Effect of Wind Field Parallelization on Forest Fire Spread Prediction*

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Abstract. Forest fire spread prediction is a crucial issue to mitigate forest fire effects. Forest fire propagation models require several input parameters describing the conditions where the fire is taking place. However, some parameters, such as wind, present a different value on each point of the terrain due to topography. So, it is necessary to couple a wind field model that evaluates the wind on each terrain point. However, calculating the wind for each point on large maps is a time consuming task that can make the prediction unfeasible. So, it is necessary to parallelize the wind field computation. One approach is to apply a map partitioning technique, so that the wind field is calculated for each map part. The wind field obtained is lightly different from the one obtained with a single global map, and it is necessary to evaluate the effect of such difference on forest fire spread prediction.

Keywords: Wind field model, Forest fire spread prediction, Coupling models, Parallelization.

1 Introduction

It is well known that wind speed and direction are the parameters that most significantly affect forest fire propagation. Therefore, an accurate acknowledge of such values is mandatory to successfully estimate forest fire spread beforehand. Wind depends on meteorological conditions, but the meteorological wind is modified by the topography of the terrain so that the wind speed and direction are different on each point of the terrain under consideration. It means that the wind is not represented by a single value of speed and direction for the whole map, but there is a complete wind field with a value for wind speed and direction for each point of the terrain. However, it is not possible to measure the wind on each point of the terrain in a real emergency. Moreover, when predicting forest fire spread it is necessary to use meteorological values provided by weather forecast models, such as WRF [9], that provide values with low resolution (approximately 2.5 Km). Such resolution does not take into account

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the effect of terrain topography on wind variables. So it is necessary to use a wind field model that takes the meteorological wind or the values measured on certain meteorological stations and generates a wind field with high resolution (30 or even 10 meters depending on the digital elevation map available).

In this way, the meteorological wind data are introduced to a wind field model that evaluates the wind field at high resolution and the obtained wind field is introduced to a forest fire spread simulator to provide an accurate prediction of forest fire propagation [8]. In this work the wind field simulator used is WindNinja [5][6] and the forest fire simulator is FARSITE [4]. The complete prediction scheme coupling wind field model and forest fire propagation model is shown in figure 1. FARSITE is one of the most widely used forest fire spread simulators in the forestry community. It has been designed to accept a wind field map as input data. WindNinja is a wind field model that was originally developed to be directly coupled to FARSITE.

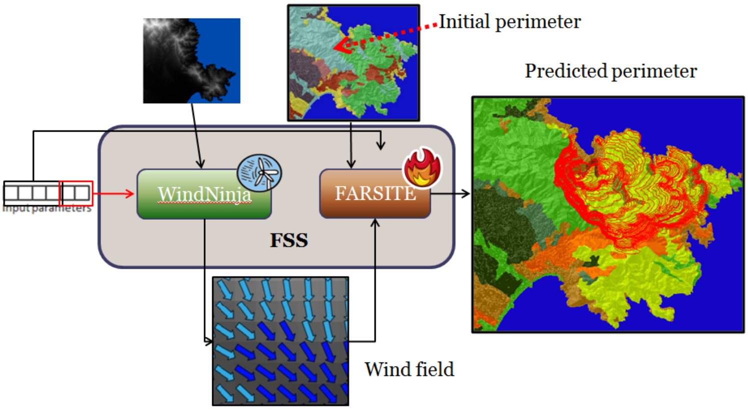

Fig. 1. Coupling wind field and forest fire spread models

This scheme is very promising and the accuracy in forest fire spread prediction is significantly increased, but the computation time to reach such a prediction is also significantly increased, specially when terrain map is large (30x30 Km) and the resolution is high (30x30 m). However, computation time is not the only constraint, but also data structures size is a significant constraint due to amount of memory available on a single node. To overcome these constraints it is necessary to apply some parallelization method that reduces execution time and distributes data structures along parallel system memory.

