New Stochastic Simulator for Fire Forest Management

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Fire Growth Model: Prometheus Simulator

Prometheus

is a deterministic wildland fire growth simulation model based on the Fire Weather Index (FWI) and Fire Behaviour Prediction (FBP) sub-systems of the Canadian Forest Fire Danger Rating System (CFFDRS). The model computes spatially-explicit fire behaviour and spread outputs given heterogeneous fuel, topography and weather conditions.

General Characteristics:

- It is based on FBP System, a series of mathematical equations relating fire characteristics to wind, fuel moisture, and topographic conditions for 16 benchmark fuel (vegetation) types, used to predict the behaviour, during a single burning period, of a fire spreading from a single point or line.
- It is based on wave propagation equations developed by Richards (1990, 1993, 1995, 1999).

Fire Growth Model: Prometheus Simulator

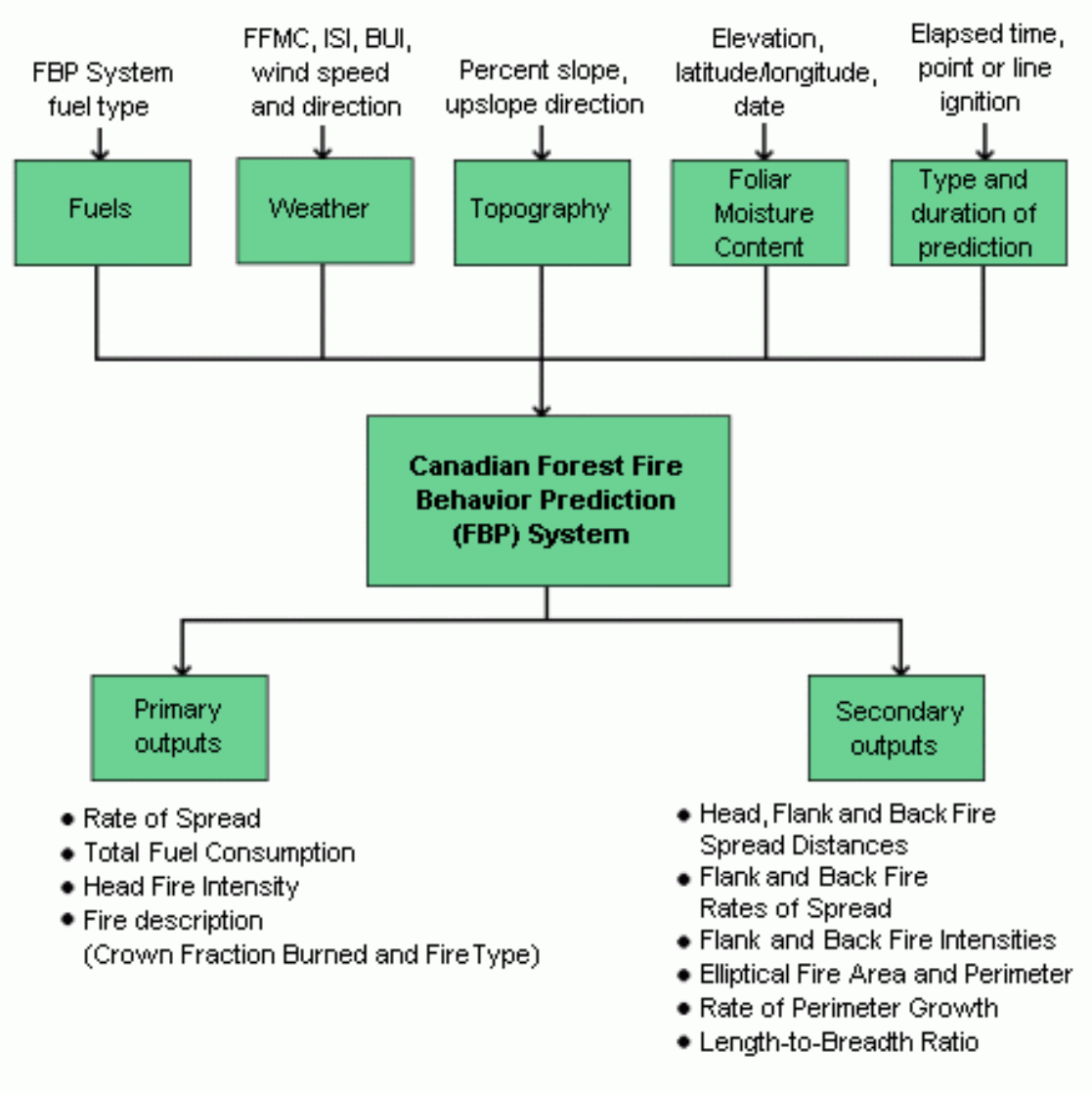


Figura: FBP System

Prometheus Simulator

- Inputs:
  1. FBP Fuel Type: fuel lookup table.

grid_value	export_value	descriptive_name	fuel_type	r	g	b	h	s	l
1	1	Spruce-Lichen Woodland	C-1	209	255	115	57	255	185
2	2	Boreal Spruce	C-2	34	102	51	95	128	68

  2. Landscape Grid:
     1. FBP Fuel Grid: fbp_fuel_type.asc

ncols	357				
nrows	223				
xllcorner	457900				
yllcorner	5716800				
cellsize	100				
NODATA_val	-9999				
101	101	101	101	101	101
31	31	101	101	31	31
31	31	31	31	101	101
31	31	31	31	31	31
31	31	31	31	31	31

     2. Elevation Grid: elevation.asc
     3. Degree of Curing Grid: degree_of_curing.asc
  3. Ignitions: Ignitions point: ignition_point_20011016_1300.kmz
  4. Physical Features:
     1. Access gravel road: access_gravel_road.kmz[1]
     2. Access unimproved road: access_inimproved_road.kmz
     3. Hydrology river: hydrology_river.kmz
     4. Hydrology stream: hydrology_stream.kmz
  5. Weather Stream: weather_B3_hourly_20010925to1030_2001_orig.csv

HOURLY	HOUR	TEMP	RH	WD	WS	PRECIP
25-09-01	0	2.5	94	90	2	0
25-09-01	1	1.1	96	90	2	0

[1] KMZ es a file extention for a placemark used by Google Earth.

Prometheus Simulator

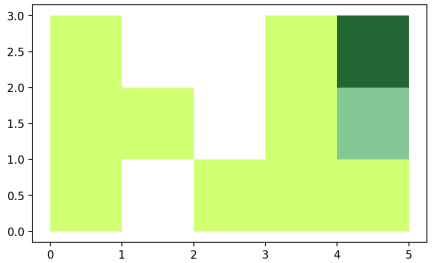
Main Outputs

1. Scenario Report
2. Fire Perimeter
3. Grid Outputs
   1. Burn Grid: **0-1 cells. if the value of the cell is 1, then the cell burned. Otherwise, the cell survived the fire.**
   2. Flam Length Grid (meters)
   3. ROS (m/min)
   4. FROS (m/min)
   5. BROS (m/min)
   6. RAZ (º)
   7. etc

Test Instances

We have built several instances to test our simulator.

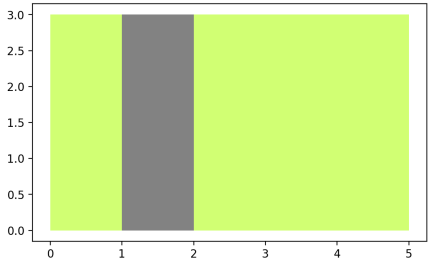
- Instances:
  - 15CellsHet_Water



1	-9999	-9999	1	2
1	1	-9999	1	3
1	-9999	1	1	1

Figura: FBP Fuel Grid for 15CellsHet_Water

  - 15CellHom_Water



1	101	1	1	1
1	101	1	1	1
1	101	1	1	1

Figura: FBP Fuel Grid for 15CellsHom_Water

Test Instances

- Artificial Instances:
  - 15CellsHet_Water
  - 150CellsHom_Water
  - 400CellsHet
  - 400CellsHom
  - 2500CellsHom
- Real instances
  - Dogrib
    - Dogrib_original
    - Dogrib_East
    - Dogrib_North
    - Dogrib_South
    - Dogrib_West

New Stochastic Simulator

- It's based on the FBP system.
- Inputs: Same of the Prometheus simulator and others.
- Parameter that change to provide it a stochastic nature. Random numbers are chosen: $\alpha_i \in U\left(\underline{\alpha}_i, \overline{\alpha}_i\right)$, $i = 1, ..., 5$. This is not strict.
  - $WindSpeed_t = WindSpeed_{t-1}\left(1 + \alpha_1\right)$.
  - $WindDirection_t = WindDirection\left(1 + \alpha_2\right)$.
  - $Temperature_t = Temperature_{t-1}\left(1 + \alpha_3\right)$.
  - $DewPoint_t = DewPoint_{t-1}\left(1 + \alpha_4\right)$.
  - $Rain_t = Rain_{t-1}\left(1 + \alpha_5\right)$.
- Important Functions:
  - $sendmsg(Period, Weather, AvailSet)$: A cell will send messages to its adjacent cells only if some conditions are satisfied:
    - ★ Wind Speed $\geq$ WST
    - ★ Temperature $\geq$ TMT
    - ★ Precipitation $\geq$ RNT
    - ★ Radiation $\geq$ RDT
    - ★ Net effective wind speed (WSV) $\geq$ WST
    - ★ Surface fire rate of spread (RSS) $\geq$ RSST
    - ★ Rate of spread (RSO) $\geq$ RSOT
  - $gotBurnt\left(Period, Weather, NMsg\right)$: Based on the number of messages (with at least 1 msg) weather and cell characteristics, determine if the cell gets burnt.

New Stochastic Simulator

Several points are important:

1. A cell sends messages to its available adjacent cells if two conditions are satisfied:
   1. Weather conditions of above (in blue).
   2. FBP conditions of above (in red).
   3. Time decay factor:

$$psm = P\left(cell_t\left(j\right) = 1 \mid cell_s\left(i\right) = 1\right) = e^{-(t-s-1)/3}.$$

Available adjacent cells is defined in function of Wind Direction.

