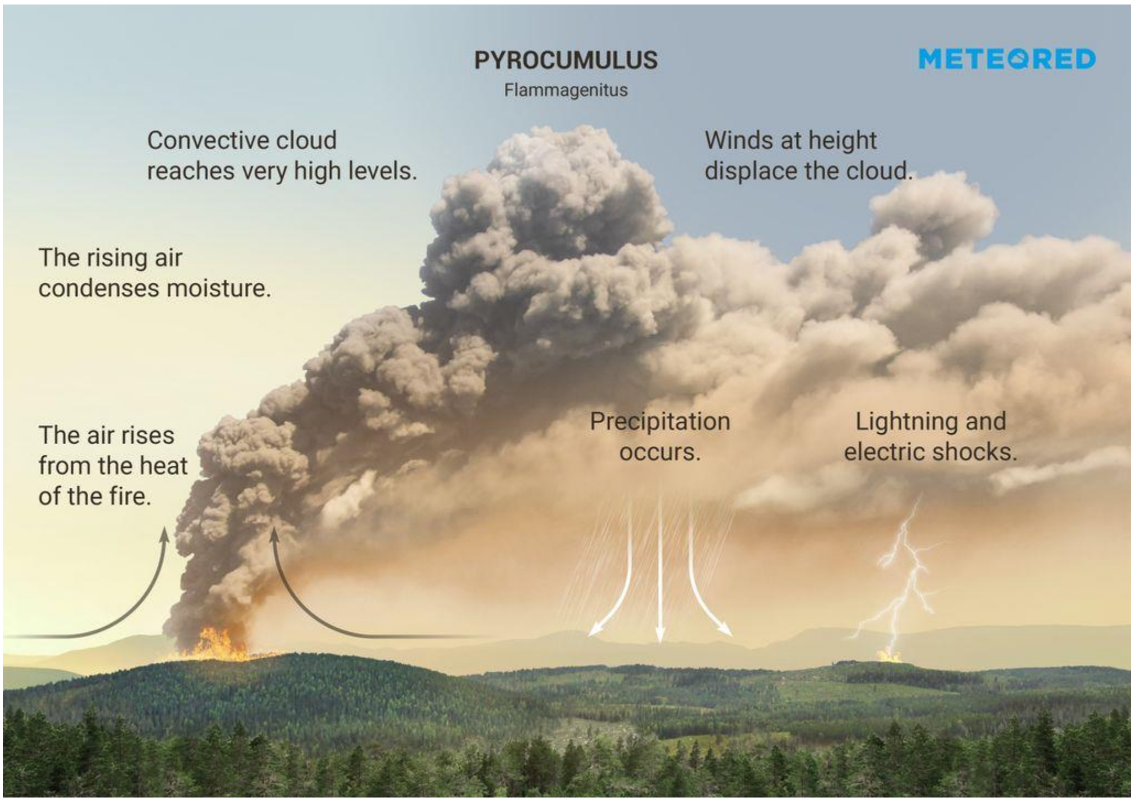

Figure 14 https://www.yourweather.co.uk/news/science/what-are-pyrocumulus-or-flammagenitus-clouds-volcano-fires.html

SPOTTING

Spotting means fires that start ahead of the current fire. When a tree is on fire, parts become loose or spit amber and these can drift with the wind. Sometimes these ambers or twigs can travel many kilometres and cause a fire where they land. Of course, it all depends on the size of these ambers and twigs. Larger parts can hold on to their temperature much longer but are heavier and don’t travel as far. Smaller parts can’t keep their temperature for so long but travel much further. These smaller ones are not a big threat when dealing with a wildfire, but the larger ones are. Certain tree species are prone to spitting which gives more chance to spotting. Trees like pines and cedars do this because of the sap they have[5].

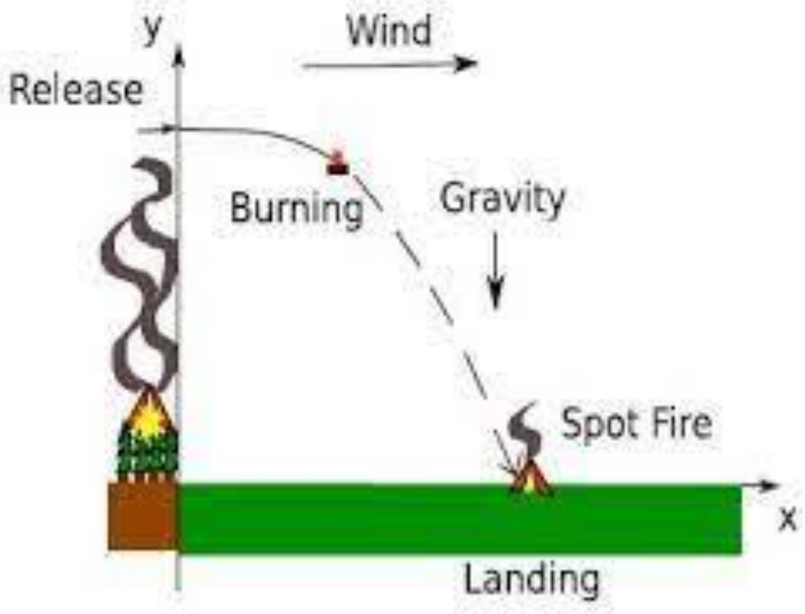

Figure 15

THE EFFECT OF TREE SPECIES ON A FIRE

As we now, trees come in different shapes. Some have needles, some have leaves. Despite them being a tree, they each have different quantities that affect a fire.

WOOD TYPES

Generally, the wood of a tree will be classified in one of two categories. Either hardwood or softwood.

Hardwood are trees where their seeds have a coating, like oak, maple…

Softwood are trees where their seeds have no coating, like pines, Fir, Spruce…

The reason why this is important, is because softwood has more moisture than hardwood.[6] Despite having more moisture, forests with softwood trees, are more prone to catching fire. This is because they also have a lot of sap in their branches. This sap burns very quickly.[7]

Hardwood is also, always a leafy tree. These trees are wider, covering more ground to protect against heat from the sun. They also grow less dense, where fires have less chance of getting towards other trees.