This work focuses on WindNinja Parallelization and studies the effect of the parallelization method selected on forest fire spread prediction, considering execution time and prediction accuracy. So, Section 2 describes WindNinja wind field simulator and determines the main constraints of such simulator. Section 3 shows the parallelization method proposed based on map partitioning considering overlapping. Section 4 presents the experimental results considering execution time and prediction accuracy. Finally, section 5 summarizes the main conclusions of this work.

2 WindNinja Wind Field Simulator

WindNinja is a wind field simulator that calculates the effect of topography on wind. WindNinja does not predict wind fields for future times, but computes the spatially varying wind field on the surface for one instant time. WindNinja requires as basic input parameters the elevation map of the underlying terrain (Digital Elevation Model -DEM- file), the global meteorological wind speed and wind direction and the required output resolution. As output, WindNinja delivers wind speed and wind direction at the specified output resolution. Usually, the resolution delivered in the output wind field is set to be the same resolution as the input elevation map. Using this one-to-one relationship, each map cell will have its own wind components. Figure 2 shows the internal structure of WindNinja and the steps that it carries out to calculate the wind field.

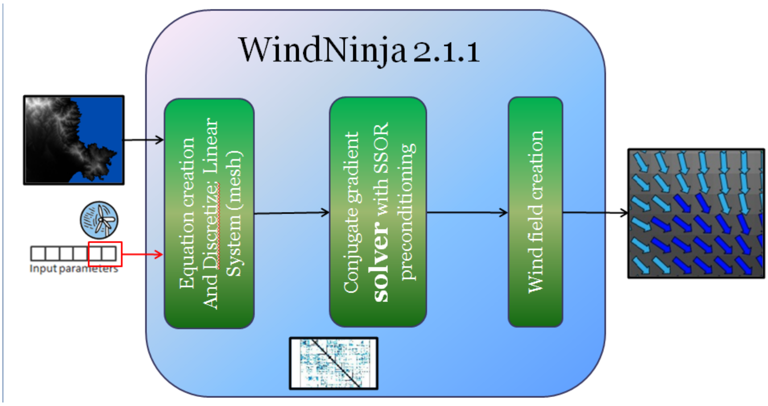

Fig. 2. WindNinja System

The main problem with WindNinja is that as the number of cells increases, the execution time increases significantly. The number of cells of the input map depends on the map size in absolute terms and on the resolution of the map. If the map size or the resolution are increased the execution time is increased. Moreover, the amount of memory required to solve the wind field increases linearly with the number of cells of the map making unaffordable to be solved a map with a large number of cells in a single node. Therefore, it is necessary to apply some parallelization technique to reduce execution time and memory requirements. It means that calculating the wind field of a 1500x1500 cells map on a single node with 4GB of main memory fails and no output is delivered. According to WindNinja documentation the maximum amount of memory required to execute the simulator can be expressed by equation 1. This equation shows that the amount of memory directly depends on the number of columns of the map (NColumn) and the number of rows of the map (Nrows).

$$\text{M (Bytes)} = 20480 + 15360 * \text{NRows} + 15360 * \text{NCols} + 11520 * \text{NRows} * \text{NCols} \quad (1)$$

Execution time is another issue to be considered, because forest fire prediction time must be much faster than real time in order to be operational. The execution time of WindNinja depends on the number of equations that form the system. So, it is directly proportional to the number of cells of the map. WindNinja has been executed on a DELL cluster based on Poweredge C6145 with a total of 8 CPUs with 16 cores and 128 GB of memory considering different map size and it has been determined that the relationship between execution time and the number of cells can be approximated to a straight applying linear regression. Figure 3 show the execution time depending on the number of cells of the map.