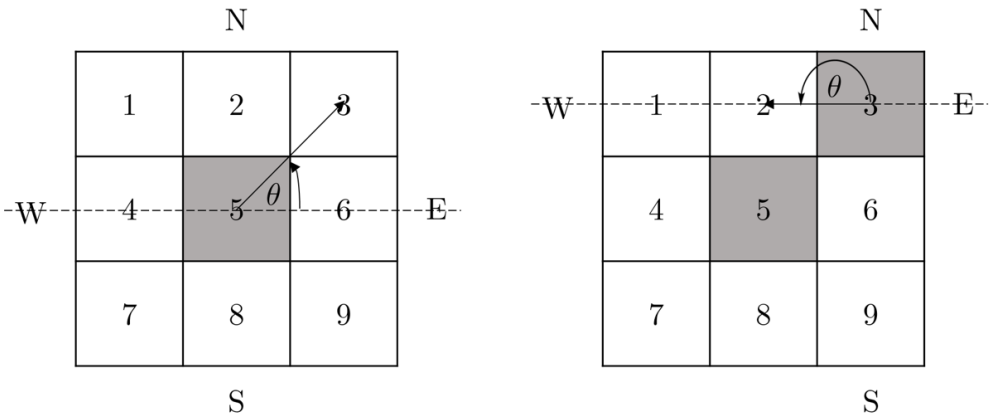


Figura: Adjacent cells

New Stochastic Simulator

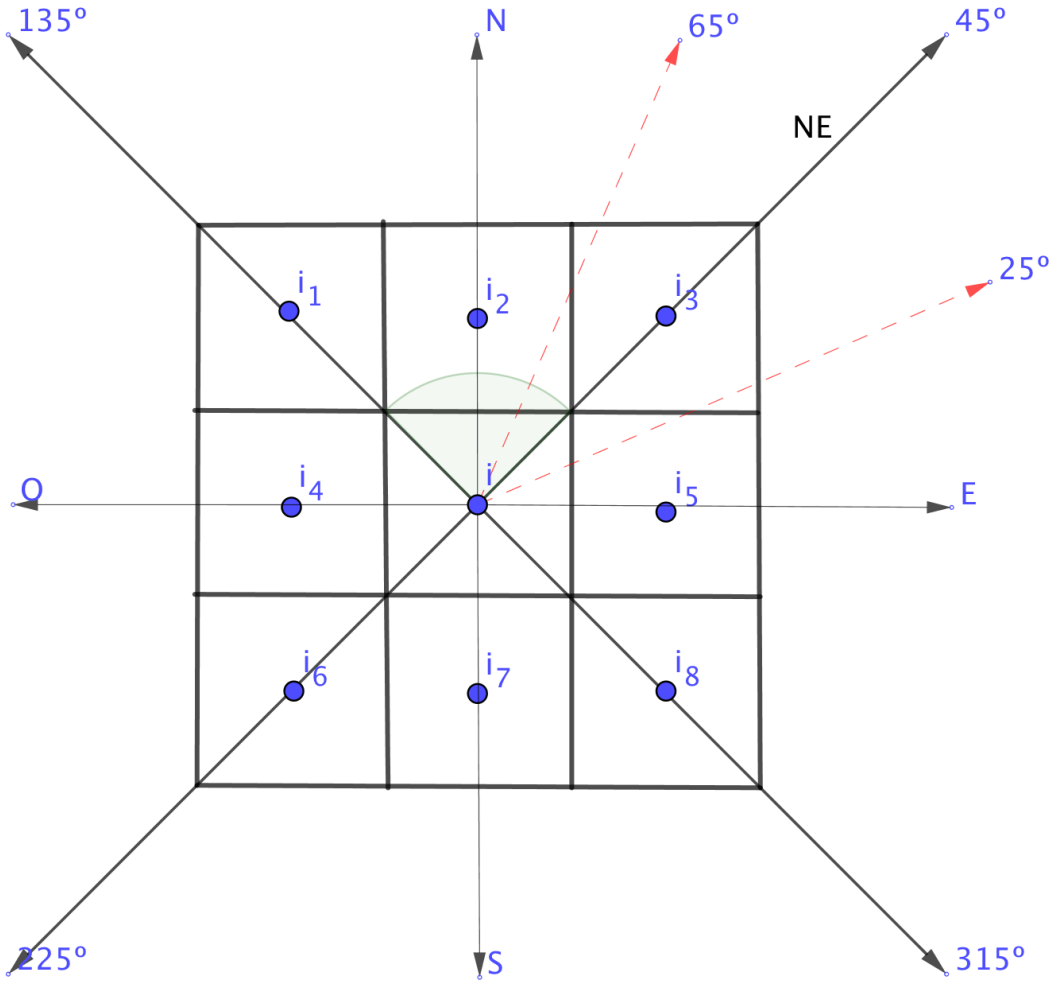


Figura: Adjacent cells

NewStochSim Pseudocode

The *cell* (j) that receives message is burned if:

1. Weather conditions is satisfied
2. If *cell* (j) is 'burnable'.
3. If its age is greater than a threshold (This is not strict).
4. The number of message is greater than 2.

If these conditions are not satisfied, then in order to add more randomness, it is allowed a second chance to be burn:

$$\beta \leq 0{,}8, \; where \; \beta \in U\,(0,1)$$

- RAZ = Net effective spread direction
- WSV = Net effective wind speed, based on the influence of both wind and slope
- RSO = Rate of spread
- RSS = Surface fire rate of spread

Notations

Weather Conditions:

$$WeatherConds_t = \begin{cases} 1 & \text{if } WS_t \geq WST,\ TM_t \geq TMT,\ PR_t \leq PTR \\ 0 & otherwise \end{cases}$$

$$FBPconds_t\,(i) = \begin{cases} 1 & WSV_t\,(i) \geq WST, RSS_t\,(i) \geq RSST, ROS_t\,(i) \geq ROST \\ 0 & otherwise \end{cases}$$

$$TimeDacayConds_t\,(i) = \begin{cases} 1 & \alpha \leq e^{-(t-s-1)/3} \\ 0 & otherwise \end{cases}, \alpha \in U\,(0,1)$$

$$AdjCells1_t\,(i) = \begin{cases} \{i_1, i_2, i_3\} & WD_t \in (45^{\underline{o}}, 135^{\underline{o}}) \\ \{i_1, i_4, i_6\} & WD_t \in (135^{\underline{o}}, 225^{\underline{o}}) \\ \{i_6, i_7, i_8\} & WD_t \in (225^{\underline{o}}, 315^{\underline{a}}) \\ \{i_3, i_5, i_8\} & WD_t \leq 45^{\underline{o}} \text{ and } WD_t \geq 315^{\underline{o}} \end{cases}$$

New Stochastic Simulator

We define the following

$$AdjCells2_t\left(i\right) = \begin{cases} \{i_3\} & WD_t \in (25^{\underline{o}}, 65^{\underline{o}}) \\ \{i_1\} & WD_t \in (115^{\underline{o}}, 155^{\underline{o}}) \\ \{i_6\} & WD_t \in (205^{\underline{o}}, 245^{\underline{o}}) \\ \{i_8\} & WD_t \in (295^{\underline{o}}, 335^{\underline{o}}) \end{cases}$$

The cell i sends messenge to cell j in t time if:

1. $WeatherConds_t = 1$ & $FBPconds_t\left(i\right) = 1$
   1. If $TimeDecayCond_t\left(i\right) = 1$

   Nivel 1 Its determined $AdjCells1_t\left(i\right)$ in function of WD_t
   Nivel 2 A new random is chosen and cell j is selected in $AdjCells2_t\left(i\right)$.

New Stochastic Simulator

Notations:

$$TypeConds_t(j) = \begin{cases} 1 & \text{if } Age_t(j) \geq AGT,\ Cell_t(j) \text{ is } 'burnable' \\ 0 & otherwise \end{cases}$$

The cell j that receives the message burns in t time if:

1. $WeatherConds_t = 1$ & $TypeConds(j) = 1$
   1. If $NumMessages_t(j) \geq NMT$
   2. else-if $\beta \leq 0{,}8$ $(\beta \in U(0,1))$
2. $WeatherConds_t = 0$ & $TypeConds(j) = 1$
   1. if $\gamma \leq 0{,}2$ $(\gamma \in U(0,1))$

Comparative Analysis

Methodology

1. Choose a ignition point for each instance and run on Prometheus. Output: $BurnGrid^0$ (0-1 Cells Matrix).
2. Choose the same ignition point as above and then run NewStochFire 100 times from this point. Outputs: $BurnGrid^k$, $k = 1, ..., 100$.
3. Set $X = BurnGrid^0$ and $Y^k = BurnGrid^k$ and Calculate for all k:
   1. Mean Squared Error:
   $$MSE\left(X, Y^k\right) = \frac{1}{nm}\sum_{i=1}^{n}\sum_{j=1}^{m}\left|X_{ij} - Y_{ij}^k\right|^2.$$
   2. Structural similarity Measure:
   $$SSIM\left(X, Y^k\right) = \frac{\left(2\mu_X\mu_Y + C_1\right)\left(2\sigma_{XY} + C_2\right)}{\left(\mu_X^2 + \mu_Y^2 + C_1\right)\left(\mu_X^2 + \mu_Y^2 + C_2\right)}.$$
   3. Correlation:
   $$Corr(X, Y^k) = \frac{\sum_i\sum_j\left(X_{ij} - \overline{X}\right)\left(Y_{ij}^k - \overline{Y}\right)}{\sqrt{\sum_i\sum_j\left(X_{ij} - \overline{X}\right)^2\sum_i\sum_j\left(Y_{ij}^k - \overline{Y}\right)^2}}.$$
4. Measures analysis: Histograms, etc. of the MSE, SSIM and Corr.
5. Change the ignition point and repeat steps 1,2,3 and 4.

