

Highlights

Visualization and modelling of forest fire propagation in Patagonia

Monica M. Denham, Sigfrido Waidelich, Karina Laneri

- We developed the *Simulador de Incendios Patagonia (SIP)* in the framework of High-Performance Computing and Real Time.
- SIP was programmed for GPGPUs architectures and can be executed on Linux (Ubuntu), Windows and NVIDIA Jetson Nano hardware.
- Different scenarios can be used for fire propagation and visualization (a calibration stage is necessary before using it).
- The Fire Weather Index (FWI) and the resulting fire risk map are embedded in the SIP.
- Two mathematical models for fire propagation are implemented within the SIP application.

Visualization and modelling of forest fire propagation in Patagonia

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ABSTRACT

Fire propagation is a big concern all over the world. Visualization is a valuable tool to test possible different scenarios for fire spread, specially for designing strategies for fire control, mitigation and management. We present a parallel High-Performance Computing (HPC) forest fire simulator with an interactive and intuitive user interface that offers several functionalities to the user. The visualization interface allows to choose the propagation model of preference, the scenario of interest, as well as numerous simulation features including firebreaks and ignition points. We show some of the outputs for two different mathematical models for fire spreading. The simulator was developed with an open source philosophy in the framework of Faster Than Real Time (FTRT) applications thinking on its possible use in the field during a forest fire propagation. It can be run in Linux (Ubuntu) and Windows Operating Systems and for portability purposes the simulator was also implemented on a NVIDIA Jetson Nano.

1. Software Availability and requirements

Name: SIP (Simulador de Incendios Patagonia).

Bitbucket: https://bitbucket.org/unrnfuegos/simulador_patagonia/src/master/

Hardware requirements: computer with NVIDIA graphic card installed.

Our simulator can be installed and executed in NVIDIA Jetson Nano.

2. Introduction

Forest fires, whose frequency and severity are increasing in an alarming rate all over the world, constitute a huge ecological and environmental hazard (Stephens, Agee, Fulé, North, Romme, Swetnam and Turner (2013), Bowman, Balch, Artaxo, Bond, Carlson, Cochrane, D'Antonio, Defries, Doyle, Harrison, Johnston, Keeley, Krawchuk, Kull, Marston, Moritz, Prentice, Roos, Scott and Pyne (2009), World Wildlife Fund (2022)). For instance, during the summer season of 2019-2020 Australia was devastated by forest fires affecting 10 millions of hectares, destroying more than 2500 buildings and producing more than 26 human losses. Due to this disaster, more than 1000 millions of animals died. The Amazonian rainforest, which produces the 20% of the oxygen of the planet, was seriously affected by 91,823 wildfires in Brazil, 20,066 in Bolivia, and 14,469 in Colombia from January to September 2019. Those wildfires quickly reduced the Amazonian forest's capacity of acting as the lungs of the world. In addition, in the big forest fires which are reported frequently all over the world, apart from the concomitant economic losses, thousands of CO_2 tonnes are released to the atmosphere contributing to the phenomena known as "green house effect", also increasing the global temperature (The Guardian (2021)).

Our country has also been strongly affected by forest fires recently. Two of the most destructive forest fires occurred during the 2022 summer. The first one, in Argentinian Patagonia, lasted more than three months (Telam digital (2022)). The second one, in Corrientes province (Argentina's Mesopotamia) lasted more than one month (Infobae (2022)). Low budget and few resources are assigned to forest fire control and mitigation in our country, so these fires got extinguished mainly by natural rain.


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Table 1

Estimated burned hectares in the last decade in Argentinian Patagonia (Gobierno Argentino (2022a)).

Year	Chubut	Neuquen	Rio Negro	Santa Cruz	Tierra del fuego	Total
2010	1261	595	645	40	5	2546
2011	4169	10682	15354	62	96	30363
2012	4698	16057	3093	20499	2575	46922
2013	106	2449	1732	1504	10	5801
2014	147	626	49373	277	8	50431
2015	40346	20564	105108	158	5	166181
2016	9552	38356	60175		10	108093
2017	521	6787	61076	303	5	68692
2018	100	2825	33281	4688	2	40896
2019	4253		388	5166	188	9995
2020	6365	16252	42613	302	1	65533
2021	16919	1350	20381	2263	0	40913

Our region in particular, the Argentinian Patagonia, is a huge extension of 1,043,076 km² bounded by the Andes mountains on its western side and the Atlantic sea on its eastern side. It extends to the south from approximately latitude 37°22'26.1" S. In order to quantify the problem of forest fires in Patagonia, we show the estimated hectares burned during the last decade (Table 1), which includes both native as well as exotic vegetation (Gobierno Argentino (2022a)). These wildfires have several possible causes: property speculation, human negligence, lightning, and uncontrolled burning (Tiribelli (2019)). The 95% of wildfires is caused by human actions/activities (Gobierno Argentino (2022a)).