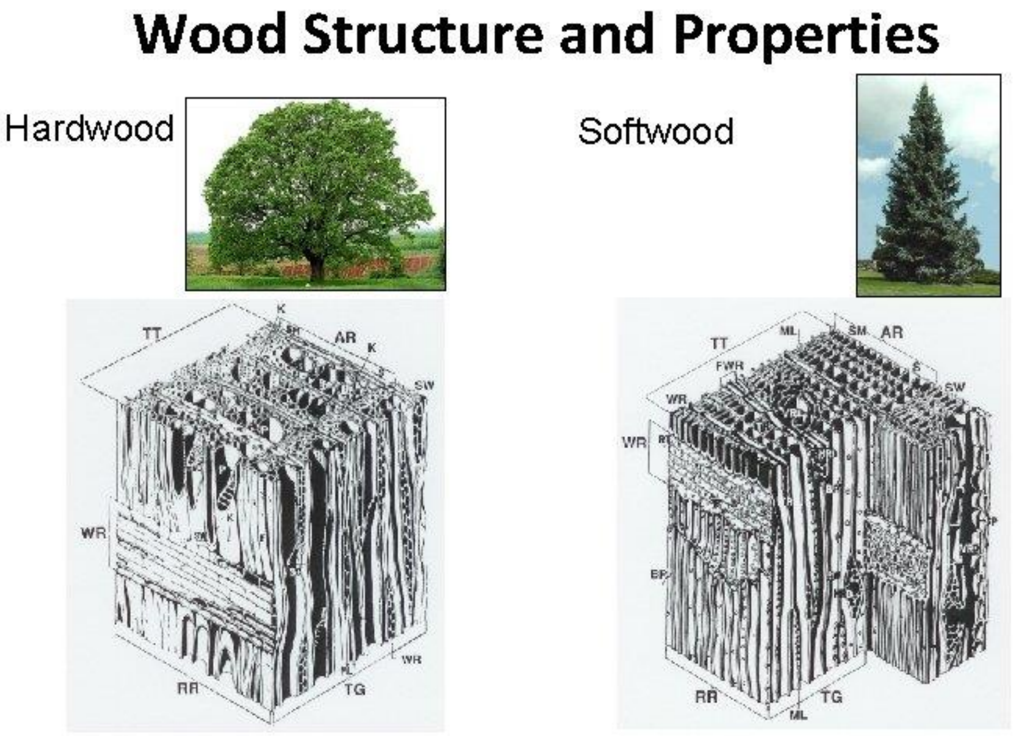

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Figure 16

DENSITY

The reason why the moisture level is different depending on the wood type, is because of the density of the wood. The lesser the density of the wood is, the more water can pass. But this has also solely to do with where a tree grows. Softwood generally grows in colder regions. Because of the lower temperature, water is more violent, and this must be compensated[8]. This has effect on the spread of a fire, a higher density slows down the spread rate.

METHODOLOGY

ENGINE CHOICE

To start the case study, an engine choice had to be made. At first, Unreal Engine 4 was in mind, since this is a collaboration with the KU Leuven, a beautiful program would be more presentable. Another reason was because of the already acquired knowledge about using terrain for placing trees and importing heightmaps. But after carefully considering the pros and cons, Unity had to be used The program will be small, and graphics are not important, all it needs to do is run and show results.

GEOGEBRA

Before starting anything in the engine, to understand some of the formulas, Geogebra 5 was used. This program lets users easily thinker with formulas while not having to go back to your code.

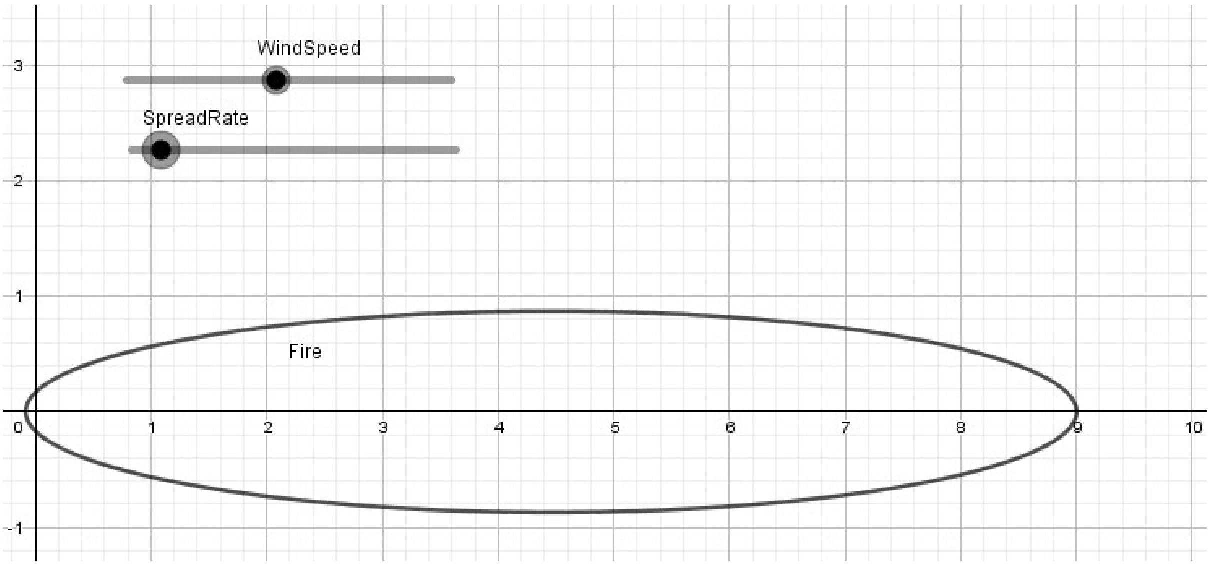

Figure 17

COMPARE MODELS

After the initial research 2 fire models came out. FARSITES[1] Fire Area Simulator-Model and the model used by Andrew P.[9]. Both use the Rothermel spread equation, but the model by Andrew P.[9] doesn't use a 3D to 2D conversion when implementing the slope parameter.

TERRAIN

For the terrain, a suitable location with a noticeable height difference is needed. For this case a location from the region Spa in Belgium was picked.

In order to get a terrain in Unity, terrain.party was used. It is a site where you can get the height map from a selected area of your choice. A site recommended by people playing the game Cities: Skylines. Because of problems they would give when selecting a lower area, the standard area had to be imported, this is an 18 by 18 km terrain. At first, this was divided by 4 leaving an area of 4.5 by 4.5 km, but for performance settled down with a 2.25 by 2.25 km area.

All that was left, was smoothing the area so it looked natural and add a texture.