Comparative Analysis

- 15CellsHet_Water

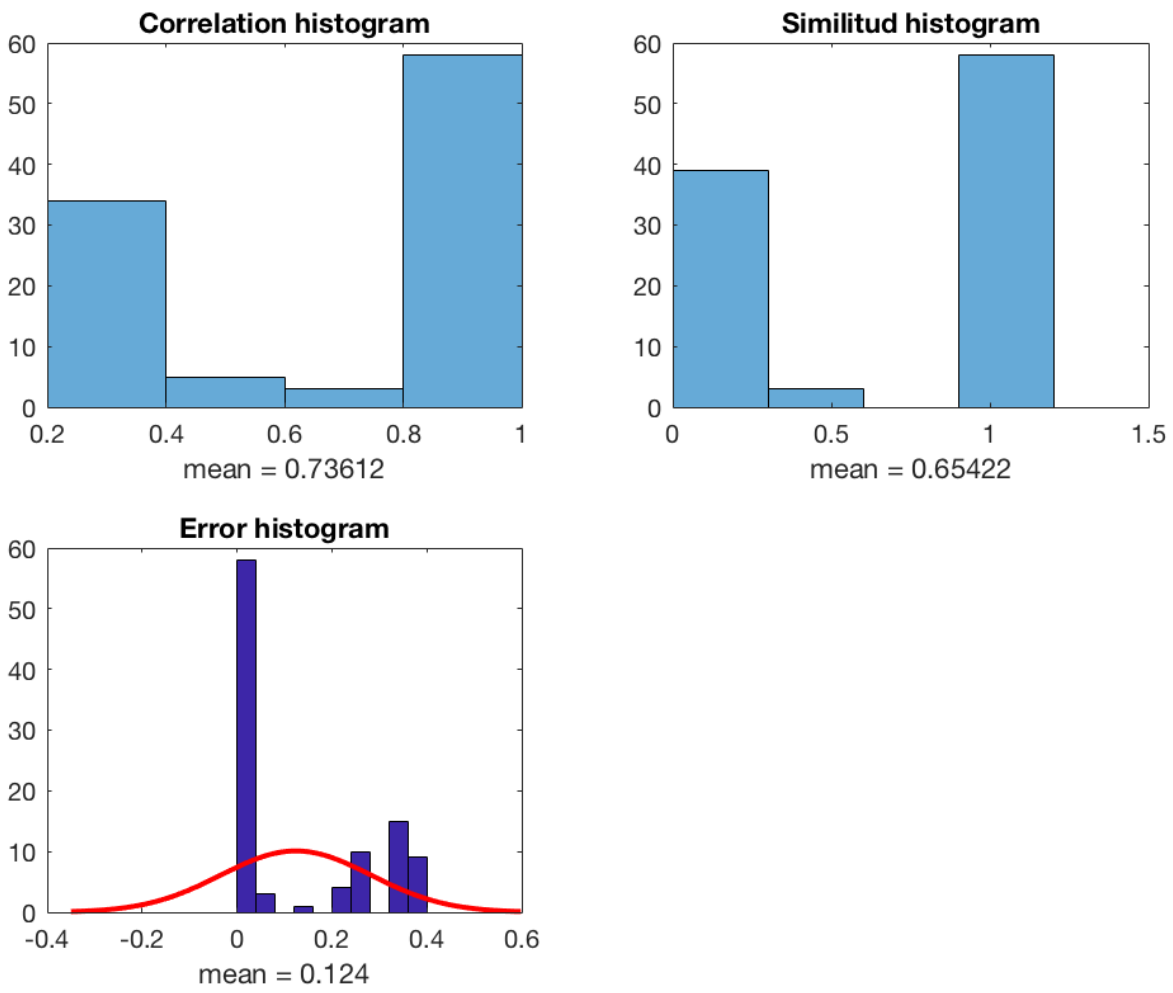


Figura: NewStochFire and Prometheus Comparison

Comparative Analysis

- 400CellsHom

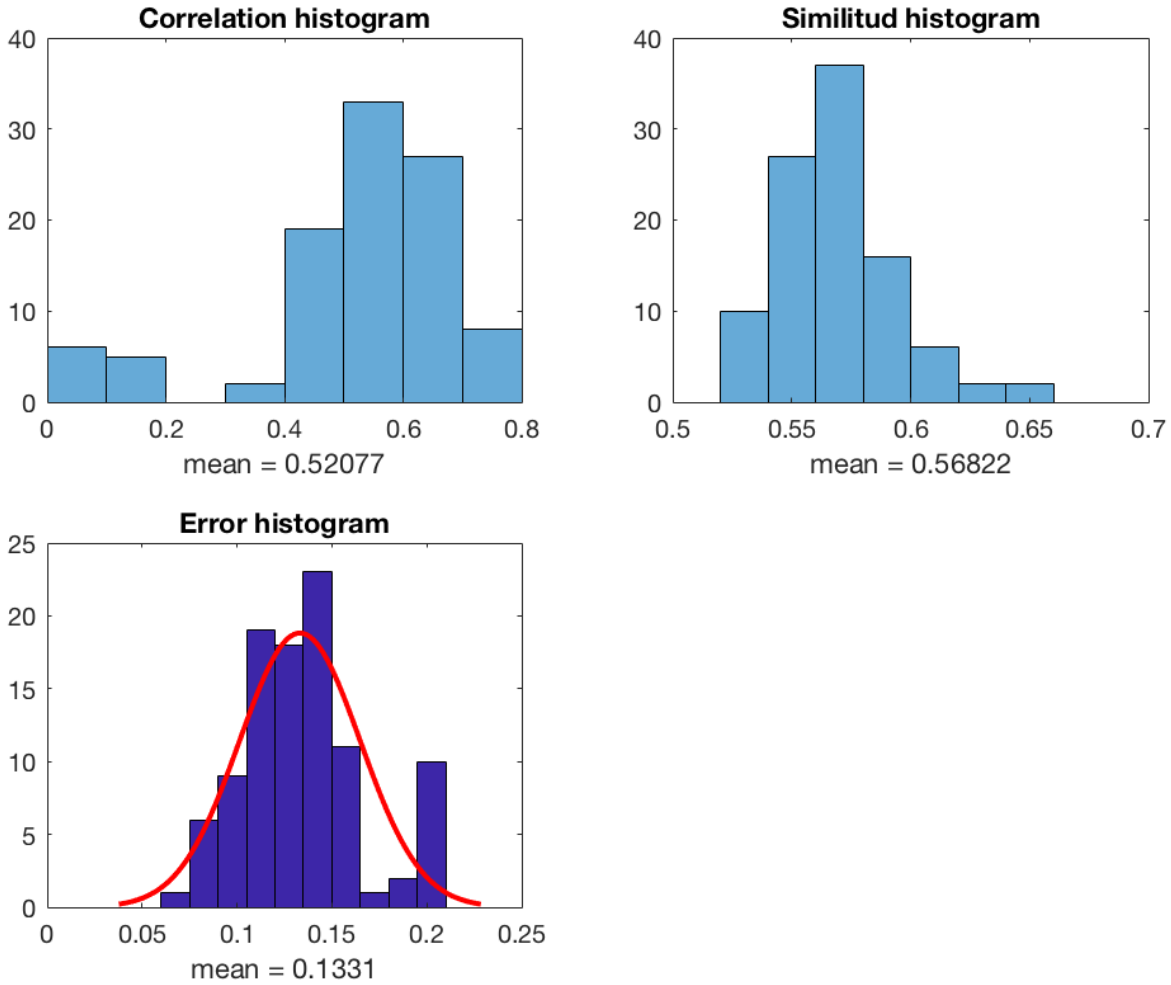


Figura: NewStochFire and Prometheus Comparison

Comparative Analysis

Dogrib Instance

- The Dogrib fire started on September 25, 2001 in the Rocky Mountain front ranges of southwest Alberta. Canada.
- The fire was detected late in the afternoon on September 29 and assessed early the next day at 70 ha in size. Fire fighting started early on October 1.
- The fire was 828 ha and out of control on October 15.
- A wind event resulted in a major fire run on October 16.
- Local terrain funnelled wind flow along the Red Deer River, and through a gap in the surrounding mountains.
- This pushed the fire east along the river valley.
- Local terrain funnelled wind flow along the Red Deer River, and through a gap in the surrounding mountains.
- The fire jumped the Red Deer River and a road and then resumed a northeast spread direction.
- The final fire size was 10,216 ha.
- The October 16 fire run accounted for 90 % of the total area burned and resulted in high to very high burn severities.