Patagonia native forest species have a slow process of growing. First stages of that forests have features similar to shrubs, with high inflammability. When those forests reach mature ages, their inflammability decreases due to forest canopy and their separated underbrush. Unfortunately however, our forests are changing irreversibly due to the tendency to get reburned before they achieve these mature features, thus becoming in low shrub typical plants with high inflammability features (Tiribelli (2019)). Last years several wildfires affect the region of the western Patagonia. For instance, during January and February 2021, 7800 hectares of native vegetation were burned near to *El Bolsón* (41°580 S, 71°320 W). A few days later, seven new ignitions were registered in the surroundings and 200 buildings were destroyed. Lots of families lost their belongings due to these fires.

The "Servicio Nacional de Manejo del Fuego" (SMNF) in Argentina (Gobierno Argentino (2022b)) exists since 1996. SNMF main task is the control and mitigation of the fire on rural or natural areas. In addition, the SNMF draws fire risk maps, fire occurrence reports, and works on early alert information and past fires reports (Gobierno Argentino (2022c)). The data collected by this national service and the possibility to interact with their members has opened a new perspective for interdisciplinary scientific collaboration in our country, particularly regarding the quantitative analysis through numerical simulations, the problem we tackle in this work.

Forest fire behaviour is a complex process to simulate (Rothermel (1972), Albini (1976), Finney (2004), Scott and Burgan (2005)). Physical and chemical processes of ignition can vary drastically depending on the different fuel types, such as live or dead fuels, organic or inorganic material, fine or coarse fuel, and fuel conditions, such as dry or wet. While fuel load determines the continuity of burning, it is crucial to classify the typical vegetation according to its influence on fire behaviour (Anderson (1982), Government of Canada (b)). Weather conditions of the previous days are also important for fire spread because they produce dry or wet fuel. During a wildfire, on the other hand, rainfall can weaken and eventually stop a fire front, while wind can favor combustion by injecting oxygen, facilitating fire spatial spreading, or pushing the combustion smoke accelerating the drying process of the surrounding fine fuel (Rothermel (1972), Van Wagner C. E. and Pickett T. L. (1985), Van Wagner C.E (1987)). Topography can modify fire spreading too. When the terrain is not flat, fire propagation can be faster uphill and slower downhill, due to convection processes and buoyancy. West Patagonia landscapes are mainly large mountain chains and typical "V" format valleys conform our typical scenarios. The aspect of the slope in turn varies according to the sun and wind exposition hence leading to changing humidity conditions of live and dead fuel (Rothermel (1972), Albini (1976)).

Several computational open-source tools are currently used for wildfire simulation and forecasting. The implementation of this kind of simulation tools was done in the last decade mainly by developed countries (i.e. Canada, USA, etc).

For example, Cell2Fire (Pais, Carrasco, Martell, Weintraub and Woodruff (2021)) is an open-source cell-based fire growth simulator for laptop, desktop computers or High-Performance Computer systems. The landscape is divided into a regular grid of cells (raster files) and the Ratio of Spread (ROS) is computed depending on fuel, moisture content, weather, and topographic attributes. Cell2Fire validation is performed by comparing with Prometheus (Tymstra, Bryce, Wotton, Taylor and Armitage (2010)) outputs, that are static JPG files showing the fire spread. The application was parallelized using OpenMP which is an important difference with our SIP simulator, that is designed using CUDA model for its parallel execution on graphic cards.

In (Mangiameli, Mussumeci and Cappello (2021)) a GIS-based application, using the Rothermel model (Rothermel (1972)) and Albin (Albin (1976)) extensions, is used to predict fire movement in wooded areas. It is based on the use of open-source software like QGIS, GIS GRASS, and PostGIS. One important difference with our simulator, is that they make use of already developed platforms for visualization and computation.