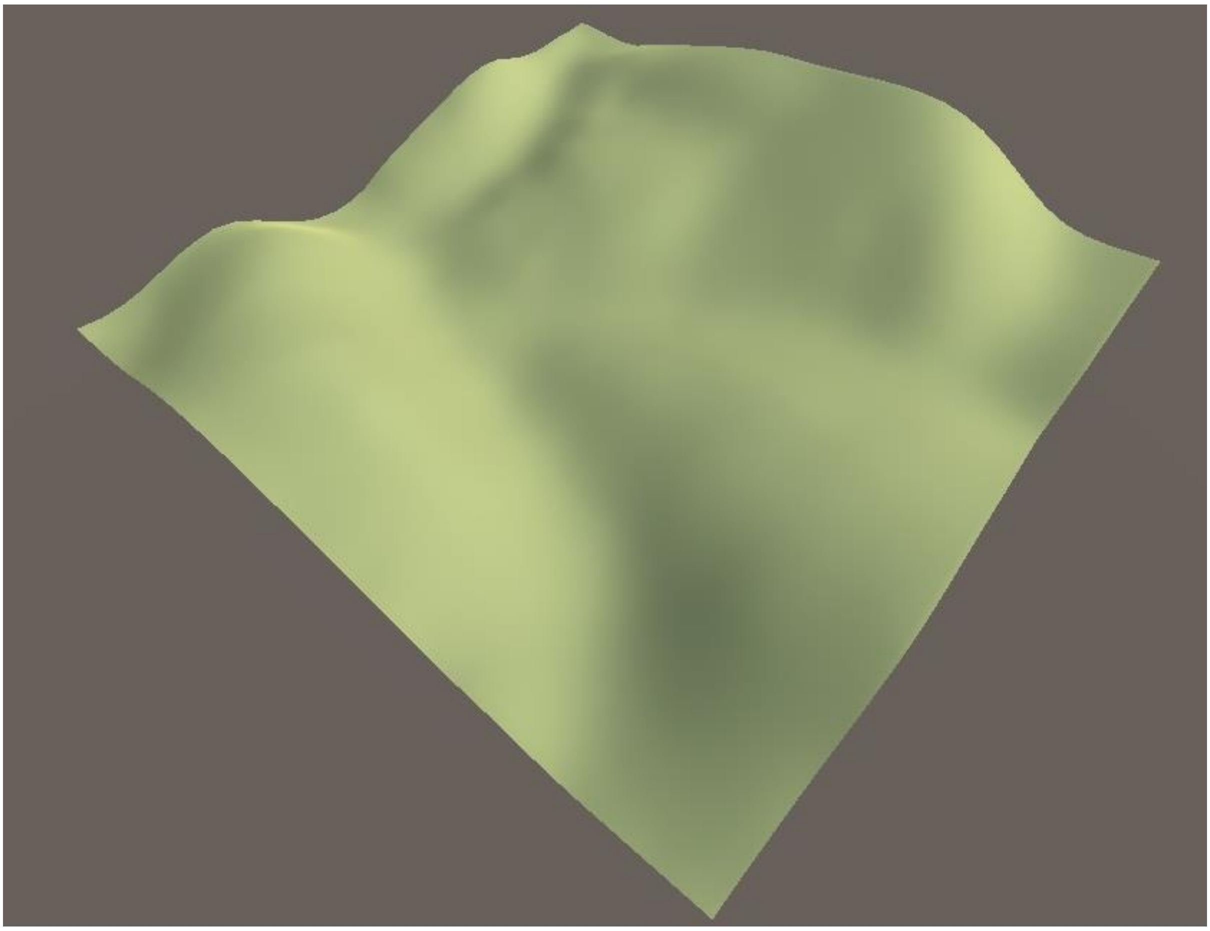

Figure 18

TREES

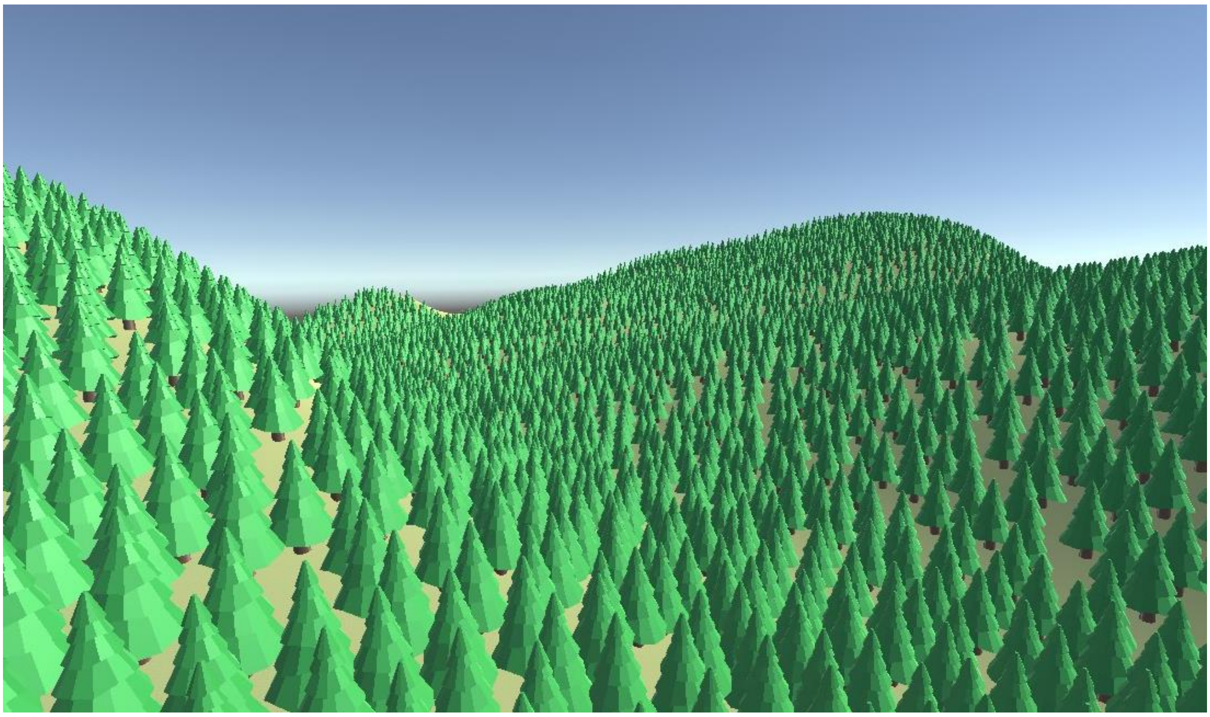

Figure 19

For the trees, a model with two materials was used. With multiple materials, it is possible to change one of its materials at runtime to visualize the state of the tree. All that was left is to place it on the terrain, since manually placing trees would be inefficient.

First, place some trees with the tree tool of the terrain, as to see if it looked any good. This way, changes to the density of the forest could be made. The problem arose when the trees had to be placed with scripts. There was a solution where we can use a tree object, but after adding those to the scene it was noticeable that the painted trees are not running scripts.

In order to have working trees in the scene, paint the whole scene with the mesh for the tree. In script you can access these trees from the Terrain class. With the locations, it is possible to initialize every tree and put them in a separate class managing all the trees.

At first, every tree looked through the whole list I order to find its affected neighbour. To increase the performance the tree gets a radius where at the start and hold trees that are in that range. This is for the flames from the tree and does not involve spotting. In stopping forest fires, trees must be cut in order to stop a forest from spreading. A natural barricade would be a wide river.

A tree also gets a radius of its size. As mentioned in both models' papers[1], [9]. The ellipse is drawn from a vertex as ignition point and not a whole tree.

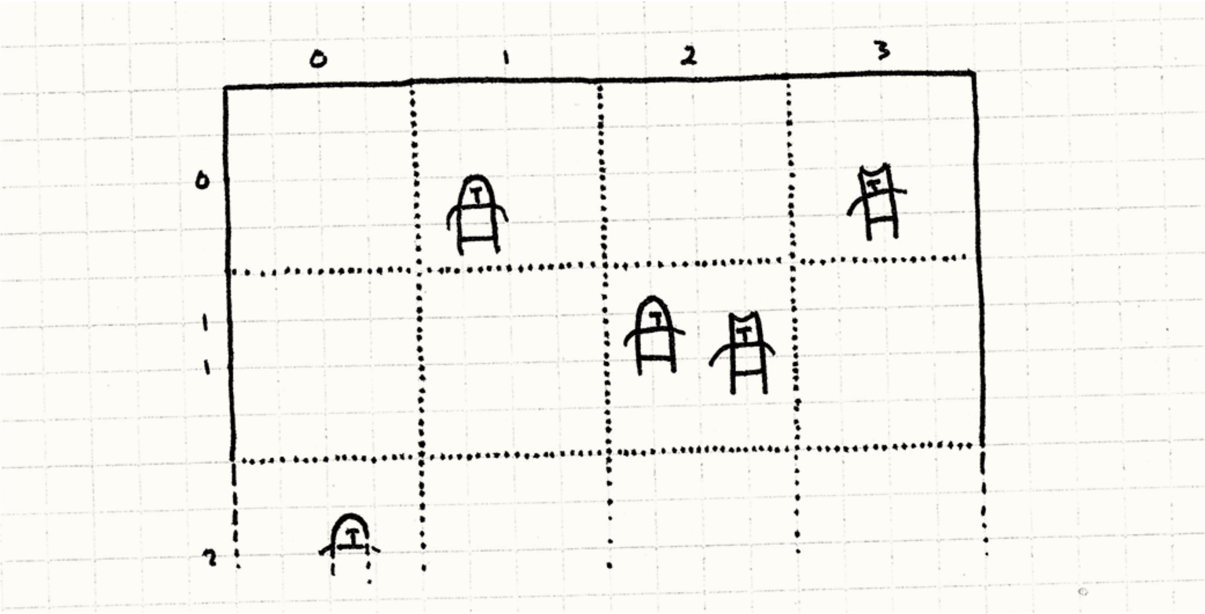

Figure 20

Through the first tests, it was clear there was a need for some optimization. Not during test but by starting the program. Since every tree goes through the whole list, it takes a while before every tree got his neighbours. Here comes spatial partitioning in place. Spatial partitioning is storing an object position in space into a spatial data structure[10]. One scene can be seen as one spatial structure. With spatial partitioning this scene will be divided.

In case of the forest, each spatial data structure has the position of a tree that is in that area. Imagine placing a grid onto a piece of land and everything inside a cell of the grid will be stored in the grid.