Comparative Analysis

Dogrib Instance

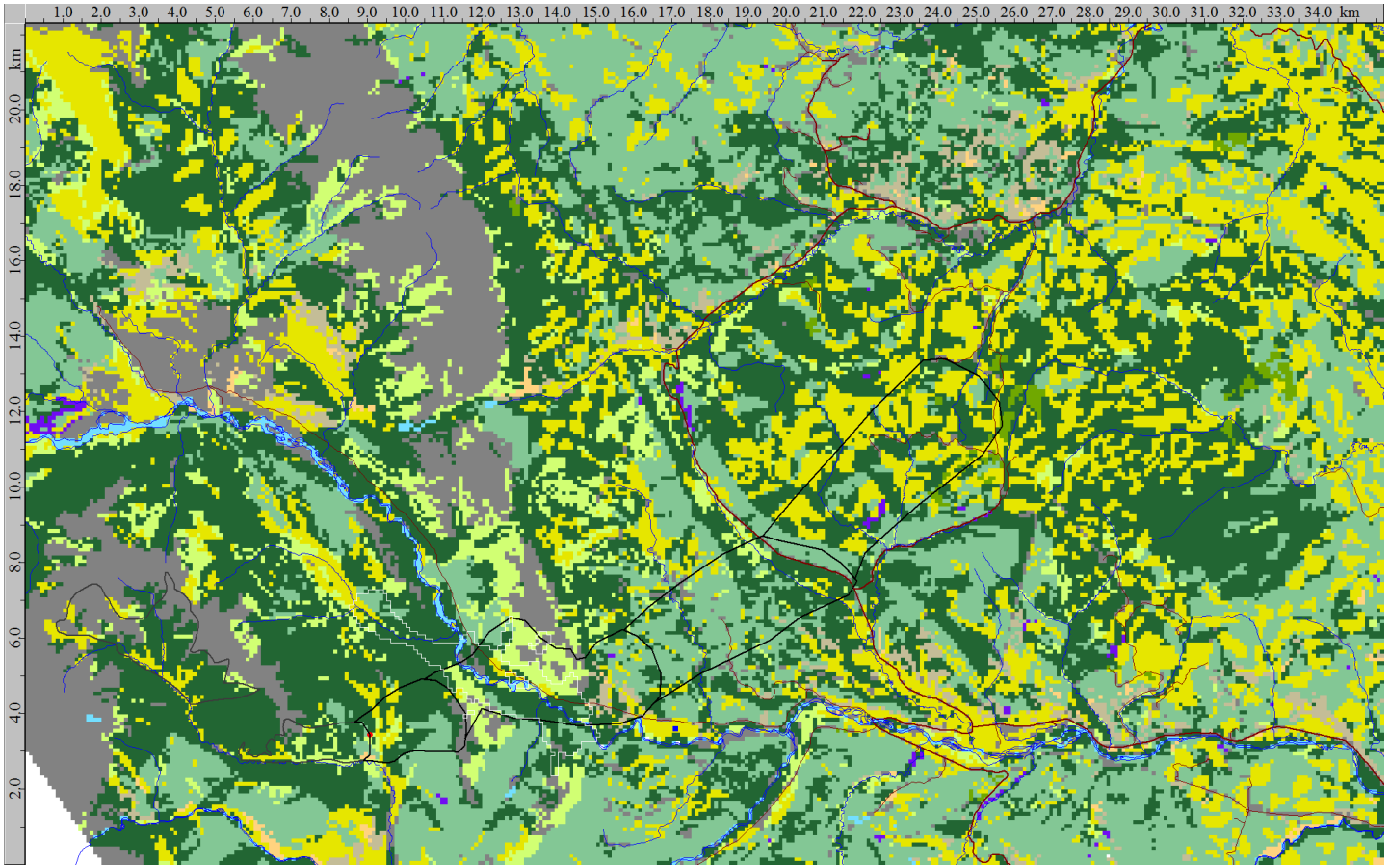


Figura: Dogrib map

Comparative Analysis

Dogrib Instance

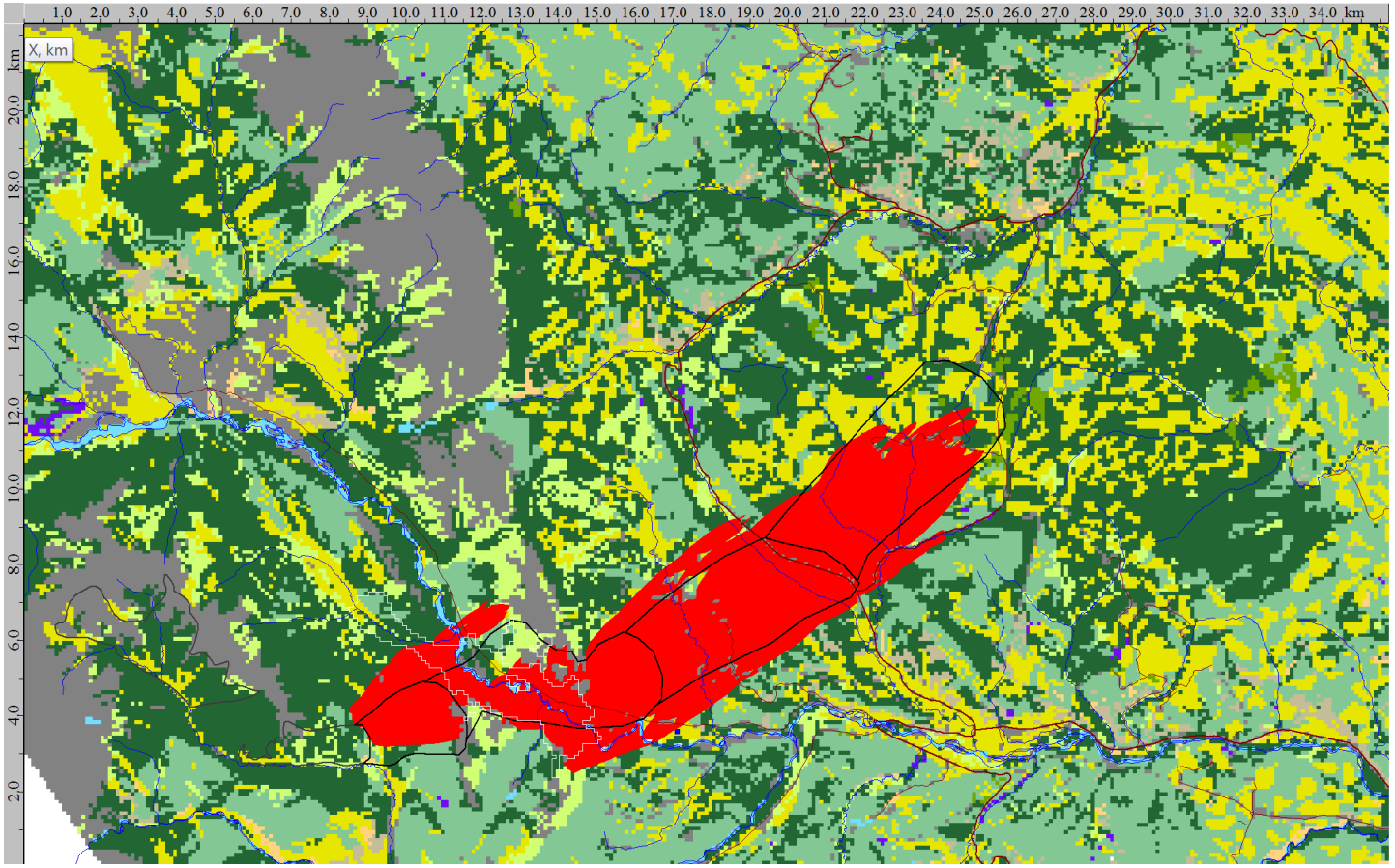


Figura: Dogrib Fire Simulated with Prometheus

Comparative Analysis

Dogrib Instance

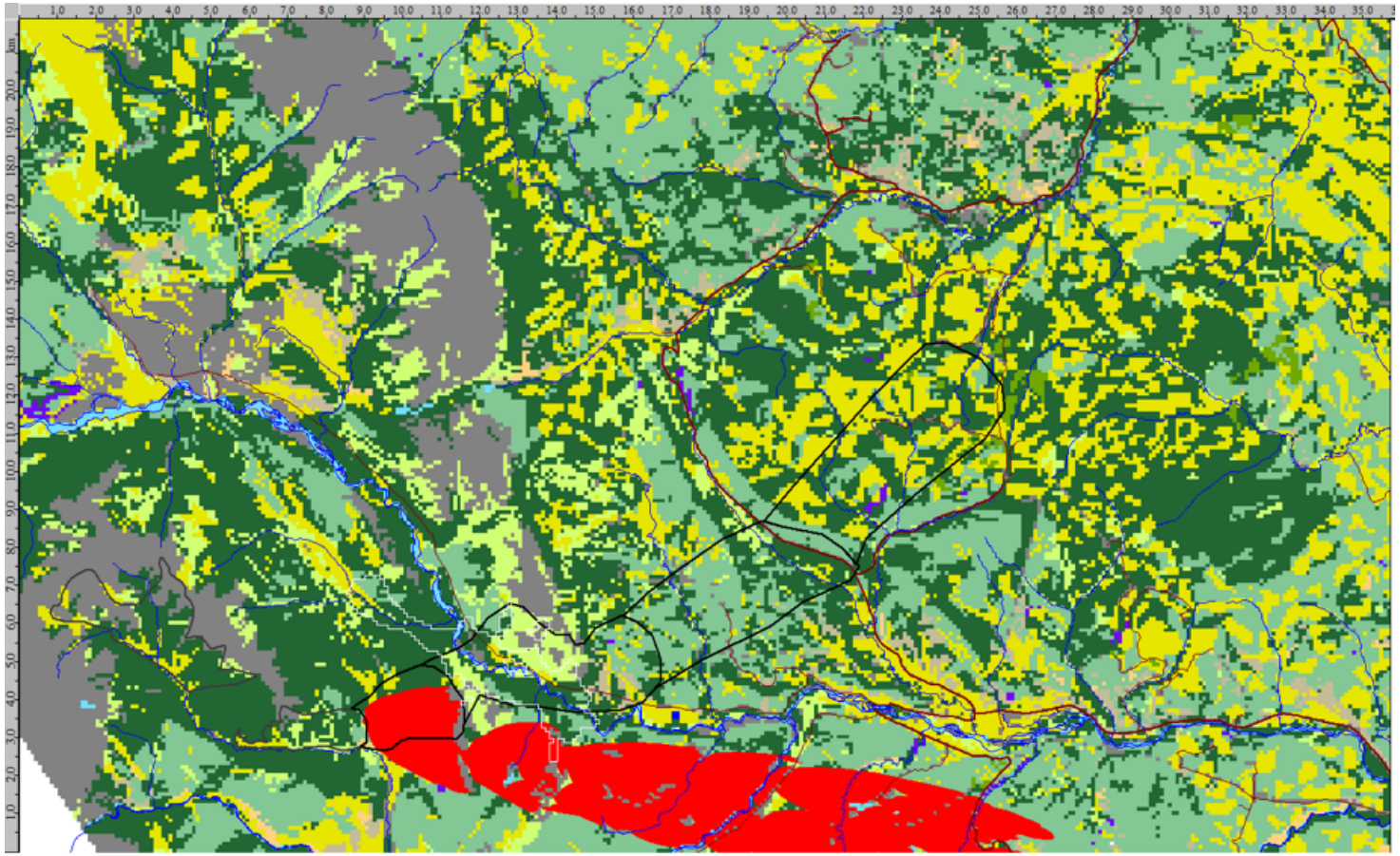


Figura: Dogrib_East

Comparative Analysis

Dogrib Instance

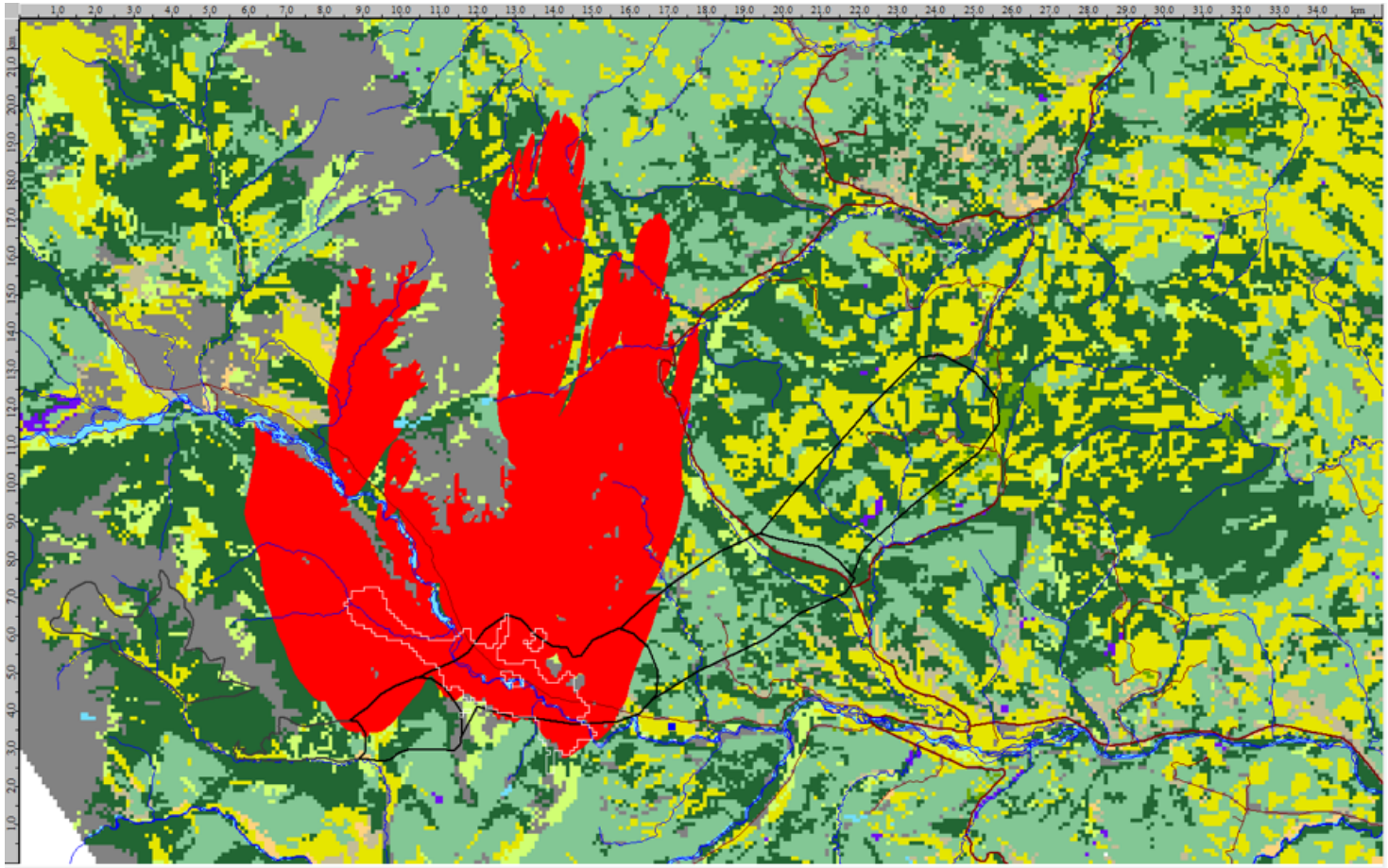


Figura: Dogrib_North

Comparative Analysis

Dogrib Instance

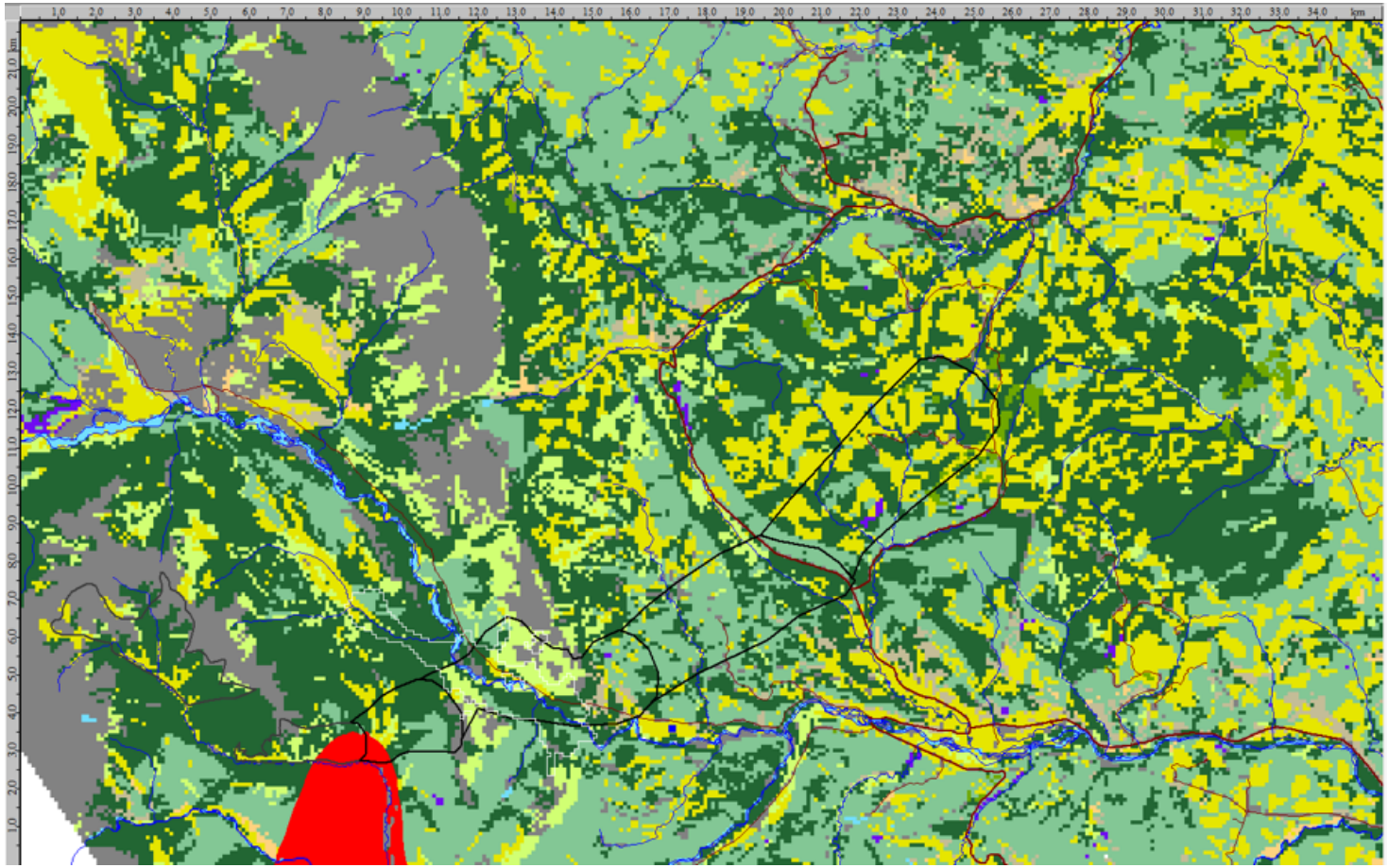


Figura: Dogrib_South

Comparative Analysis

Dogrib Instance

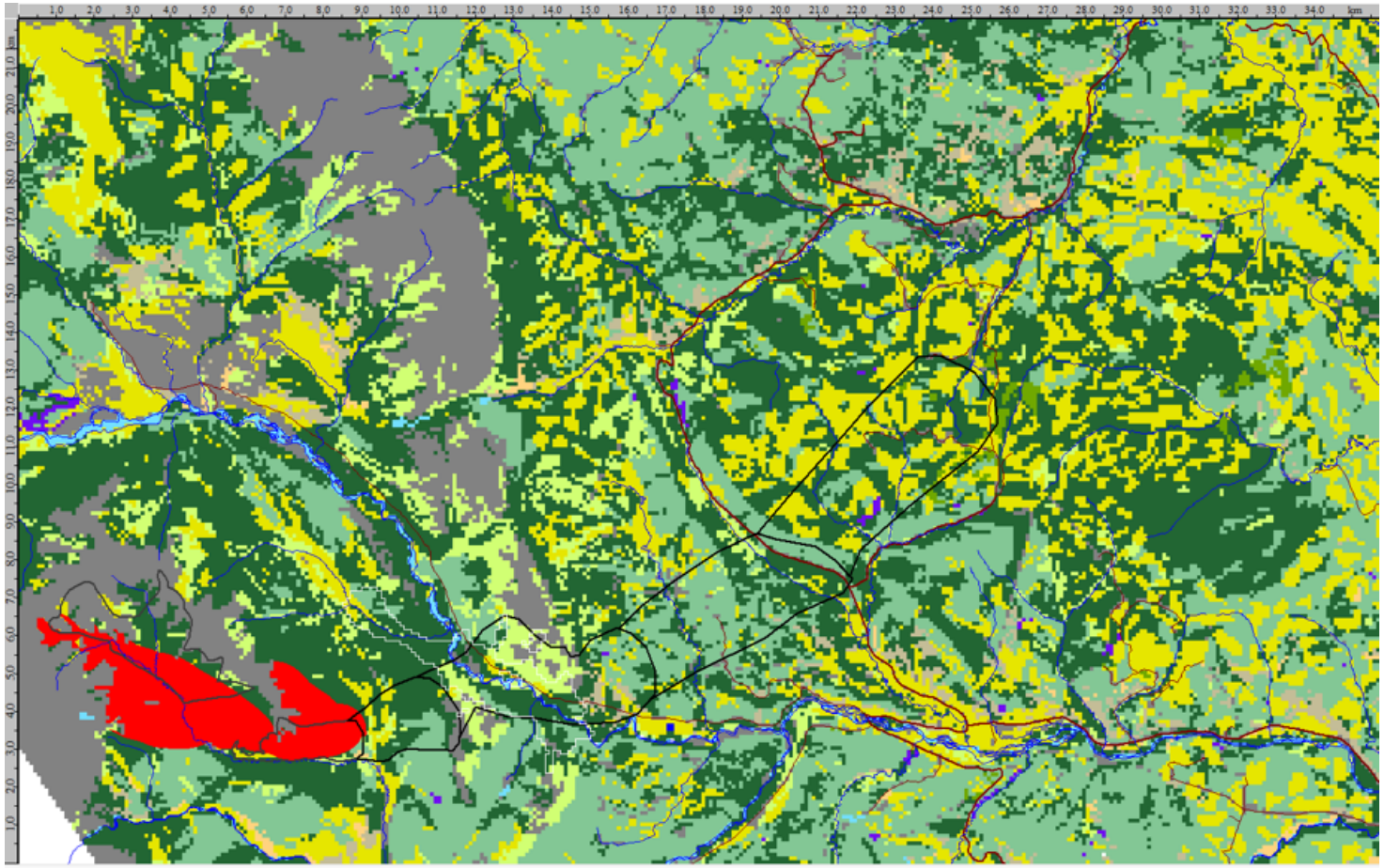


Figura: Dogrib_West

Comparative Analysis

Dogrib Instance

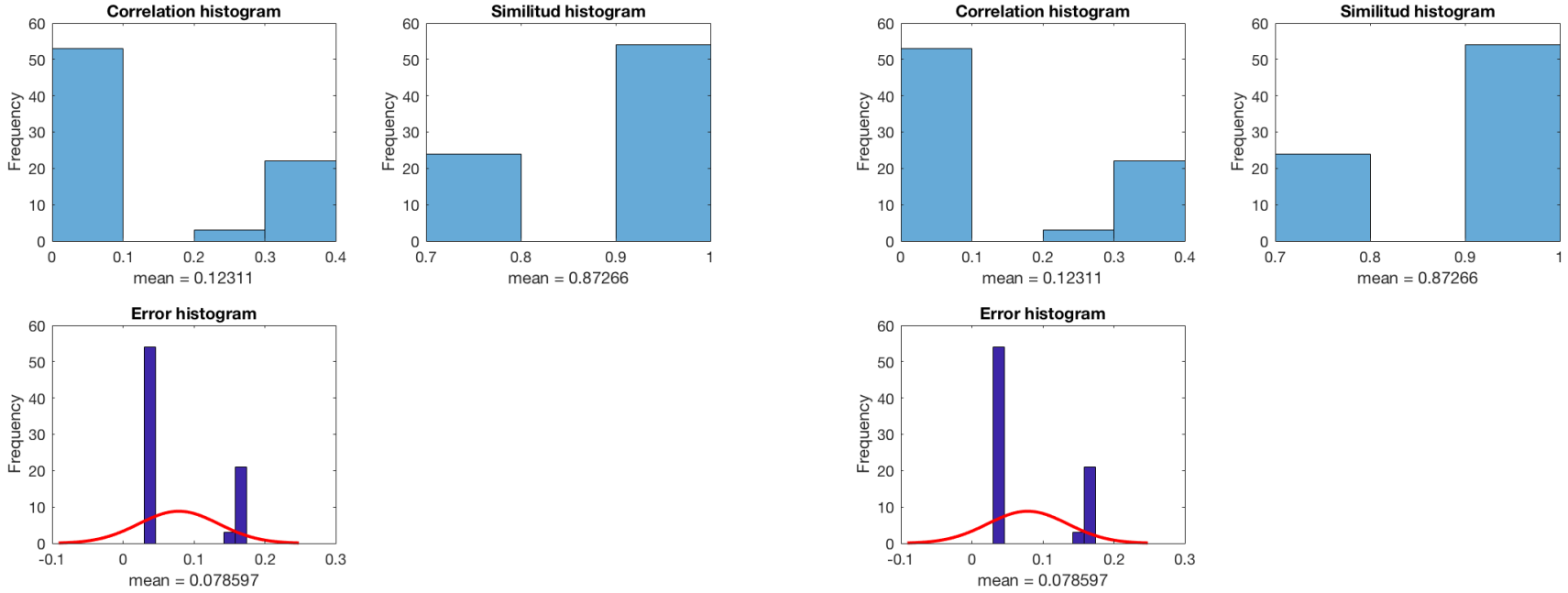


Figura: Dogrib East and West

Comparative Analysis

Dogrib Instance

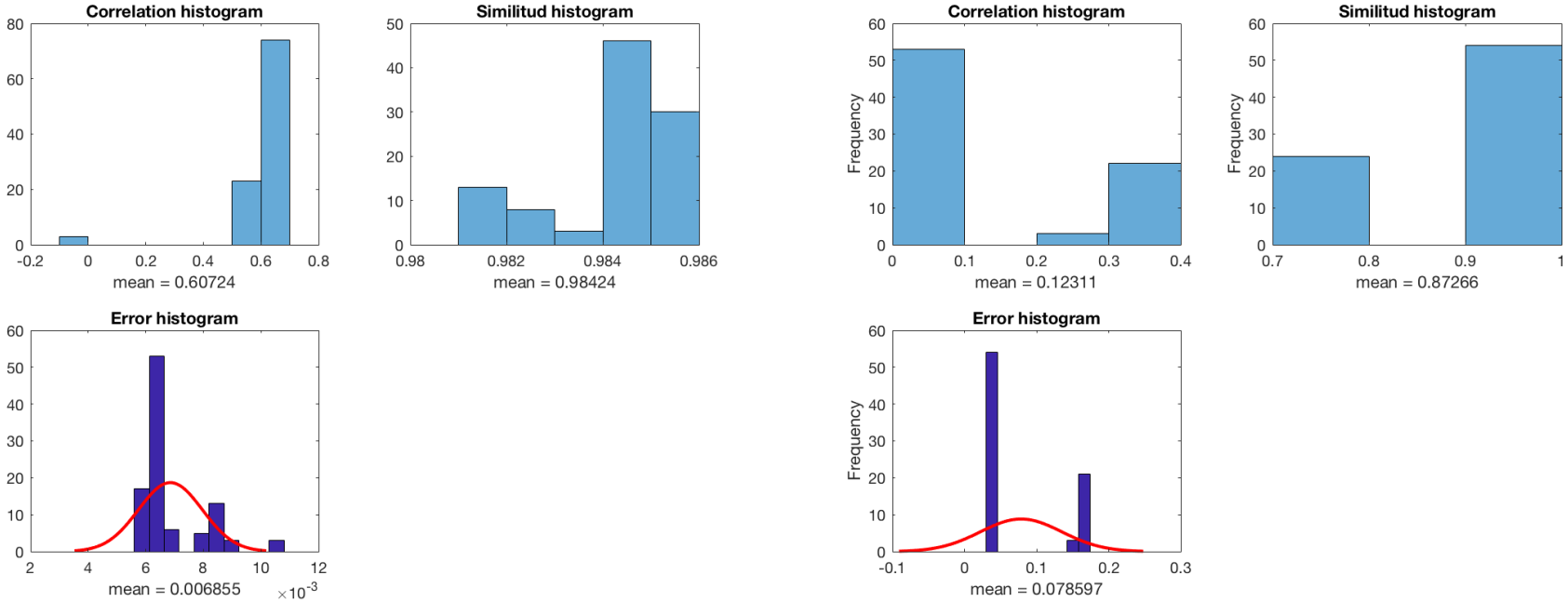


Figura: Dogrib South and North

Comparative Analysis

Dogrib Instance

Weather	MSE	Correlation	SSIM
Real	0.05	0.23	0.78
East	0.0786	0.1231	0.8727
North	0.1186	0.3436	0.8008
South	0.0069	0.6072	0.9842
West	0.0185	0.5806	0.9566

Cuadro: Comparison of results

Comparative Analysis

Qualitative differrences

1. Prometheus does not incorporate any aspect of randomness, so for same conditions, you get the same fire scar, to difference of NewStochSim.
2. Using Prometheus in order to incorporate some type of action in one or more cells, in different periods, is difficult (or maybe impossible) because changing the condition of a cell (in a next period) would change the input files, and the latter is a complex task (not automatic). In NewStochSim, in successive iterations, the cells change their condition automatically according to what happened previously.