Previous similar developments, that in some cases inspired the newest simulators are, for example: BEHAVE (Rothermel (1984)), BEHAVE plus (Andrews (2014)), FARSITE (Finney (2004)), Prometheus (Tymstra et al. (2010)), fireLib (Bevins (1996)) to mention a few. However, the use of these simulators is not straightforward for our local landscapes and needs. Another important issue is the lack of fuel type definition for our region, so we have to find a correspondence between our typical vegetation and a fuel type defined for Canadian (Government of Canada (b)) or United States landscapes (Anderson (1982)). This motivated us to develop a new open-source forest-fire simulator that can be easily customized for our local needs.

We developed a parallel forest fire simulator called *Simulador de Incendios Patagonia* or its acronym *SIP*. This application simulates the propagation of surface wildfire on a landscape. Topography, weather, vegetation, slope and wind, and also the mathematical model for spreading are inputs for the *SIP*. Our simulator performs two fundamentally different stages to accomplish its purpose. On the one hand, it executes the mathematical model of fire propagation. On the other hand, it shows an intuitive graphical representation of the simulations, taking as input layers where propagation takes place. From a scientific perspective, our simulator is also a convenient platform to test different mathematical models on realistic substrates. These models, which can be deterministic or stochastic, based on cellular automata or differential equations, and different levels of coarse-graining, can be indeed easily incorporated into the code. Even for the simplest mathematical models, for a useful realistic description, it is necessary to process a huge amount of input layers (i.e., topography, weather, fuel descriptions), over extended spatial regions, yielding typically millions of interacting cells or sites for a moderate useful resolution. Since we are interested in a faster than real-time simulator we were forced to develop a high-performance massively parallel application. This work hence lies at the intersection of big areas, HPC, large-scale visualization, and forest-fire simulation.

In summary, the original contributions of the current work are: a) The embedding of two mathematical models for forest fire spreading into our simulator, allowing the user to choose the model for fire propagation (a feature that can be easily extended to any number of models); b) New functionalities of the simulator visualization like layer transparencies, customized firebreaks, forward, and backward simulation, etc.; c) Expanded portability of the simulation and visualization code on Windows and Linux Operating Systems; d) Implementation and testing of the simulator as an embedded solution on NVIDIA Jetson Nano architecture.

The paper is organized as follows: the next section will present the mathematical models for forest fire progress. Section 4 shows the methods used in our developments as well as the main features of our interactive simulator. Subsection 4.3 explains the use of Jetson Nano for the *SIP* simulator. In the last section, we expose the conclusions and future steps.

3. Mathematical models for fire progress simulation

We included two mathematical models for fire propagation that the user can select within the *SIP* menu: the statistical model explained in previous works (Morales, Mermoz, Gowda and Kitzberger (2015); Denham and Laneri (2018)) and the Reaction-Diffusion-Convection (RDC) model, presented in (Laneri, Waidelich, Zimmerman and Denham (2020)). If the model is changed, the fire restarts from the initial ignition point and the simulation starts using the selected model. The parallel implementation of both models was done using CUDA C and C++ and GLSL shaders for visualization purposes. An important contribution of this work is the embedding into the *SIP* application of the RDC model explained below.

3.1. Reaction Diffusion Convection model

The RDC mathematical model describes fire propagation on a two-dimensional grid. For each cell of the grid we computed the following set of equations:

$$\frac{\partial I}{\partial t} = \beta(\vec{r})S \cdot I + D\nabla^2 I - \vec{v}(\vec{r})\nabla I - \gamma I \quad (1)$$

$$\frac{\partial S}{\partial t} = -\beta(\vec{r})S \cdot I \quad (2)$$

$$\frac{\partial R}{\partial t} = \gamma I \quad (3)$$

with \vec{r} the position of each cell of the grid, where we have a fraction of susceptible fuel (S), a fraction of burning fuel (I), and a remaining fraction (R) of burnt fuel that can not be burnt again. This model is inspired in the spatial SIR model of epidemiology (Kolton and Laneri (2019)) and in its present form contains the simplest reaction term, which is also the single source of non-linearity. More complex reaction terms, can be easily included.

The total fuel in the whole grid is conserved, therefore the following condition must be fulfilled:

$$\int dx dy \left[\frac{\partial S}{\partial t} + \frac{\partial I}{\partial t} + \frac{\partial R}{\partial t} \right] = 0$$

In other words, the integral of the quantity of fuel over the whole grid is constant. For instance, fuel (or vegetation) can not be lost, but it can be distributed in one of the three states, i.e. not burnt, burning and burnt.