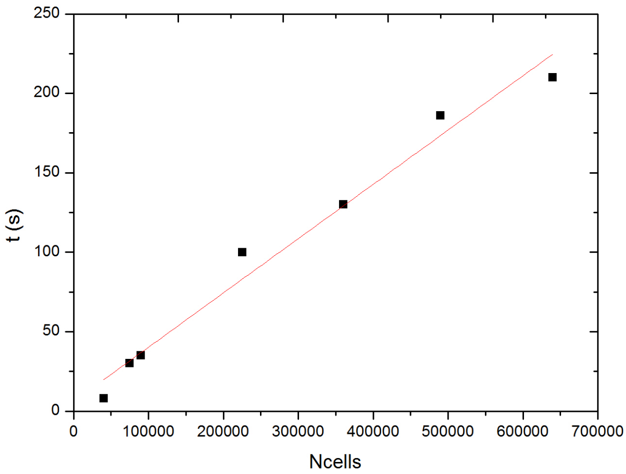

Fig. 3. Execution time depending on the number of cells

The expression obtained from linear regression is the following one:

$$\text{t} = 3.42 * 10^{-4} * \text{NCells} + 6.11 \quad (2)$$

Since it has been determined that the maximum time to evaluate the wind field should be around 60 seconds, from expression (2), it can be deduced that the maximum number of cells that can have a map is 160000. The results of the wind direction and speed of a cell depend on the cells that are around. Therefore, the squarer the part the fewer exposed cells were found in the partition, since the square is the geometric figure that has the minimum perimeter. So, the map should be of a maximum size of 400x400. For this map size the amount of memory required according to equation (1) is 1.7 GBytes.

The execution time and amount of memory required are reasonable, but this map size is very small and in most real cases maps will be larger. So it is necessary to apply some parallelization technique that reduces execution time and memory requirements.

3 Map Partitioning WindNinja Parallelization

The initial approach that has been considered to parallelize WindNinja is map partitioning. However, far from being an easy approach, this map partitioning scheme involves new issues that must be tackled. WindNinja is based on the equations that describe air flow variation in the atmosphere. Specifically, it is based on mass conservation and delimited boundary conditions. This implies that terrain slope variation generates wind changes and, due to boundary conditions, the obtained results in regions close to the borders of the map will not be correct since the system needs some cells to stabilized. Consequently, many external map cells have a non reliable value and, therefore, a set of cells around the evaluated map must be dismissed as a final result. When the global map is partitioned into parts, this problem is extrapolated to all parts and a direct combination of output wind fields results in an aggregation of boundary errors introducing additional uncertainty in wind values. So, if the map is partitioned and the wind field is calculated for each part of the map without considering the neighbour parts of the original map, the wind field resulting can be significantly different from the original one in the cells close to part boundaries. The inclusion of an overlapping is necessary to reduce the variation and uncertainty in the wind field near the part boundaries. Including a certain degree of overlapping among map parts increases execution time but reduce the degree of difference among the wind field calculated using a global map and the partitioned one.

To overcome this problem, a certain degree of overlapping among parts must be considered for all adjacent parts to soften border errors. An example of this partitioning and overlapping approach can be seen in figure 4 where the result of applying overlapping in AxB parts partitioning is shown. So, we propose a map partitioning with overlapping scheme for wind field evaluation as follows:

1. partition the input DEM map into X parts with a given overlapping,
2. run in parallel as many executions of the wind field model as parts have been generated at the partitioning process and,
3. combine the outputs of the X parts discarding the overlapping cells to obtain the global map.

Finally, the resulting wind field map, once the map partitioning scheme has been applied, has the same dimensions as the original one. It must be taken into account that even when some overlapping is introduced the system of equations to be solved is not exactly the same and the numerical solution obtained from the global map and the one obtained from the partitioning map may not be exactly the same. This map partitioning approach has been implemented in a Master/Worker MPI [7][3][1] application where the Master creates the map parts

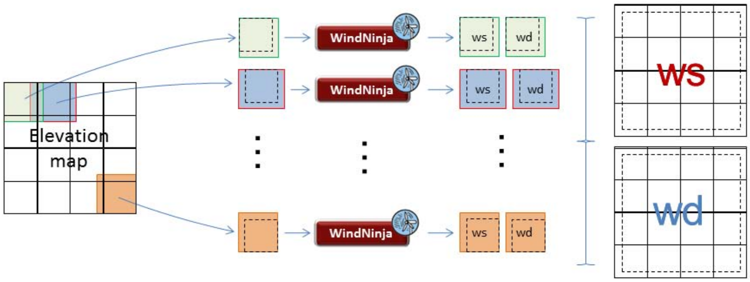

Fig. 4. AxB partitioning with overlapping

and distributes them to the workers and the workers calculate the wind field for each part and return the results to the Master that aggregate the wind fields in a complete wind field.