With the case of searching through the trees for every tree that is a neighbour, it is possible to search which cells the search radius overlaps and only take those trees into consideration. As an example the terrain will be split in 25 parts. With an area of $2.25km^2$, each of the spatial data represents an area of $450m^2$. With a range not exceeding $200m$, we have a maximum area of $900m^2$. While it is possible to divide it into even more parts, this already gives us much better results and is useful for other application that involve these trees

HUYGENS PRINCIPLE

Huygens principle uses an ellipse, and this ellipse can change its shape. The shape represents the affected area of the fire and the heat[9]. So, this will be used to know when a tree will catch fire.

WIND

A basic wind system is used to get the direction of the wind and not CFD (Computed Fluid Dynamics). Since it is an open terrain, wind will generally travel in the same direction and there is no need for CFD.

When wind goes faster, the spread area will be larger, but the width will be smaller since the heat and fire will be pushed more into one direction[1].

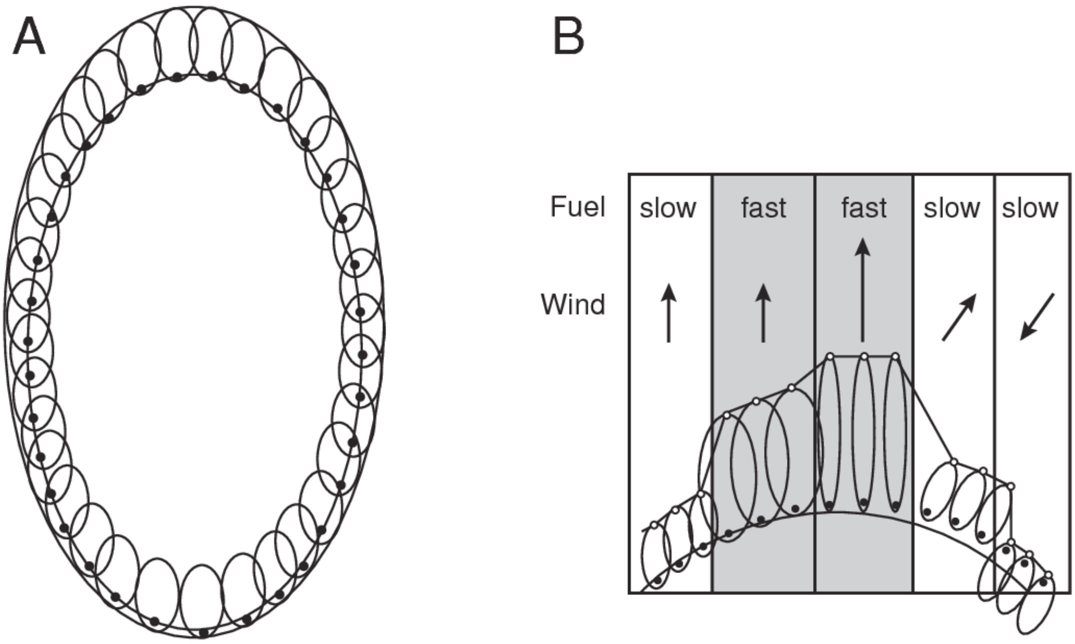

Figure 21

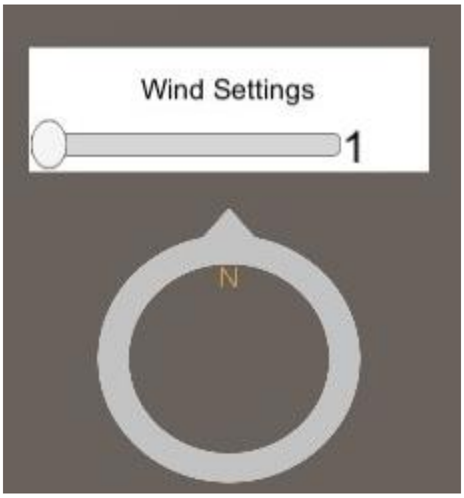

Figure 22

The wind direction is a two-dimensional vector. To be able to see the effect of wind change, a UI input will be used. The inputs are able to change the velocity of the wind and also the direction. This let the user have control over the real-time environment.

SLOPE

Upwards slope has a faster spread rate and downwards a slower rate. First the solution from Andrew P[9] was used. The algorithm used $(\tan \emptyset)^2$ for calculating the slope factor, but this has one problem. Regardless of the angle being negative or positive, the outcome will always be positive. This is a problem for lowering the spread rate when the fire goes down.

To find a better solution there first needs to be a way to get the angle. To get the angle, there has to be a way to know when it can be considered downwards or upwards. For this, it is possible to take the wind direction, Because the wind direction decides whether the fire will go to the valley or against the slope.

Take the root position of the tree and add the direction of the wind. Like this, there will be a position a unit vector further. In Unity it is possible to use a function in the terrain class that returns the height of the terrain at a designated world position. This function is called SampleHeight. The returned result replaces the new positions height.

```
var lookDirection = new Vector3(Wind.WindDirection.x, 0.0f, Wind.WindDirection.y);
var newPosition = transform.position + lookDirection;
newPosition.y = _Terrain.SampleHeight(newPosition);
```

Figure 23

With the new position it is possible to get the direction of the slope by subtracting the new position with the position of the tree. With this vector, it is possible to calculate the angle by using the SignedAngle function from the Vector3 class. The first parameter is the direction of the slope and the second the direction of the wind, because the angle should be from the slope to the wind. It is important that the third parameter is the right vector from the wind direction. This vector determines the rotation direction. At the end the function returns a float.

```
var slopeDirection = (newPosition - transform.position).normalized;
float slopeAngle = Vector3.SignedAngle(slopeDirection, lookDirection, rightDirection);
```

Figure 24

The wind and the slope are very identical, both increase the spread rate. The only difference is that the slope does not change the width of the ellipse.

BASE SPREAD RATE

Base spread rate means the rate at which a fire spread when there is no wind nor slope. Here, temperature plays a role. If a fire grows larger, the temperature grows and if we have a larger fire, we have a larger spread rate.

A tree start burning at 120°C and the minimal temperature for having a maximum spread rate is 450°C. The spread rate in between does not increase linear and to achieve this the following formula is used[11]. sT is the current temperature clamped between 0 and 1.

$$(3 * sT^2) - (2 * \ sT^3)$$

```
float n = 0.0f;
if (_Temperature >= T0)
{
    float sT = (_Temperature - T0) / (T1 - T0);
    n = 3 * Mathf.Pow(sT, 2) - 2 * Mathf.Pow(sT, 3);
    n *= 100.0f;
}
```