Using a spatial finite difference scheme for solving Eqs.1, 2 and 3 leads to a large number of coupled cells whose time-continuous dynamics must be solved synchronously. Each cell has a fuel type that determines the heat transmission rate β , that we consider constant for each grid cell but that can change between cells as in (Kolton and Laneri (2019)). Therefore, the product ($\beta(\vec{r}) \times S$) is the effective fuel that can burn in each cell of the grid at a given time. For instance, if β is small, even if there were lot of fuel available to burn, the number of burnt fuel will be small.

The first term in Eq. (1) represents the fuel fraction that is burning due to local combustion in the cell, i.e. the effective number of fuel that can burn times the burning fuel fraction. Therefore in Eq.(2) this term is subtracted from the fraction of burnable fuel $S(\vec{r}, t)$ given that once burnt, that fuel can not be burnt again.

The second term of Eq. (1) accounts for local diffusion, where D is the diffusion constant, and the laplacian is defined as:

$$\nabla^2 I = \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} \quad (4)$$

with x and y the Cartesian coordinates. Hence, spatial curvature effects are neglected. In this equation we are assuming that there is a heat current that is proportional to the temperature gradient ($J \propto -\nabla T$), where:

$$\nabla T = \left(\frac{\partial T}{\partial x}, \frac{\partial T}{\partial y} \right) \propto \nabla I \quad (5)$$

Therefore, if we assume that the temperature gradient is proportional to the fraction of fuel that is burning, we obtain the second term of Eq. (1). For simplicity we assume that diffusion is constant in space and time.

The third term in Eq. (1) corresponds to convection:

$$\vec{v}(\vec{r}) = A * \vec{w}(\vec{r}) + B * \nabla h(\vec{r}) \quad (6)$$

where $\vec{w}(\vec{r})$ is the wind intensity that depends on the cell position. For simplicity we consider it constant in time, taking the average wind intensity in each cell of the grid. The first term thus represent wind-induced advection of the burning fuel I . The second term in Eq. (6) is proportional to the height gradient between a cell and its neighbouring cells, and the sign is defined such to model the fact that fire tends to propagate faster uphill than downhill in the absence of wind due to convection and buoyancy of hot air.

Finally the last term of Eq. (1) accounts for the fuel that is extinguished (and thus contributes to the last term

in Eq.3), with γ the turn off rate. Accordingly, this fraction of burnt vegetation becomes part of the remaining burnt fraction R (Eq. (3)), that can not be burnt again. The functions $\beta(\vec{r})$, $\vec{w}(\vec{r})$, $h(\vec{r})$ are extracted from the vegetation, wind and height maps respectively, while the parameters D, γ, A, B are adjusted by comparing with real data, so to approximate real forest fire behaviour.

3.2. Cellular Automaton model

As in the finite-difference scheme of the previous model, the landscape is represented as a grid of cells where fire spreads, but the propagation is discrete in space and also in time. The state of a cell is defined as: burnt, unburnt and burning. They can spread fire to their eight nearest neighboring cells according to the following probability:

$$p = \frac{1}{1 + \exp(-(\beta_0 + \beta_1 I_f + \beta_2 \psi + \beta_3 \omega + \beta_4 \sigma))} \quad (7)$$

where the propagation probability p takes values between 0 and 1, and is a function of fuel/vegetation type, relative wind direction, slope, and aspect of the target cell (I_f, ψ, ω and σ respectively) as explained in (Morales et al. (2015), Denham and Laneri (2018)). In Eq. 7, I_f is a vegetation indicator variable equal to 1 for cells occupied by forest and 0 otherwise. Fuel type coefficient β_0 is the baseline fire propagation probability for shrubland cells and β_1 is the difference between shrubland and forest. Parameters β_2, β_3 , and β_4 modify the propagation probability according to aspect (ψ), wind direction (ω), and slope (σ) respectively. We used DEM (Digital Elevation Model) data for obtaining raster files with slope and aspect. Wind direction for each cell (ψ) was derived from the average dominant wind direction during fire season and it was modified by the topography (WindNinja was used for that purpose). Each cell of the grid has its own attributes that describe topography, vegetation, and weather conditions.

The ignition probability of each cell at every time step of the simulation was calculated taking into account the state of the 8-cells neighborhood. At each time step of the simulation, all grid cells are checked in parallel and a given target cell is burnt according to the probability $1 - (1 - p_i)^8$, with $i = 1, 2, \dots, 8$ the number of neighbors cells and p defined in Eq. 7. Fire propagation stops by itself or when fire reaches the grid boundaries.