As it has been stated above a map part of 400x400 cells has reasonable execution time and memory requirements. But this map part size must include overlapping. An overlapping of 50 cells per side is reasonable, so, each part should contain around 300x300 cells of the global map.

The wind fields obtained from the global map and the partitioned one has been compared. To carry out this comparison the measures has been used to estimate the difference. These measures are:

1. The RMSE (Root Mean Square Error) that is a statistical measure of the difference in the wind speed (or direction) among the wind obtained in both cases for each cell. The main problem of such value is that it does not include information about the deviation of the differences.
2. The number of cells with an error higher than a particular values (1 mph for wind speed). This measure shows the points of the map where the differences are larger than this reference value.
3. The maximum difference value along the whole map.

Table 1 summarizes the differences obtained for a particular map of 1500x1500 cells considering different meteorological wind speed and different partitioning methods.

Figure 5 shows in red the points of the terrain map where the difference in wind speed in both fields is larger than 1mph. It can be observed that this points are concentrated on the map zones with abrupt slope change. But, this points are not so much. The point with a wind direction difference larger than $5°$ are approximately the same.

WindNinja parallelization by map partitioning is a feasible approach that significantly reduce execution time and memory requirements. But, as it has been shown there is a difference among the wind field obtained from a global map and a partitioned one. So, the next point to analyze is the influence of these wind field differences on the forest fire spread prediction. Therefore, an experimental study

Table 1. Similarity indexes for different partitioning methods

Speed (mph)	Partitioning	$RSME_{sp}$ (mph)	Speed ≥ 1 (mph)	Max_{sp} (mph)
5	5x5	0.187	7818	3.76
5	15x15	0.250	16369	4.16
10	5x5	0.373	49565	7.50
10	15x15	0.499	102412	8.33
15	5x5	0.559	140826	11.30
15	15x15	0.749	258006	10.20

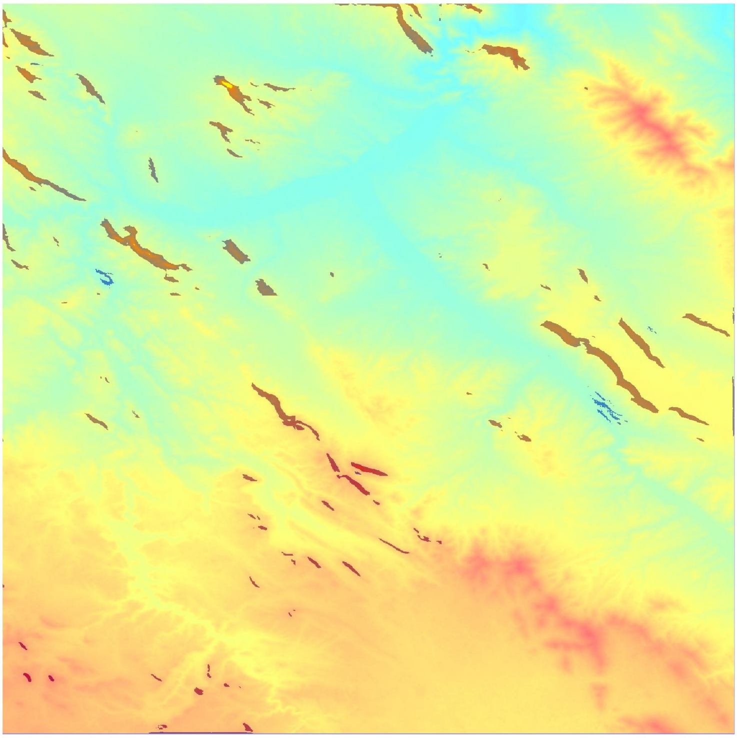

Fig. 5. Points with wind speed difference higher than 1mph

has been carried out to determine such effect using different terrain maps, different ignition points and different meteorological wind conditions. The experiments and the results obtained are described and analysed in the following section.