Figure 25

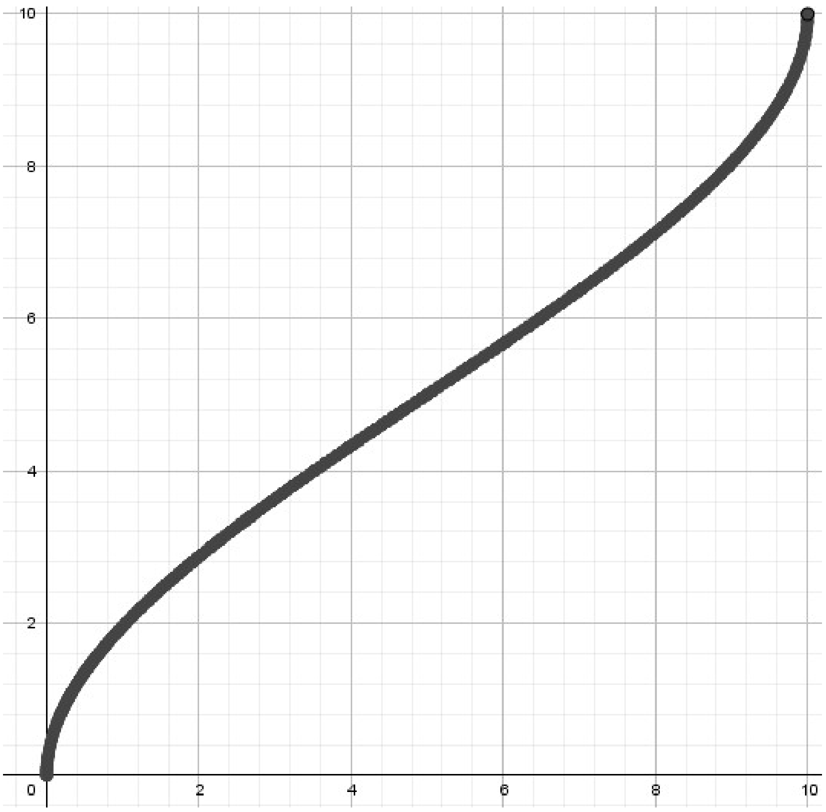

Figure 26

ELLIPSE

With all parts in place, the ellipse can be made. The ellipse is constructed as done by Andrew P[9].

First, there needs to be a wind (m/s^2) and slope (rad) factor. The wind factor is the wind speed, but for the slope factor , the following formula should be used:

$$SlopeFactor = 5.275(\tan \emptyset_s)^2$$

With the wind factor and the slope factor, now it is possible to calculate their distance Ds and Dw.

$$Ds = BaseSpreadRate * SlopeFactor * \Delta t$$

$$Dw = BaseSpreadRate * WindFactor * \Delta t$$

They indicate their own distance in world space and are separate, but now they have to be combined.

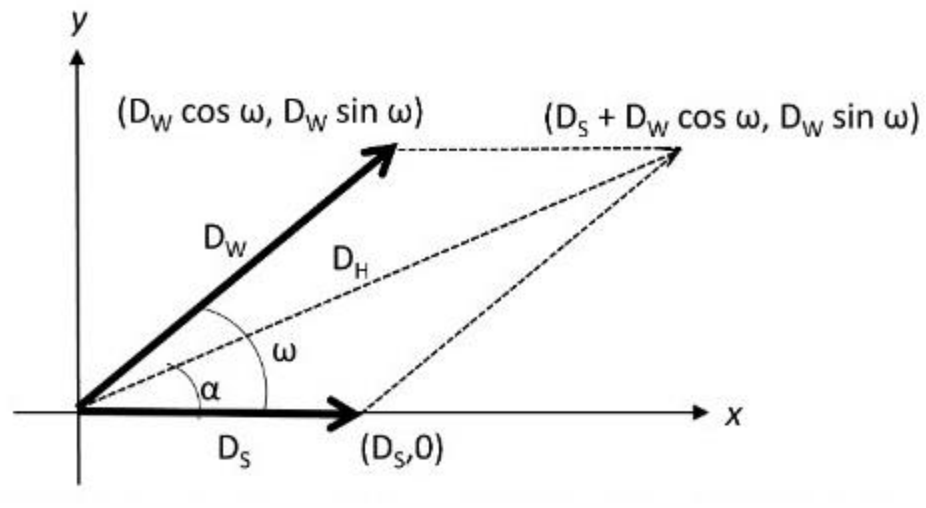

Figure 27

The combined vector is the heading spread distance (Dh) and used the combined length and height as distance. The following formula does this:

$$X = Ds + Dw \cos \omega$$

$$Y = Dw \sin \omega$$

But this has one problem, it does not consider if the fire goes up or down. Cosine would return the same value when negative or positive. A way to counter this is to use the sine and add one to it. This would have a value between 0 and 2. Which means uphill goes twice as fast then on a flat surface. So, the formulas should look like this:

$$X = Ds + Dw * (1 + \sin \omega)$$

$$Y = Dw * (1 + \sin \omega)$$

And to get the actual heading spread distance:

$$Dh = \ (X^2 + Y^2)^{0.5}$$

With this, the ellipse grows longer, but keeps growing and ignore rivers who can stop the spread because there is no fuel to ignite. Small rivers are still possible, due to the flying ambers.

A solution to this is by clamping the heading spread distance. The best limit is the radius to find the neighbours since all neighbours will still be able to get ignited and when done. The head spread rate (Rh) can be calculated.

$$Rh = BaseSpreadRate + (Dh * \ \Delta t)$$

With the head spread rate, the ratio between the length and the width can be calculated. Stronger wind gives longer and shaper shapes, while slow wind gives short but wide shapes. The formula for this uses the effective wind speed (U_E) that is the current windspeed divided by the ideal windspeed U_{ref} (15 m/s) according to Rothermel[9]. The ideal windspeed is where a fire will spread the most.

$$LengthWidthRatio = 1 + \ U_E$$

With the ratio, it is possible to calculate the eccentricity of the ellipse. The eccentricity is the ratio of the distance between the centre of the ellipse and each focus to the length of the semimajor axis[12]. The formula is a followed:

$$e = \frac{(LengthWidthRatio^2 - 1)^{0.5}}{LengthWidthRatio}$$

Now only the length between the tree and the furthest point are known, but not the shortest or backside. For this the spread rate for the back (Rb) must be calculated and uses the eccentricity.

$$Rb = Rh * (1 - e)/(1 + e)$$

With the spread rate, the distance can be calculated.

$$Db = Rh * \ \Delta t$$

After this the total length and width of an ellipse can be found.

$$length = Dh + Db$$

$$width = length/LengthWidthRatio$$

But in order to draw an ellipse two radius are needed.

$$X_{Radius} = length/2$$

$$Y_{Radius} = width/2$$

Drawing also happens from the centre. This offset is the distance between the centre and the focus where the tree is.

$$offset = Dh - X_{Radius}$$

Now everything is there to draw and test collisions.

COLLISION

During the first attempt, the collision check happened with the centre point of the neighbour tree. However, the ellipse has no knowledge of its rotation from the wind. A solution is to bring the neighbour tree to the space of the ellipse and can be achieved by rotating the neighbour around the main tree. The angle is the angle of the wind direction and after doing this it is possible to use this point to find whether it is in the ellipse or not. The equation of an ellipse helps with this.

$$\frac{(x-h)^2}{a^2} + \frac{(y-k)^2}{b^2} = 1$$

x and y: 2D position on the boarder of the ellipse
h: offset where the ellipse centre is on the x-axis.
k: offset where the ellipse centre is on the y-axis.
a: horizontal radius
b: vertical radius

When x and y are filled in, it is possible to know when a point is in the ellipse. Because a point in the ellipse would return a value smaller or equal to one. Also, k is not needed since the ellipse only moves in one direction. This becomes the following formula:

$$value = \frac{(possiblePointX - offset)^2}{{radius_x}^2} + \frac{possiblePointY^2}{{radius_y}^2}$$

But a tree can also catch fire through its branches. In order to simulate this, a tree gets a radius which forms a circle around him to mark its affected area. The previous equation is still viable with this change, but it not the most optimal solution. With the solution, a few segments will be calculated that are on the circle and those points will be used as the points for the previous equation.

TREE SPECIES

For the test, four different trees will be used out of the list from The Engineering ToolBox[13] The trees were selected based on their density. But for more diversity, their family should be different. With this in mind, the four selected species are:

- Pinus ponderosa: Ponderosa pine
- Quercus alba: White oak
- Thuja occidentalis: White cedar
- Liriodendron tulipifera: yellow poplar; tulip tree

Figure 28 Pinus ponderoza

Figure 29 Quercus alba also known as the white oak

Figure 30 Liriodendron tulipifera; yellow poplar; tulip tree

Figure 31 Thuja occidentalis; White cedar

MOISTURE, DENSITY AND VOLUME

In Unity by using scriptable object, multiple types of trees can be easily made. These objects are used to retrieve the usable data for changing the trees parameters. And there are three basic variables needed for easy use. Volume (m^3), density of a living tree $(\frac{kg}{m^3})$ and density of a seasoned tree, where the moisture content is 20% $(\frac{kg}{m^3})$.