Using this model, we fitted it to data and we determined the best set of values for $\beta_0, \beta_1, \beta_2, \beta_3$, and β_4 after an intensive search over the parameter space. Also the geographical position of the ignition point and the associated error were assessed after fitting computer simulations with the real fire scar (Denham and Laneri (2018)).

After the calibration performed in Denham and Laneri (2018), the β_i values are used to simulate the fire progress for the corresponding scenario, using the simulator and the user interface presented in this work (Section 4.1).

4. Methods

Our application is developed in the framework of HPC and Real Time technologies, to achieve efficiency and reduce run times for an optimal use of hardware components. During the application development we performed an exhaustive study of the underlying hardware, analysing the GPU cores, memories, execution modes, application and instruction parallelism. The study of graphic card memories included a test of different access patterns for read/write operations, memory latencies and memory bandwidths.

At every time step of the simulation each cell is concurrently updated by running a kernel with a large number of parallel threads. Thread execution was divided into warps of 16 threads, executed in a Simple Instruction Multiple Data (SIMD) way to avoid divergent instruction execution (Cheng J. (2014)). This issue was not easy to accomplish due to the execution pattern of our fire propagation models that were programmed using CUDA C and CUDA C++ (Kirk and Hwu (2010), Cook (2013)).

OpenGL and GLSL (Overvoorde (2012), Meiri (2015)) were used for interactive real-time efficient visualization purposes. With this combination of techniques, we get the simulation results directly shown on the screen. These features are described in Section (4.1).

To assess and optimize the application we used profilers like nvprof (NVIDIA (2021b)), nvvp (NVIDIA (2021b)) and NVIDIA Nsight Compute (NVIDIA (2021a)).

4.1. Forest Fire spread simulator

Our interactive forest fire simulator (*SIP*) allows the user to customize the visualization in simulation time. In the next paragraphs we will expose the main simulator inputs and outputs and the most important functionalities, many of them suggested by *Parque Nacional Nahuel Huapi* firefighters and wildfire experts.

Forest Fire Simulation in Patagonia

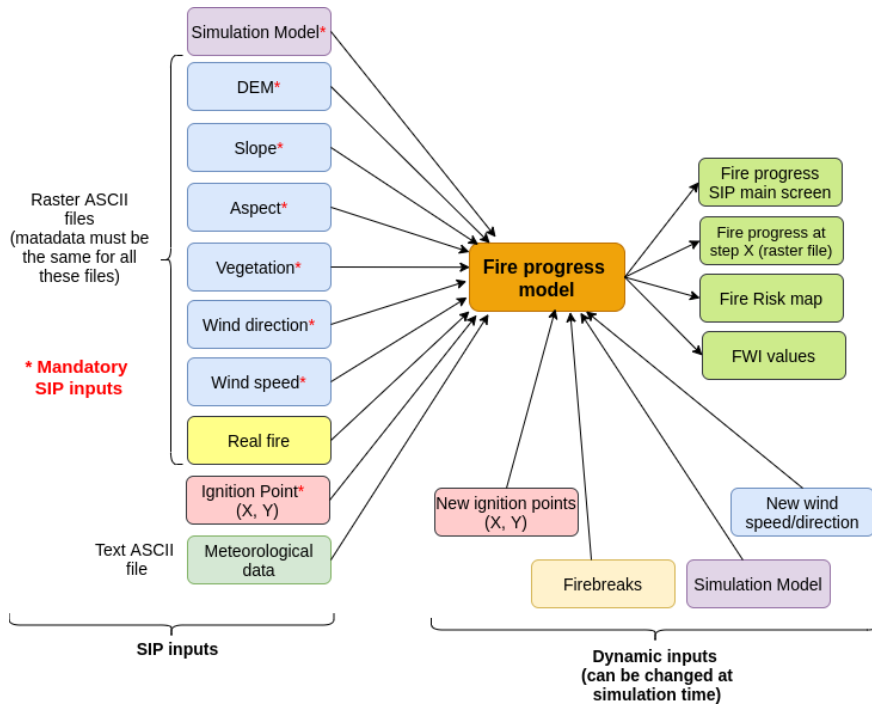


Figure 1: *Simulador de Incendios Patagonia (SIP)* inputs and outputs.