4 Effect of Map Partitioning on Forest Fire Spread Prediction

As it has been stated in previous section map partitioning does not generate extreme differences in wind fields, but it necessary to analyse the influence of such differences in forest fire spread prediction. To carry out such analysis it is necessary to execute a lot of propagation simulations considering maps with different topography terrains, different wind conditions, different vegetation types, different canopy covert and different fire positions. So, different terrain maps corresponding different areas of Spain has been selected. The raster maps used are composed by 1500 rows and 1500 columns with 30m resolution per cell. That means that the map has a dimensions of 45km x 45km.

The experiments have been executed in a DELL cluster based on Poweredge C6145 with a total of 8 CPUs with 16 cores per node and 128 GB of memory.

For comparison purpose, the propagation predicted by FARSITE has been obtained applying three different WindNinja configurations:

1. Global map WindNinja wind field: In this case the wind field is calculated from a global map. No partitioning is applied.
2. 5x5 Map partitioning wind field. The global map is partitioned in 25 parts. Each part is composed of 400x400 cells with an overlapping of 50 cell for each side.
3. 15x15 Map partitioning wind field. The global map is partitioned in 75 parts. Each part is composed of 200x200 cells with an overlapping of 50 cell for each side.

To generate the set of experiments the 4 more common vegetation types (brush, grass, conifer and rough), 3 wind directions (45, 180 and 270 degrees), 3 wind speeds (5, 10 and 15 mph) and 3 ignition point positions (over, near, far) have been considered to cover a wide range of combinations.

The difference among the predicted burned area using different WindNinja configurations is estimated by applying a fitness function expressed by equation (3). This equation calculates the difference in the number of cells burnt between the predicted area by 2 different WindNinja configurations. In this case, the area predicted using a global map wind field (GMWF) is used as reference propagation. Formally, this equation corresponds to the symmetric difference between the global map wind field area (GMWF) and the partitioned map (5x5WF or 15x15WF) divided by the GMWF area, so as to express a proportion. $\cup$(GMCell,PCell) is the union of the number of cells burned in the GMWF and the cells burned in the partitioned map, $\cap$(GMCell,PCell) is the intersection between the number of cells burned in the GMWF propagation and in the partitioned map wind field, and GMCell is the number of cells burned using Global map wind field.

$$D=\frac{\cup(\text{GMCell},\text{PCell}) - \cap(\text{GMCell},\text{PCell})}{\text{GMCell}} \qquad (3)$$

Tables 2, 3 and 4 show the difference on burned areas for different types of vegetation and different map partitioning considering a meteorological wind of 15mph and a direction of 45°. This meteorological wind has been considered because it is the wind that generate larger differences in wind field.For each configuration, the evolution of such difference according to simulation time is

Table 2. Difference for ignition points over different wind zones

	Over error 5x5					Over error 15x15				
t (h)	Brush c10	Conifer c10	Conifer c50	Grass c10	Rough c10	Brush c10	Conifer c10	Conifer c50	Grass c10	Rough c10
6	0.134	0.173	0.174	0.129	0.111	0.166	0.210	0.205	0.162	0.141
8	0.130	0.152	0.144	0.112	0.089	0.162	0.189	0.175	0.143	0.117
12	0.114	0.128	0.139	0.112	0.067	0.144	0.162	0.167	0.144	0.092
24	0.080	0.213	0.103	0.360	0.240	0.114	0.353	0.128	0.402	0.420

Table 3. Difference for ignition points near different wind zones

	Near error 5x5					Near error 15x15				
t (h)	Brush c10	Conifer c10	Conifer c50	Grass c10	Rough c10	Brush c10	Conifer c10	Conifer c50	Grass c10	Rough c10
6	0.047	0.043	0.023	0.082	0.050	0.068	0.061	0.023	0.111	0.068
8	0.051	0.041	0.040	0.070	0.051	0.072	0.057	0.048	0.096	0.069
12	0.052	0.049	0.029	0.069	0.051	0.076	0.052	0.032	0,095	0.067
24	0.063	0.035	0.022	0.072	0.051	0.073	0.047	0.029	0.096	0.069