Volume is used for the total amount of mass and moisture that a full tree would have. However, real volume numbers are hard to calculate since a tree can have a different shape and height depending on where it grows. For instance, trees at higher altitude are shorter, because of the colder temperature. But for this case, the volume will be the same for all trees, the volume of a 200-year-old tree, being $10m^3$. It is nothing compared to the "General Sherman", the currently said to be the largest tree with an approximate volume of $1487m^3$.

The following table shows the density of the four tree species.

Tree	*Density* $(\frac{kg}{m^3})$	*Density 20% moisture content* $(\frac{kg}{m^3})$
Ponderosa Pine	721	449
White Oak	1009	753
Yellow Poplar	609	449
White Cedar	384	368

Table 1

Now the only thing left is getting the initial density$(\frac{kg}{m^3})$, the mass (kg) and the moisture mass (kg)[15].

$$Density_i = Density_{20\%moisture} * 0.8$$

$$Mass = Volume * Density_i$$

$$Moisture = Volume * (Density_{living} - Density_i)$$

Moisture and mass can be seen as two health bars, but both decrease differently. Wood without moisture burns faster and the opposite is also true. To simulate this, the moisture content has to be burned first and at a lower rate. To know how much content gets evaporated, the spread rate will be used together with the approximate water released over time, this value is 53.26%. Also, the temperature has to be added to increase the amount of fuel consumed when having a higher temperature. Trees can go to $1100°\text{C}$.

$$\Delta Moisture = 0.5326 * BaseSpreadRate * ClampTemperature * \ \Delta t$$

Water release is 53.26%, which means 46.74% wood. This can be used the boost for burning the mass.

$$\Delta Mass = (1 + \ 0.4674) * BaseSpreadRate * ClampTemperature * \ \Delta t$$

And looking at the wood characteristics, it is known that the denser wood is, the longer and slower it will burn. That’s why oak trees are good for firewood[5]. Which means spread rate is lower over time. But density has no upper value as the base spread rate. A way is to bring density to a reasonable level, is by dividing 100 by the density. Base spread rate becomes:

$$BaseSpreadRate = BaseSpreadRate_T * Density_{100/i}$$

When mass and moisture are zero. The tree is dead, leaving only charcoal behind.

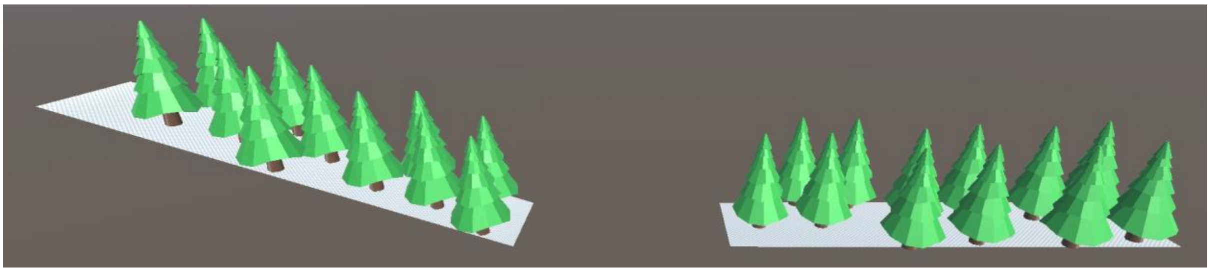

Figure 32

To test the case study, the experiment will involve the difference slope angles in corelation with the tree species and return the time from the start of the fire until the last tree has burn out. The setup requires two terrains with dimension 50x200 m. One terrain remains flat while the other will have a 20° slope.

To use it as test terrain, in the TreeManager object in the respective class, the serialize field Terrain should get the terrain for testing. The following steps all happen in the application.

The first species will always be the pine. To get another species, simply select “Edit Trees” [Figure 33] and select one of the options given in the dropdown list [Figure 34].

Figure 33

Figure 34

Now it is possible to go over the active terrain. It will be noticeable when a tree species has changed, since all species have a different colour for the crone

Depending on the terrain and slope type, the wind direction and speed will be set. This can be done with the compass and the slider [Figure 35]. For the downslope the direction is west, while the flat and upslope are to the east. For the wind speed, three values are used depending on if it’s low, medium or high. Their represented values are 1, 7.5 and 15.

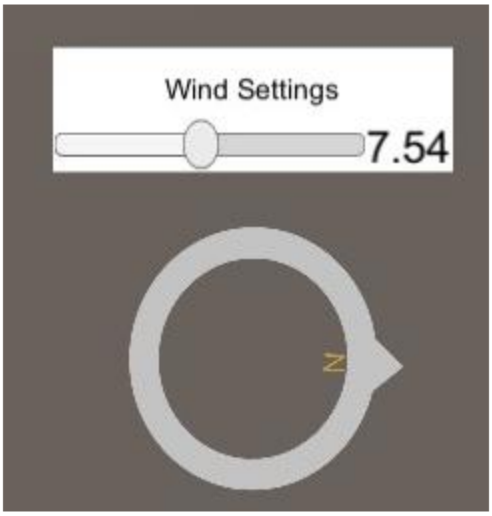

Figure 35

Next is the placement of the fire. This can be done by using the “Fire” tool, that places a fire on the terrain where the mouse is hovering and ignites the closest tree. For wind direction, east, the tree most on the left and for the west direction the tree most on the right. For the experiment the following trees in the three pictures were selected as starting point for the fire.

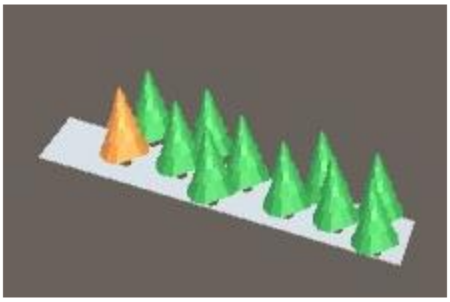

Figure 36 Downslope setup

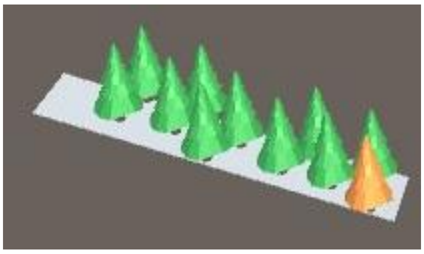

Figure 37 Upslope setup

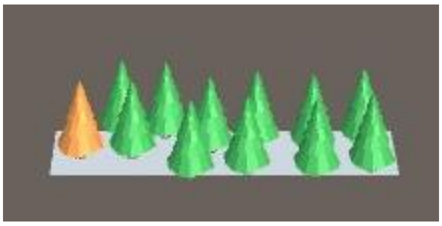

Figure 38 Flat setup

It is possible to speed up the time needed, by clicking on the wished speed-up in the top left corner.

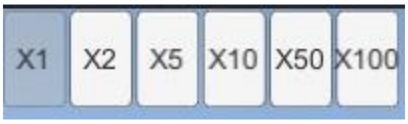

Figure 39

With this setup, by clicking start the simulation will run and will stop the moment all trees that caught fire are dead. The following tables are the results from this experiment.