Figure 1 shows in a simple way the simulator inputs and outputs. First, a default propagation model is set when *SIP* is launched. This model can be chosen between RDC and AC models (see Section 3) as shown in Figure 2. If the user changes the propagation model, the simulation starts again executing the new model.

Landscape is described using several Raster ASCII maps, each one is treated as a data layer within the simulator: Digital Elevation Model (DEM), slope and aspect of the terrain, weather (wind direction and velocity), and land vegetation. If it's available, a real fire map can be used to feed our simulator. All these raster files need to have the same metadata (i.e. rows, columns, pixel size, no data value, one of its corners' coordinates). Then, one point (x,y) is set and used as ignition point. Mandatory raster files and information (ignition point and simulation model) are marked with a red asterisk in Figure 1.

Wind speed units are km/h and wind direction units are degrees with respect to the north to south direction. Slope and aspect can be obtained from the DEM raster file (using a GIS or a geospatial data library). Slope is a file where each cell is labeled with a number (degrees) meaning the slope of the terrain. Aspect is a raster map where each pixel is labeled with the orientation of the slope. This is a number from 0 to 360, 0 for north-facing slopes and a value of 180 for south-facing slopes.

Once simulation starts, user can change simulation properties: for example, new ignition points can be set, firebreaks can be draw over the land, etc. In the next paragraphs we will explain these functionalities in more detail. In addition, during simulation time, wind direction and speed can be changed using the user interface. That feature allows *SIP* to respond to the typical wind dynamic characteristics.

The *SIP* simulator has two kind of outputs: on the one hand, fire progress is shown at the user interface (Figures 2, 3, 4, 5, and 6). On the other hand, text files with fire progress information can be saved. Fire progress can be stored in two different ways: a raster map with cells labeled with 1 when burned, and labeled with 0 for not burned cells; a raster map with cells labeled with the time step at which fire reaches that cell. These output raster files can be opened using GIS systems. Finally a raster fire risk map can be generated and the Fire Weather Index (FWI) values can be stored too. The FWI index will be presented in the next Section.

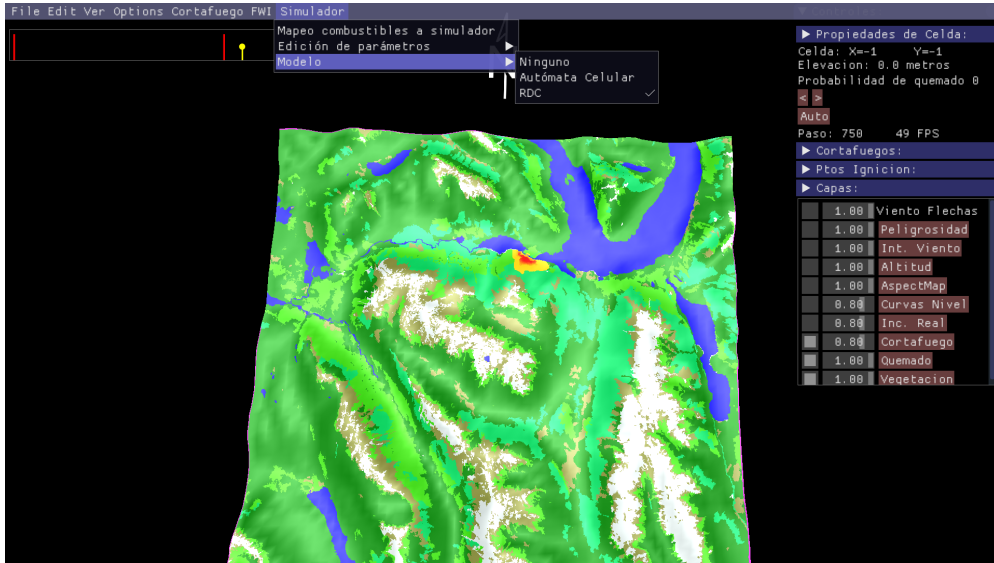


Figure 2: *Simulador de Incendios Patagonia (SIP)* main view. The main menu is on the top of the figure. The underlying fire propagation model can be selected from that menu. The frame on the right shows information about ignition points, firebreaks, and the list of input layers with buttons to turn them on and off, as well as bars to change their transparency.

4.2. Implementation details (SIP functionality)

As was already mentioned, our simulator implements two mathematical models for simulating fire propagation on a given landscape. The model selection can be done from the simulator main menu as shown in Figure 2.