New Stochastic Simulator

Technical aspects

NewStochSim still does not yet have a graphical interface, so it's worth showing how it works.

On Unix Systems (and Windows) it's recommended to use Anaconda for work with Python (2.7).

- Suppose the Simulator Files is found in the directory:
  - /Users/jaime/Google Drive/Dogrib/SimNameAugust2017/Simulator/CurrentVersionPython2.7
  - In order to work on directory, in the Unix Terminal is written:
    - **cd /Users/jaime/Google Drive/Dogrib/SimNameAugust2017/Simulator/CurrentVersionPython2.7** (and Enter):
    - If everything is going well, the following should be shown:

```
MacBook-Pro-de-Jaime:CurrentVersionPython2.7 jaime$ pwd
/Users/jaime/Google Drive/Dogrib/SimNameAugust2017/Simulator/CurrentVersionPython2.7
MacBook-Pro-de-Jaime:CurrentVersionPython2.7 jaime$ ls
CellsFBP_Thresholds_03Aug.py        HeuristicTemplate.py        ReadData.py
CellsFBP_Thresholds_03Aug.pyc       Icon?                       ReadData.pyc
FBP-LINE-newest_NoDebug.py          Lightning.py                ReadDataPrometheus_Threshold_01Aug.py
FBP5.0.h                            Lightning.pyc               ReadDataPrometheus_Threshold_01Aug.pyc
FBPfunc5_NoDebug.c                  Output.py                   Sim03Aug.py
FBPfunc5_NoDebug.o                  Output_Grid.py              SpottingFBP_01Aug.py
FBPfunc5_NoDebug.so                 Output_Grid.pyc             SpottingFBP_01Aug.pyc
Forest.py                           Parallel.py                 WeatherFBP.py
Forest.pyc                          Plot.py                     WeatherFBP.pyc
Heuristic.py                        Plot.pyc
MacBook-Pro-de-Jaime:CurrentVersionPython2.7 jaime$
```

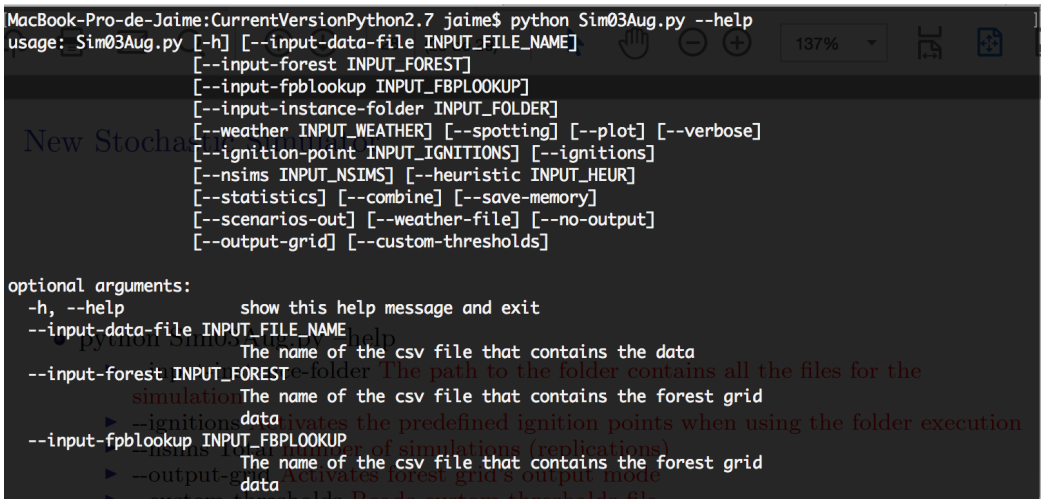
Figura:

New Stochastic Simulator

The script namely Sim03Aug.py is the 'main' of the simulator and it contains all the algorithmic operating instructions.

NewStochSim it contains a 'help' of the different input files-parameters:

- python Sim03Aug.py –help
  - --input-instance-folder The path to the folder contains all the files for the simulation
  - --ignitions Activates the predefined ignition points when using the folder execution
  - --nsims Total number of simulations (replications)
  - --output-grid Activates forest grid's output mode
  - --custom-thresholds Reads custom thresholds file
  - --weather-file Activates weather stream file
  - --no-output Activates forest grid's output mode
  - --save-memory Activates memory monitoring version (useful for very large instances)



```
MacBook-Pro-de-Jaime:CurrentVersionPython2.7 jaime$ python Sim03Aug.py --help
usage: Sim03Aug.py [-h] [--input-data-file INPUT_FILE_NAME]
                   [--input-forest INPUT_FOREST]
                   [--input-fpblookup INPUT_FBPLOOKUP]
                   [--input-instance-folder INPUT_FOLDER]
                   [--weather INPUT_WEATHER] [--spotting] [--plot] [--verbose]
                   [--ignition-point INPUT_IGNITIONS] [--ignitions]
                   [--nsims INPUT_NSIMS] [--heuristic INPUT_HEUR]
                   [--statistics] [--combine] [--save-memory]
                   [--scenarios-out] [--weather-file] [--no-output]
                   [--output-grid] [--custom-thresholds]

optional arguments:
  -h, --help            show this help message and exit
  --input-data-file INPUT_FILE_NAME
                        The name of the csv file that contains the data
  --input-forest INPUT_FOREST
                        The name of the csv file that contains the forest grid
                        data
  --input-fpblookup INPUT_FBPLOOKUP
                        The name of the csv file that contains the forest grid
                        data
```

Figura: NewStochSim 'help'

¿How is running the NewStochSim?

Any instance has several inputs files. For examples, we consider Dogrib instance whose 'path' is:
/Users/jaime/Google\Drive/Dogrib/ResultadosSimname/Dogrib_Original/Ignition1/
Then, to run this instance and to simulate 100 iterations, we write in the Terminal the following:

```
MacBook-Pro-de-Jaime:CurrentVersionPython2.7 jaime$ python Sim03Aug.py --input-instance-folder=/Users/jaime/
Google\ Drive/Dogrib/ResultadosSimname/Dogrib_Original/Ignition1/ --ignitions --nsims=100 --output-grid --cu
stom-thresholds --weather-file --no-output --save-memory
------------------------------------------------- Simulation Number  1 -------------------------------------
------------
```

Figura: Run Dogrib

Burn-P3

What is Burn-P3?

Burn-P3 (Probability, Prediction, and Planning) is a simulation model that evaluates the fire likelihood o burn probability (BP) at every point (i.e. grid cell) of a large fire-prone landscape. The spatial units consist of fuels, topography, ignition location, fire zones, weather zones, wind grids, and firebreaks.

- The fuels variable consists of classification of fuel types based on vegetation attributes. Open water, exposed rock, are considerer non-fuel.
- Each fuel type has a characteristic fire behaviour that varies according to weather and topography.
- The ignition location variable represents a spatially weighted probability of experiencing an ignition at any given point on the landscape; these probabilities may vary by season and cause.
- The fire zones stratify the landscape in areas of distinct fire regimes, as modelled in Burn-P3. The weather zones represent areas of distinct fire weather conditions with which fire growth is simulated.
- The weather zones represent areas of distinct fire weather conditions with which fire growth is simulated.
- The wind grids modify the input wind direction and wind speed as a function of the underlying topography.
- The firebreaks consist of linear features of a specified width that will interrupt fire spread.

Burn-P3

- The environment comprises the following variables: season, cause, fire duration, number of hours per day of burning, and daily fire weather conditions.
- Season consists of time periods when the daily fire weather conditions differ, as well as the state of the fuels whose phenology greatly affects fire behaviour (i.e., deciduous and grass).
- Cause is the type of fire ignition; causes and seasons can have distinct spatial ignition patterns.
- Fire duration refers to the number of spread-event days for each fire, which may vary by fire zone.
- This number may vary by season and also from a day to the next.
- The number of hours per day of burning can be constant, or vary from a day to the other, and depending on the season.
- The daily fire weather conditions variable represents the weather under which fire spread is simulated; that is, the weather attached to each spread-event day of a fire.

Burn-P3

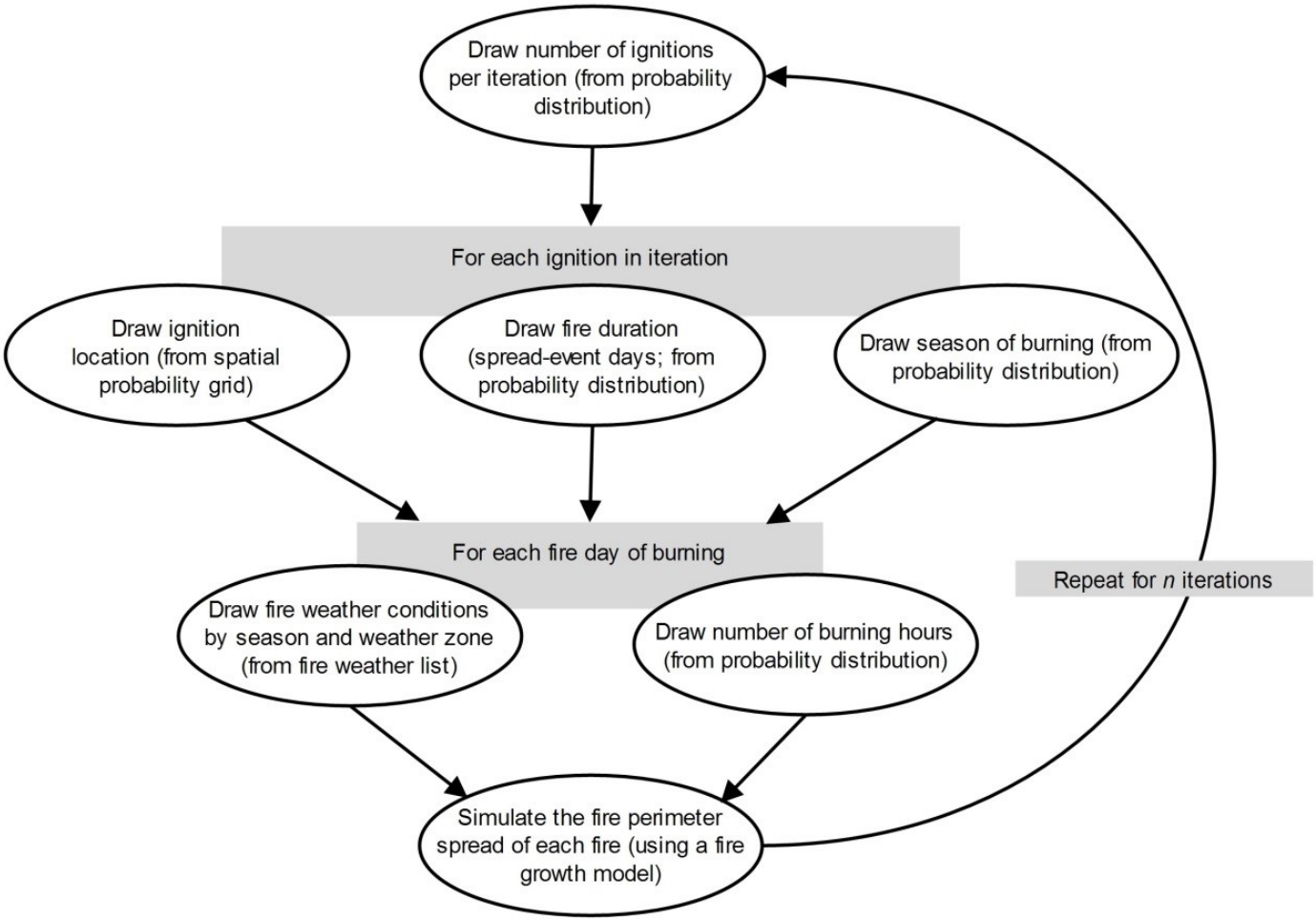


Figura: Process overview of Burn-P3 fire simulation model

Burn-P3

- Fire spread is carried out using the fire growth submodel: Prometheus for all ignitions of a given iteration.
- The areas burned by each simulated fire in an iteration are recorded on the rasterized landscape.
- Burn Probability in the cell i is calculated as follows:

$$BP_i = \frac{b_i}{N},$$

where b_i is the number of iterations in which the cell i burns and N is the number of iterations simulated.