Flat terrain	*Low wind speed*	*Medium wind speed*	*High wind speed*
Ponderosa Pine	01:05:15	00:12:43	00:07:27
White Oak	01:20:27	00:16:02	00:09:29
White Cedar	00:54:58	00:10:59	00:05:50
Yellow Poplar	01:03:17	00:12:10	00:06:59

Table 2

Downslope 20°	*Low wind speed*	*Medium wind speed*	*High wind speed*
Ponderosa Pine	01:09:54	00:14:17	00:08:14
White Oak	01:25:57	00:17:54	00:10:33
White Cedar	00:59:18	00:11:46	00:06:39
Yellow Poplar	01:07:54	00:13:45	00:07:53

Table 3

Upslope 20°	*Low wind speed*	*Medium wind speed*	*High wind speed*
Ponderosa Pine	00:59:48	00:12:03	00:07:00
White Oak	01:13:49	00:15:08	00:09:04
White Cedar	00:49:53	00:09:38	00:05:29
Yellow Poplar	00:57:47	00:11:28	00:06:40

Table 4

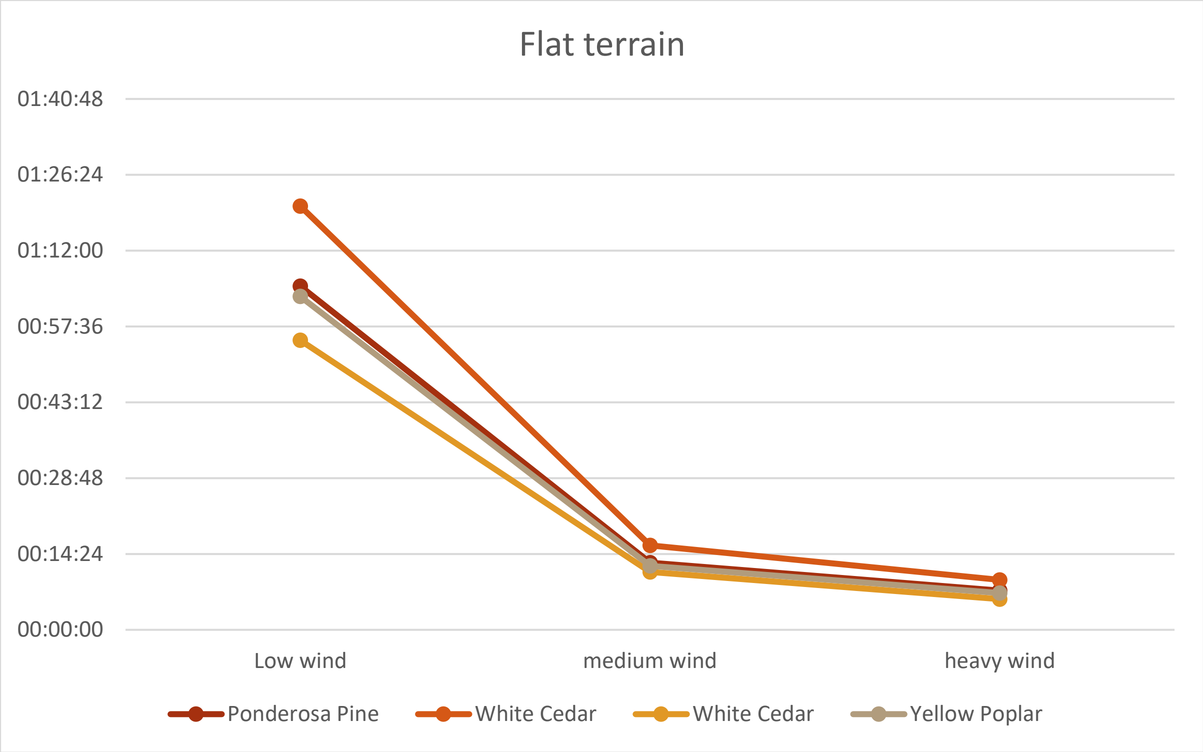

Figure 40 Flat terrain results graph

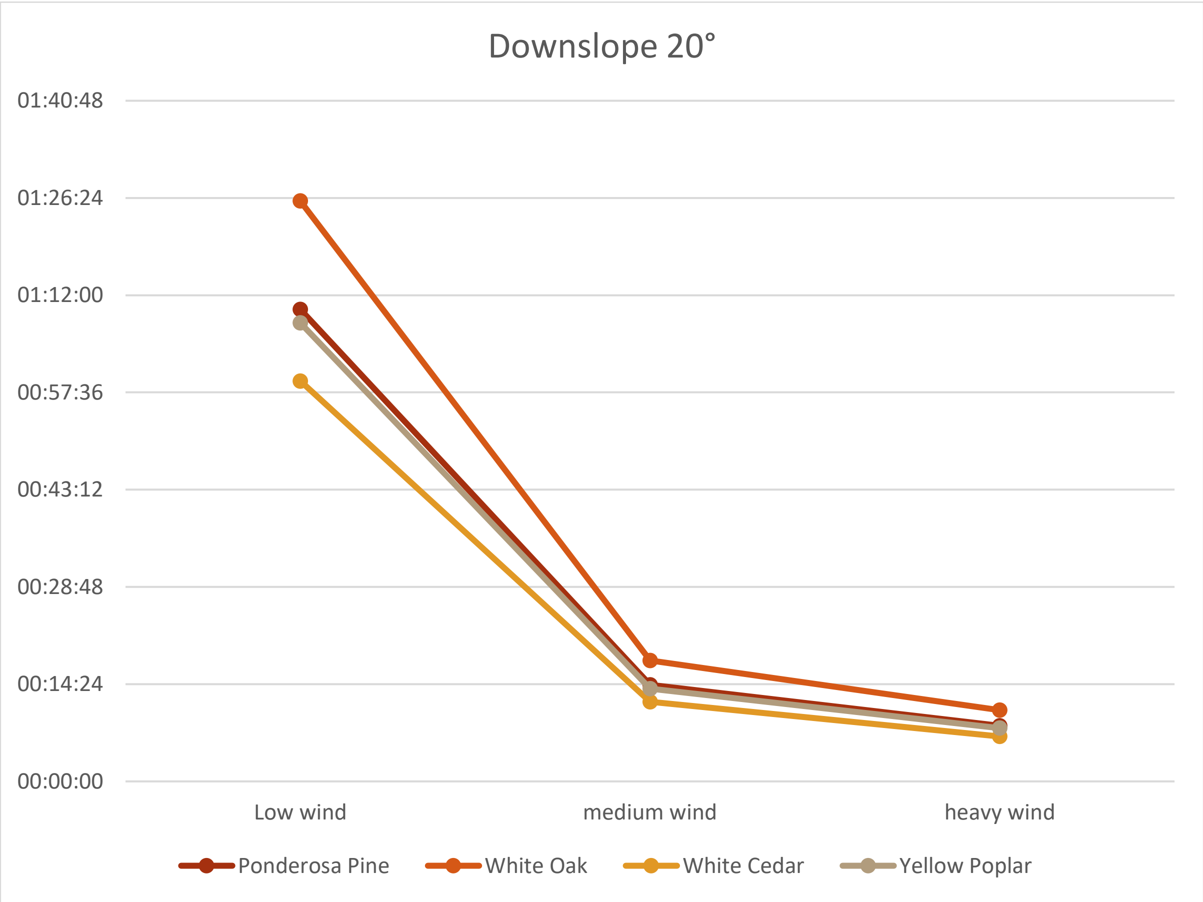

Figure 41 Downslope results graph

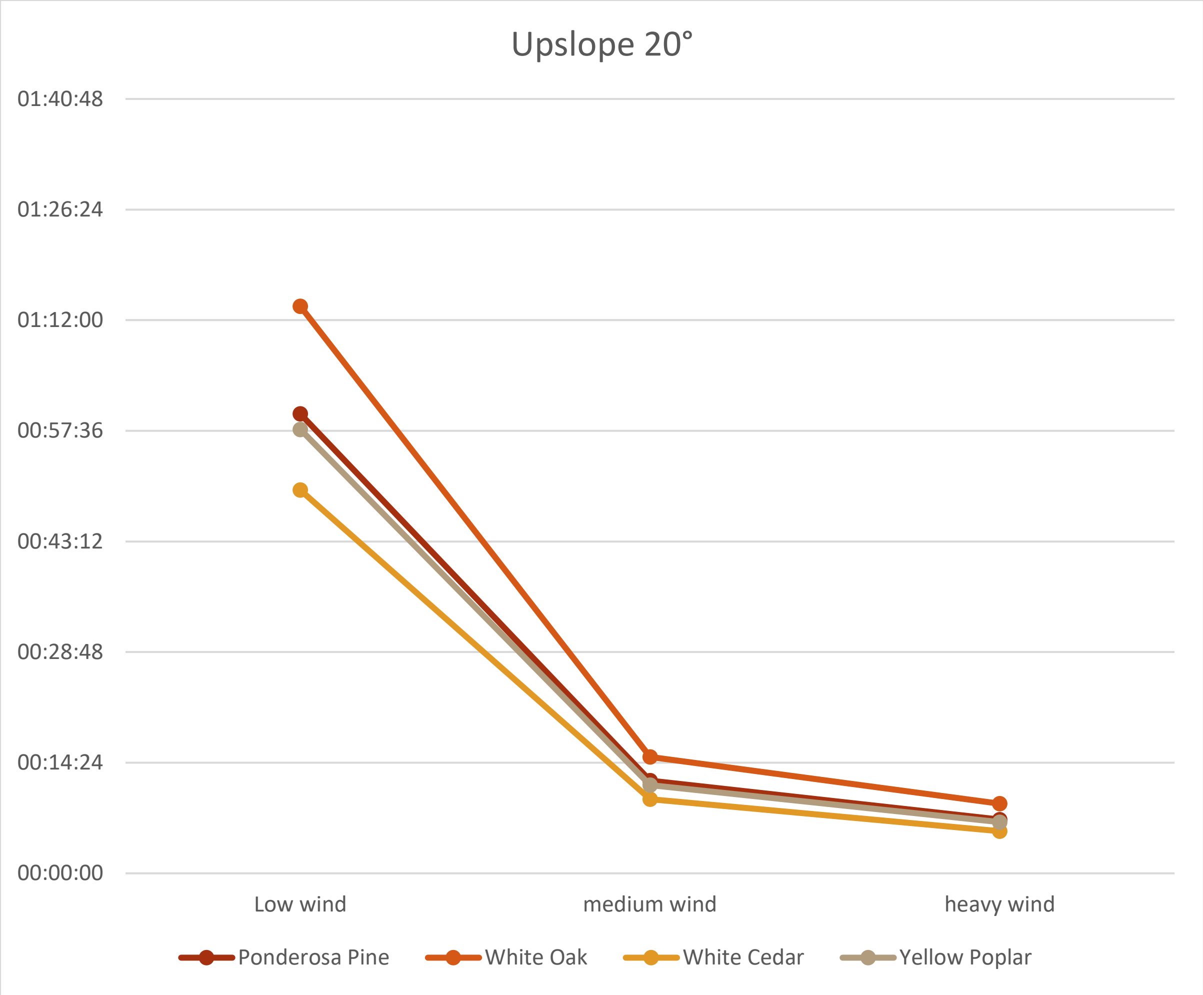

Figure 42 Upslope results graph

Another test was performed where the different tree types where placed next to each other from highest density to lowest.

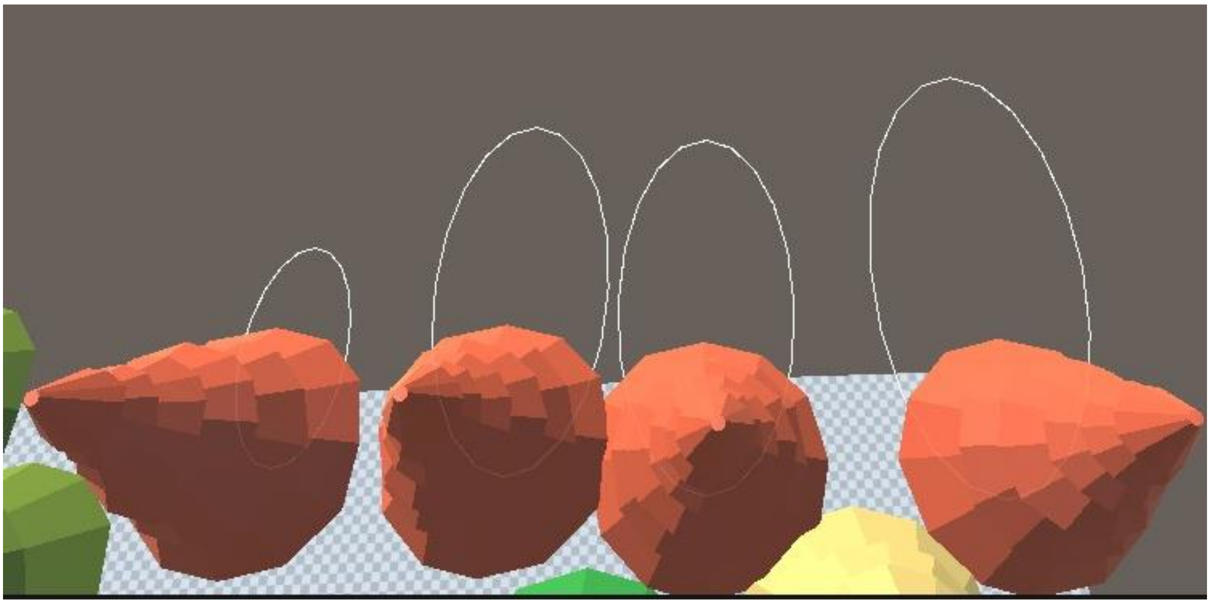

Figure 43 1: Oak; 2: Poplar; 3: Pine; 4: Cedar

Additionally, a test was performed on the larger square map, where diagonally, the fire took around one hour and twenty minutes in favourable conditions for the fire, using the pine as forest. Diagonally the distance is $3.18km$.

DISCUSSION

Looking at the results it is noticeable that the graphs look pretty much the same and is a wanted result. Compare the time it takes; it is also noticeable that upslope is indeed faster than flat terrain and flat terrain faster than downslope. But the results don't give a significant difference. The density displays a difference when the trees are compared, but because a tree has no resistance to the fire, the spread goes faster.

So, while it looks good with the density, there still needs to be something done in order to simulate the resistance against an incoming fire and the transfer of heat to increase the spread rate. A forest fire with the right conditions can go up to $\frac{12km}{h}$. Comparing this to the time taken for a 3km distance travelled. It is clear that the spread rate is not yet as it should be. But this could also be due to the fact the spread can only go to a certain distance in order to stop for open areas and there is no transfer of heat that would increase the spread even further.

CONCLUSION & FUTURE WORK

While it was an interesting topic to work on a lot can improve. Most of the improvement are for the spread rate, that currently only uses the temperature and density. The temperature rises on its own and is not affected by other incoming heat which would increase the temperature faster for larger fires. Another part that could improve here, is the importance of the moisture. Currently the moisture's purpose is a second health bar yet has no effect in the heating process which could lead to trees burning slower or not at all.

While it can improve a lot, it also has room for ideas. Like changing density of the forest when editing the trees. Not all tree species have the same density for their forest. Also, the idea for reviving a forest. Most forests revive after a wildfire, implementing this could also show the grow rate of certain species. A river system would be good, the current system relies on a specific distance and having one could remove this limitation, increasing the spread of a fire to get a more accurate spread.

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