Table 4. Difference for ignition points far from different wind zones

	Far error 5x5					Far error 15x15				
t (h)	Brush c10	Conifer c10	Conifer c50	Grass c10	Rough c10	Brush c10	Conifer c10	Conifer c50	Grass c10	Rough c10
6	0.035	0.028	0.040	0.032	0.032	0.037	0.030	0.040	0.033	0.034
8	0.037	0.040	0.000	0.028	0.028	0.038	0.038	0.001	0.028	0.029
12	0.034	0.032	0.028	0.029	0.023	0.034	0.033	0.029	0.029	0.026
24	0.037	0.028	0.043	0.025	0.013	0.038	0.030	0.040	0.026	0.014

shown. In particular, table 2 shows the results considering fire ignition points over terrain zones with a wind speed difference larger than 1mph, table 3 shows the results considering fire ignition points near the terrain point with differences larger than 1mph (it means that at some point of the propagation the fire front crosses that zones) and table 4 shows the results considering fire ignition points far from those different wind speed zones (it means that the fire front does not cross those zones).

From the experiments carried out it can be observed that as the number of parts is increased, the error increases proportionally to that number of parts. This is due to the fact that the wind field generated when the parts are very small has a larger difference from the global map wind field and this larger differences provoke larger differences in fire spread predicted area.

On the other hand, it can be observed, as it was expected, that the position of the fire is very significant. If the fire does not cross points with significant wind speed difference the spread area difference is negligible. When the fire ignition point is on large wind speed difference zones the difference in burned area is larger, but not extremely different. This results are also presented in figures 6,