Burn-P3

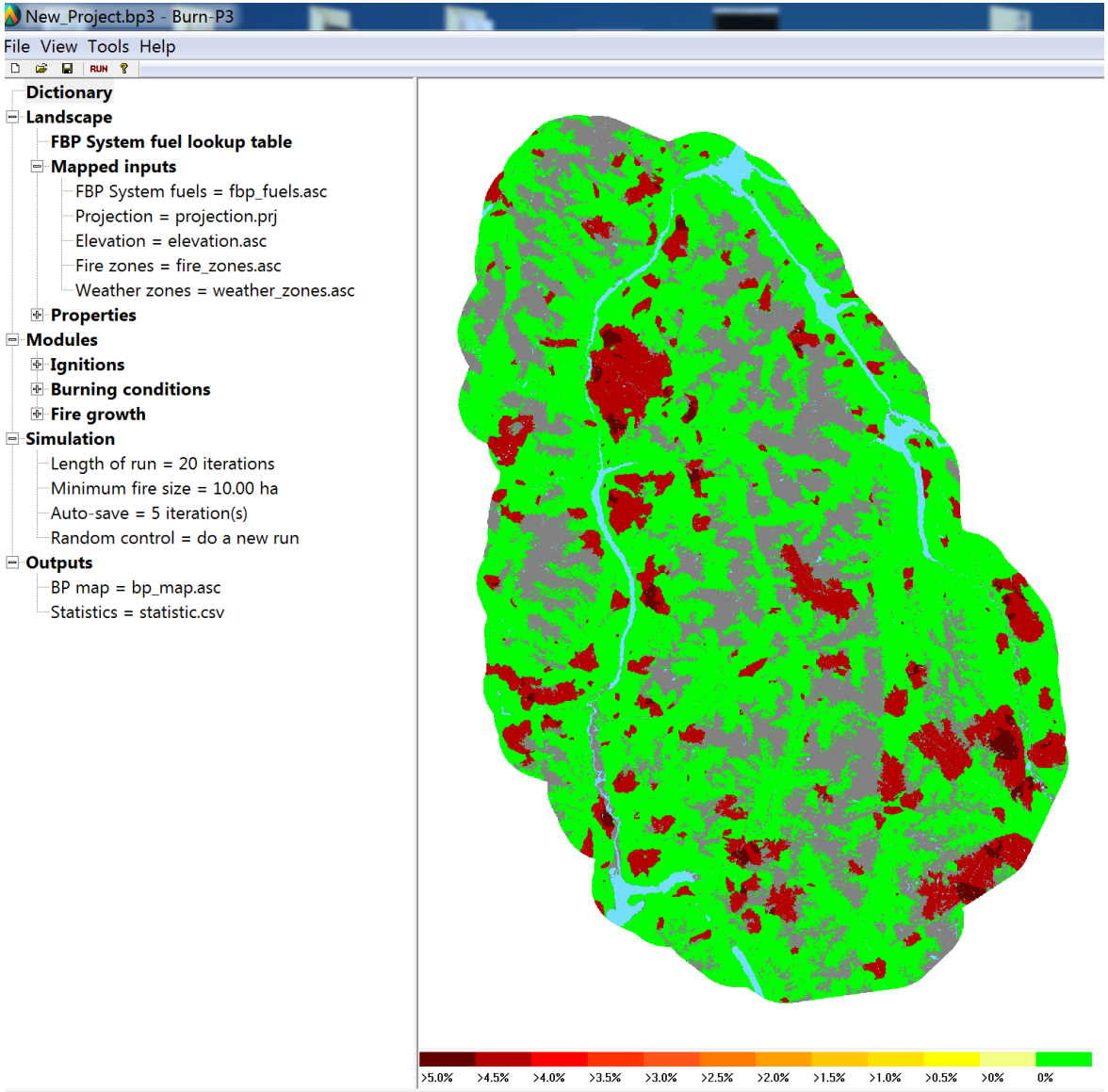


Figura: Burn-P3, 100 iterations, 254 fires

Burn-P3

Main Outputs

1. Burn Probability Maps
   - burn probability (percentage).
   - the number of times burned (integer).
2. Statistics table
   - Number of fires in iteration i
   - Total area burned by fire i
   - Hrs burning
   - etc
3. FBP System outputs
   - Fire intensity
   - etc

Burn-P3

Example:

Suppose that in one iteration three fires with the following scars occur:

$$F_1 = \begin{pmatrix} & & 1 & 1 \\ & 1 & 1 & \\ 1 & 1 & & \\ 1 & & & \\ & & & \end{pmatrix}, F_2 = \begin{pmatrix} & 1 & \\ & & 1 \\ & 1 & \\ & 1 & 1 \\ & 1 & \end{pmatrix}, F_3 = \begin{pmatrix} 1 & & & & \\ & 1 & & & \\ & 1 & 1 & & \\ & & 1 & & \\ & & & 1 & 1 \end{pmatrix}$$

Then, the BP map (integer) it is represented by:

$$BP = \begin{pmatrix} 1 & 0 & 1 & 1 & 1 \\ 0 & 2 & 1 & 1 & 0 \\ 1 & 2 & 2 & 0 & 0 \\ 0 & 0 & 2 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 \end{pmatrix}$$

Burn-P3

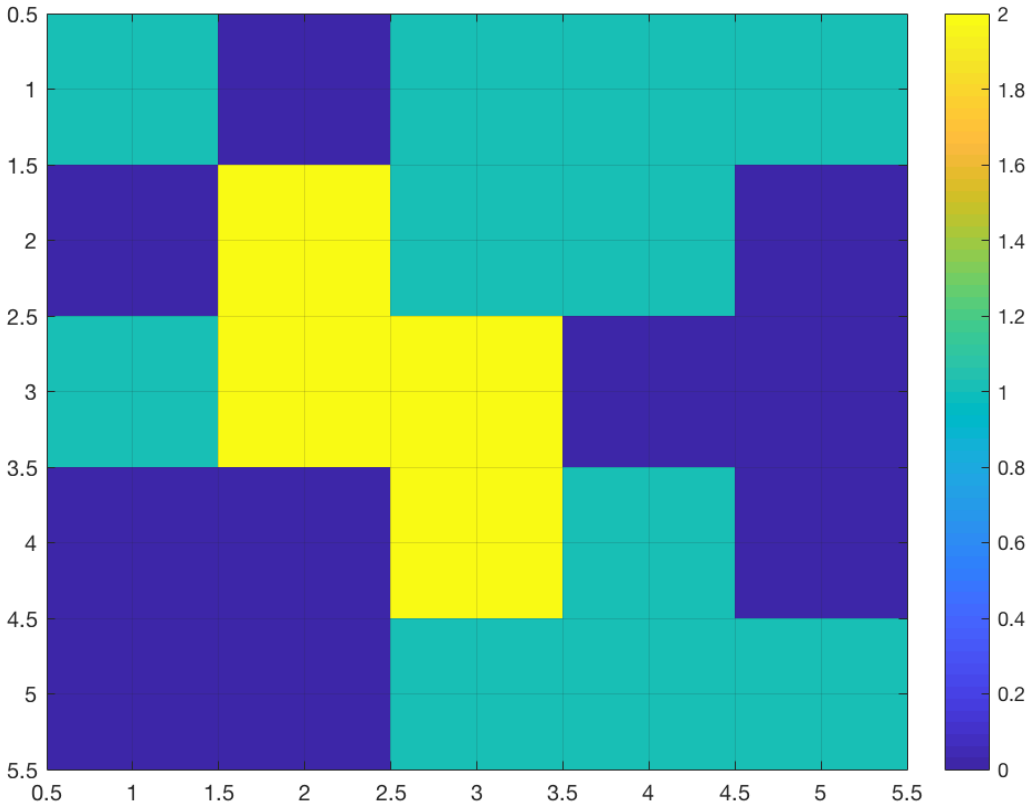
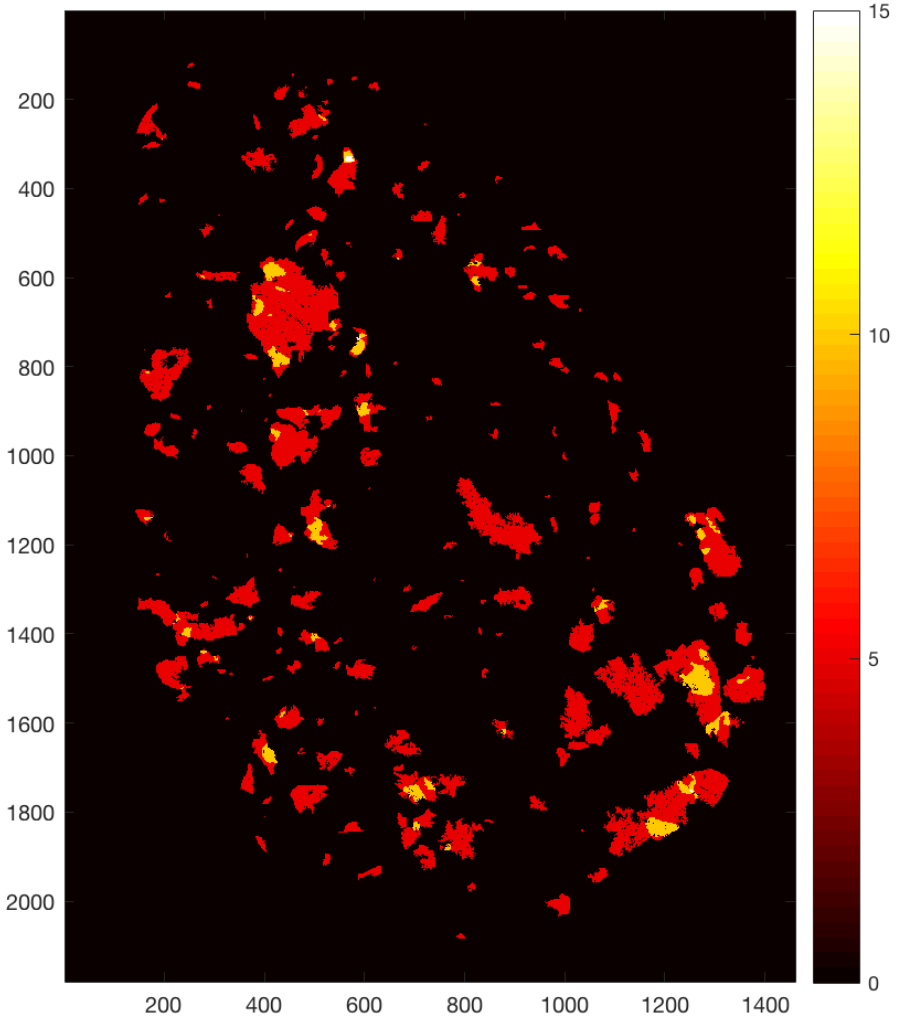


Figura: Graphic representation

Fire clustering

For Burn-P3 instance: 254 fires



Fire clustering

- When two fires are similar?
- or in other words, When two fires represent the same fire?
- In the previous example, How to build a fire that represents the three fires?
- What is better, one or two,... fires?
- How to reduce the number of fires?

First approach: spatial metrics

Let $P_1 = (x_1, y_1)$ y $P_2 = (x_2, y_2)$ on a grid, we considered the following metric between them

$$d_1(P_1, P_2) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}.$$

- Then, two fires are closed if promptly they are close.
- This metric, does not considerer the recurrence of a cell being burned several times.

Fire clustering

Second approach: spatial-frequency

Let $P_1 = (x_1, y_1, f_1)$ **y** $P_2 = (x_2, y_2, f_2)$

$$d_2(P_1, P_2) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (f_1 - f_2)^2}.$$

- Then, two fires are closed if promptly they are close.
- Two fires with frequency similar, are more close.

Fire clustering

Considerer the same fire scenarios of above, and we use kmeans++ algorithm[2]:

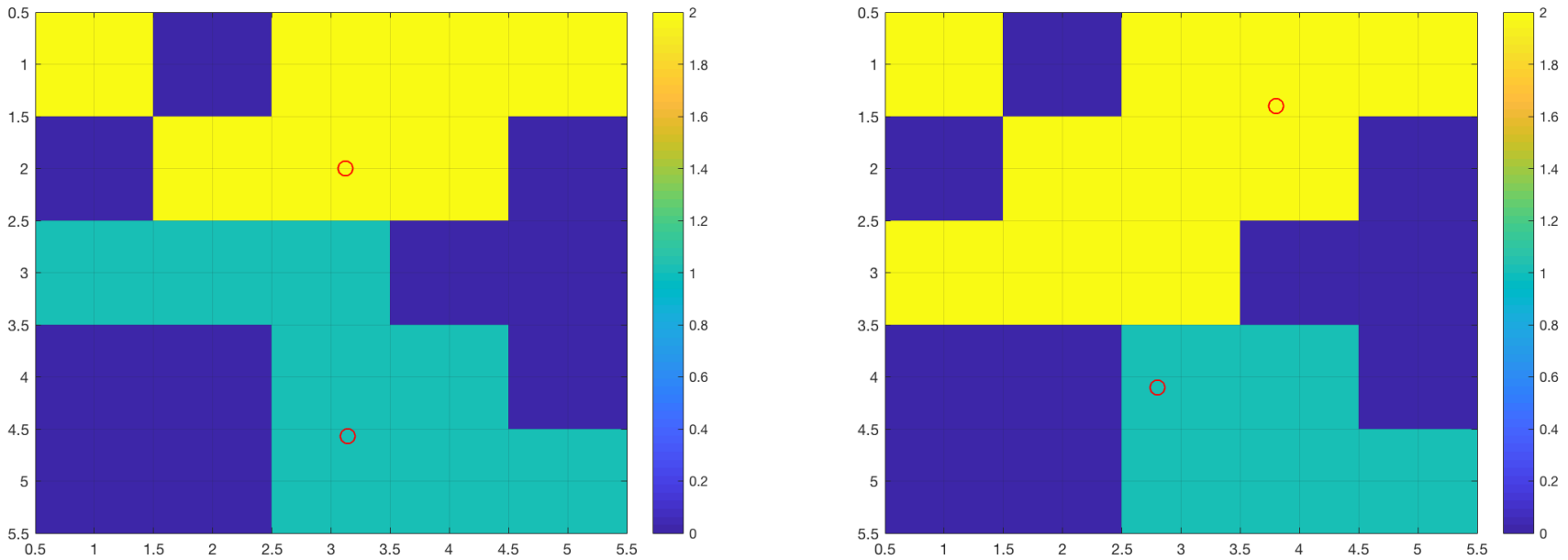


Figura: 2 clusters for d_1 (left figure) and d_2 (right figure)

[2] Arthur, David, and Sergi Vassilvitskii. "K-means++: The Advantages of Careful Seeding. SODA '07: Proceedings of the Eighteenth Annual ACM-SIAM Symposium on Discrete Algorithms. 2007, pp. 1027–1035.

Fire clustering

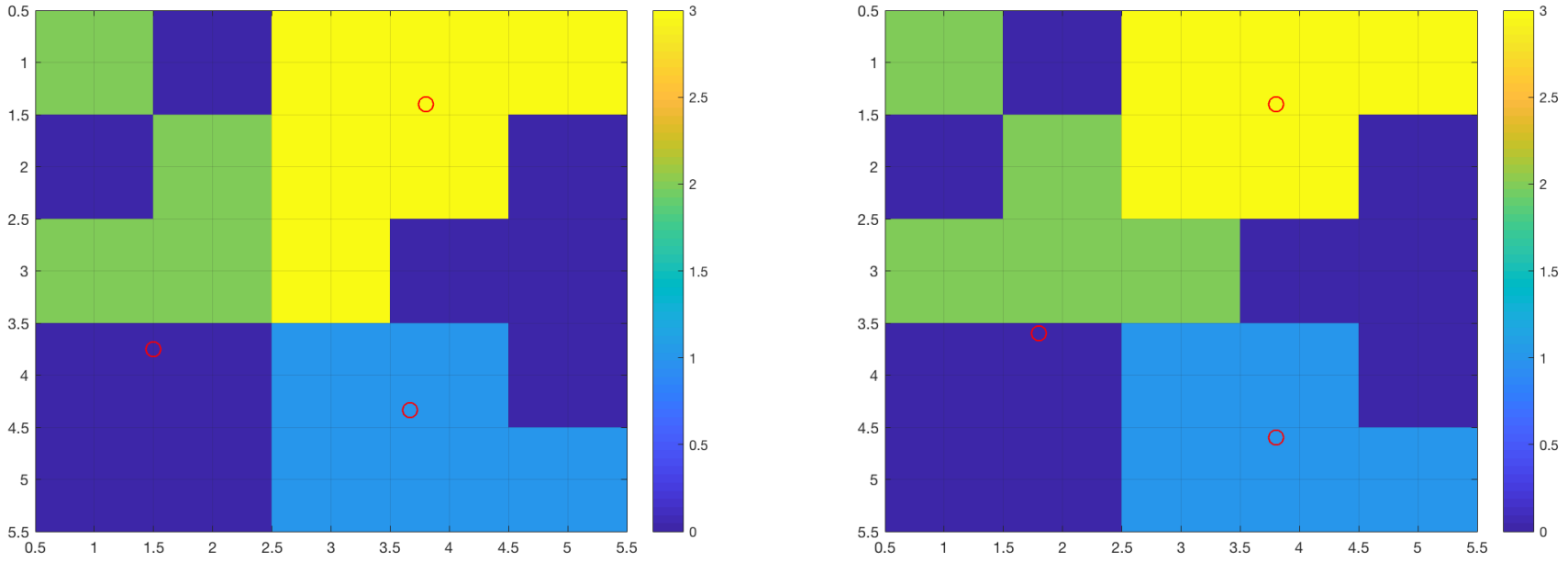
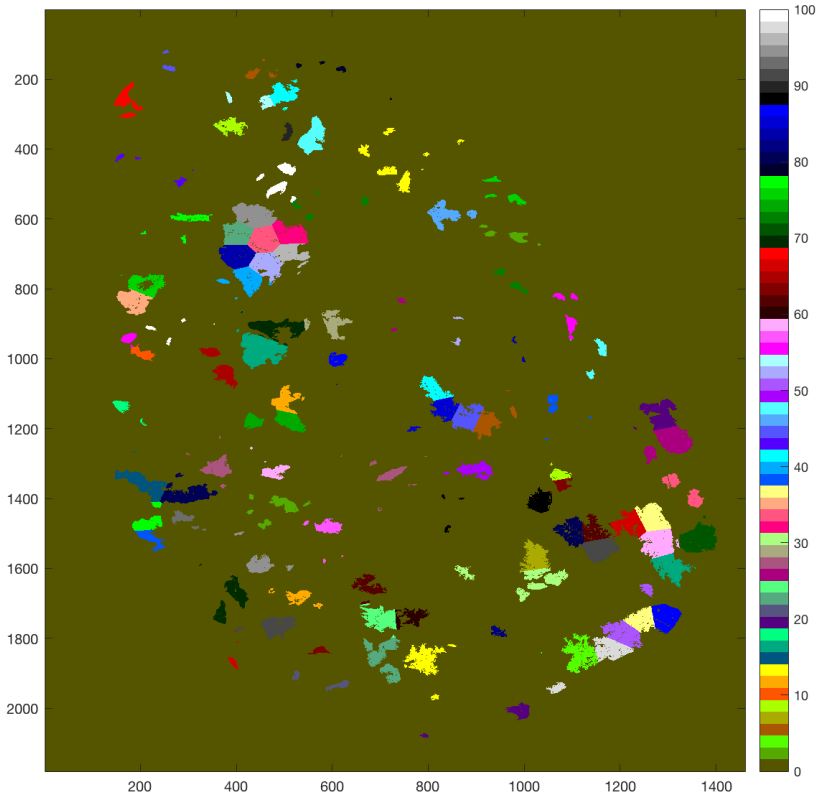


Figura: 3 clusters for d_1 (left figure) and d_2 (right figure)

Fire clustering



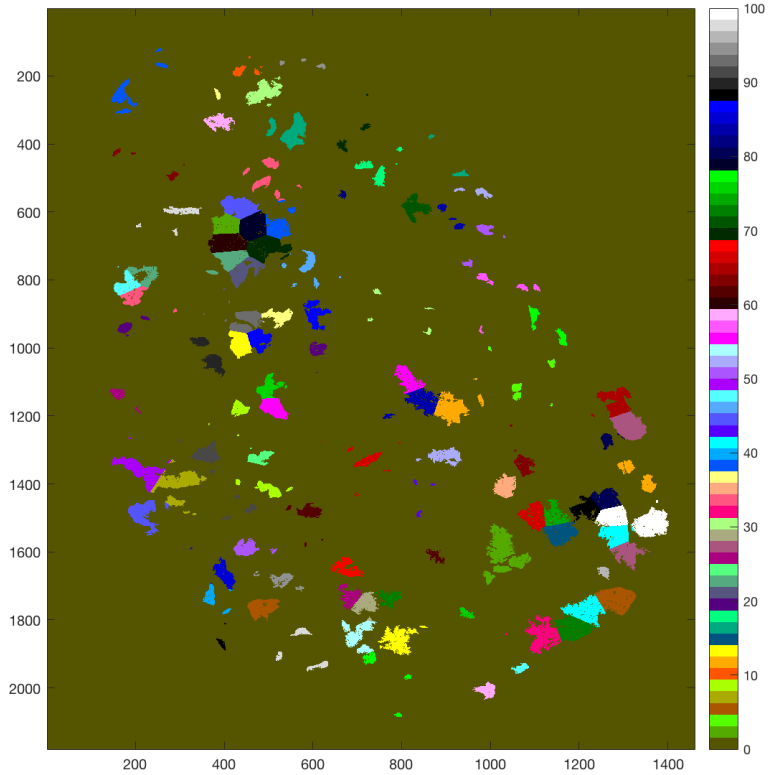


Figura: Fire clustering using k-means++ algorithm with metrics d_1 (left figure) and d_2 (right figure)

Fire clustering

- How to improve (and be more realistic) the similarity between fires?...incorporate attributes such as:
  - burned area?
  - topology of fires?
  - perimeters?
  - Probability of occurrence?
  - other metrics?