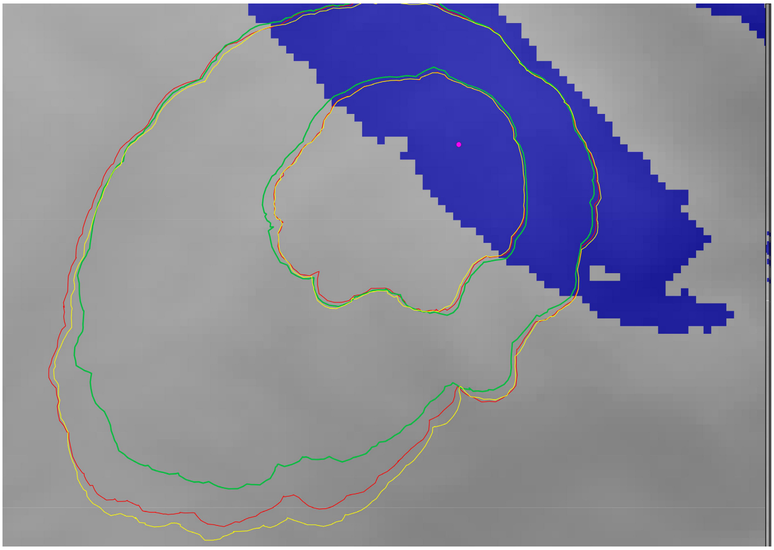

Fig. 6. Fire perimeters with ignition point over wind difference zones

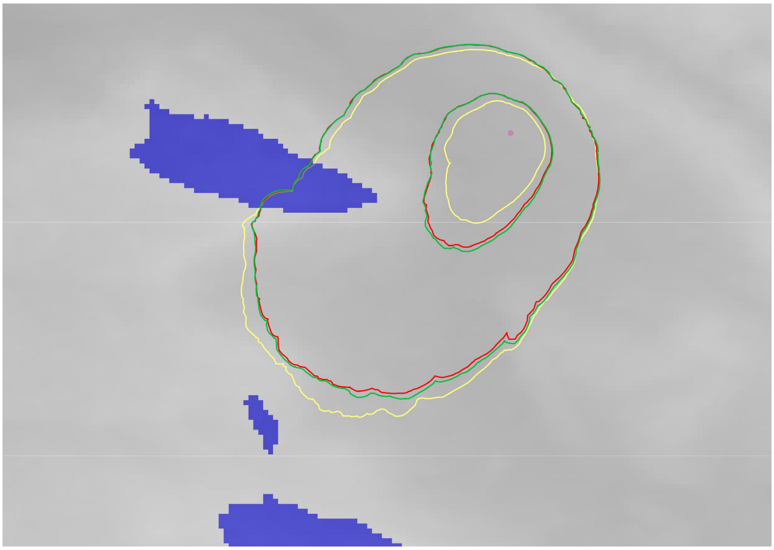

Fig. 7. Fire perimeters with ignition point near wind difference zones

7 and 8 that present an example of each one of the ignition point situation. In these figures the blue dots represent the zones with large wind speed difference, the yellow perimeter represents the Global Map Wind Field fire propagation, the red one represents the partitioning 5x5 map wind field fire propagation and

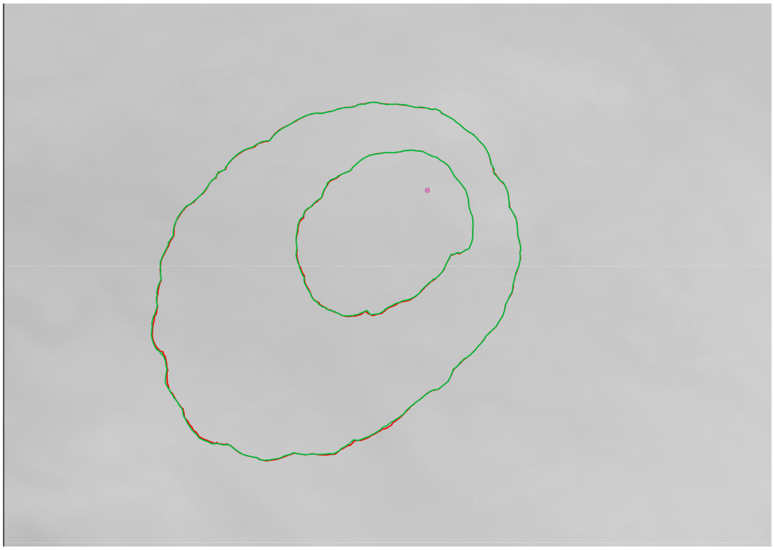

Fig. 8. Fire perimeters with ignition point far wind difference zones

Table 5. Execution time

Vegetation	GMWF (s)	5x5P (s)	15x15P (s)	FARSITE (s)
Brush	750	40	10	50
Conifer c10	750	40	10	51
Conifer c50	750	40	10	26
Grass	750	40	10	1725
Rough	750	40	10	163

the green one the partition 15x15 map wind field fire propagation. In figure 8 it can be observed that there is no appreciable difference among the three perimeters. However, figures 6 and 7 show a small difference that is increased when the partitioning divides the map in more parts. It must be considered that the shown results were obtained considering that the fire only cross a large difference zone, but if there are several of such large difference zones on the fire area, differences in fire propagation prediction will be larger since the effects are accumulative.

Another important measure is the execution time of the wind field calculation and the fire spread simulation. The average execution obtained from our experiments are shown is table 5. It can be observed that the execution time of a global map wind field takes 750 seconds for all the terrains and the map partitioning is a very effective measure since it reduces WindNinja execution time to 40 (5x5) or 10 seconds (15x15). On the other hand it can be observed that FARSITE execution time is very dependable from each particular scenario conditions [2].

5 Conclusions

Wind is a parameter that significantly affects fire propagation. However, meteorological wind is not a feasible estimation since wind is significantly modified by terrain topography. Therefore, it is necessary to introduce wind field models that calculate the wind at each point of the terrain given a meteorological wind and a terrain map. These wind field models are time consuming models when terrains maps are large and the time incurred can make unfeasible the use of such simulators. Therefore, a map partitioning approach has been introduced to generate wind fields faster. However, the wind fields obtained from map partitioning are lightly different from those obtained from a global map. So, it is necessary to study the influence of such differences on forest fire spread propagation. The experiments carried out show that the difference in fire spread prediction is not very significant and only when the fire crosses zones with a larger wind value difference the fire spread prediction is lightly different, but in any case it is not relevant to determine fire tendency.

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