Landscape features are part of the simulator inputs (Figure 1). For each simulation, the user can choose the scenario where fire spreading will take place. As was mentioned, those layers i.e., topography, vegetation, and wind (speed and direction) should be attached as raster files. The visualization of each of these raster files can be turned on and off or the transparency of each layer can be modified by the user. According to the selected propagation model, some or all of the information contained in those layers is taken as input for the model. Figure 2 right panel shows the list of layers, in this example the landscape is coloured based on each cell content. Vegetation of each cell was classified in three different forest categories, shrubland and pasture (four shades of green and brown) considered as fuel; lakes and rivers (blue), snow, rocks, high Andean vegetation (white) considered as not fuel for fire propagation.

The vegetation map is a raster map with integer values that represent each fuel type. Firefighters define the inflammability of each pixel based on their experience in the field. The raster maps derive from vectorial maps and were made using QGIS and GDAL library.

Figure 3 shows the landscape map zoomed and rotated. Different overlapped layers are showed: vegetation, beginning of the simulated fire (red cells) and the real fire map (yellow cells) with transparency set at 55%. With this layer configuration, the user can compare simulated and real fire scars. Figure 3 shows two simulated fires, starting from different ignition points that the user can easily setup with the mouse either at the beginning or during the simulation.

During simulation time, the fire can spread forward or backwards in time. Historical information of the fire spread is saved and then used in order to rewind the simulation. This feature is specially useful when is combined with the next skill.

Firebreaks can be easily drawn over the landscape with the mouse. In many cases a firebreak is a fuel treatment that avoids fire propagation. During simulation time, one or many firebreaks can be created and afterwards each of them can be activated or turned off. Firebreaks can be straight lines or can be drawn manually. The list of firebreaks can be managed from the right panel of the simulator and can be saved as a new feature of a specific scenario. Simulator firebreaks and the capability of propagating fire forward or backwards are useful tools for testing different strategies of fire control, reduction or prediction. Figures 4, 5 and 6 show three different moments of simulation, where those functionalities are used.

In Figure 7 we show the real fire scar (yellow) overlapped with the simulated fire progress using the RDC model (red). This fire corresponds to a real natural fire occurred during 1999 in the northwest Argentinian Patagonia. During

Forest Fire Simulation in Patagonia

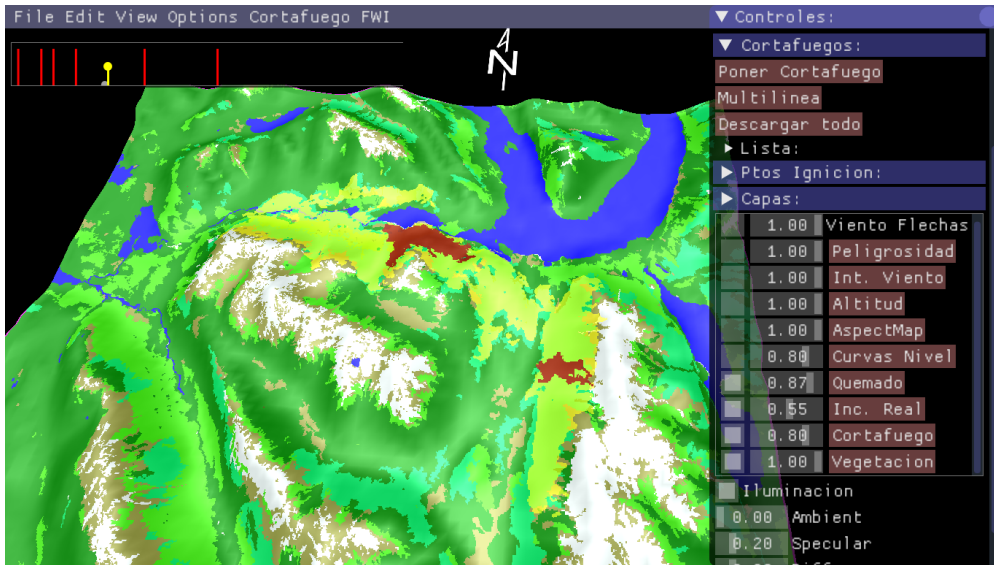


Figure 3: Real (yellow cells) and simulated fires (red cells) are overlapped in this landscape view. Data layer transparencies help to customize the information that the user wants to visualize.

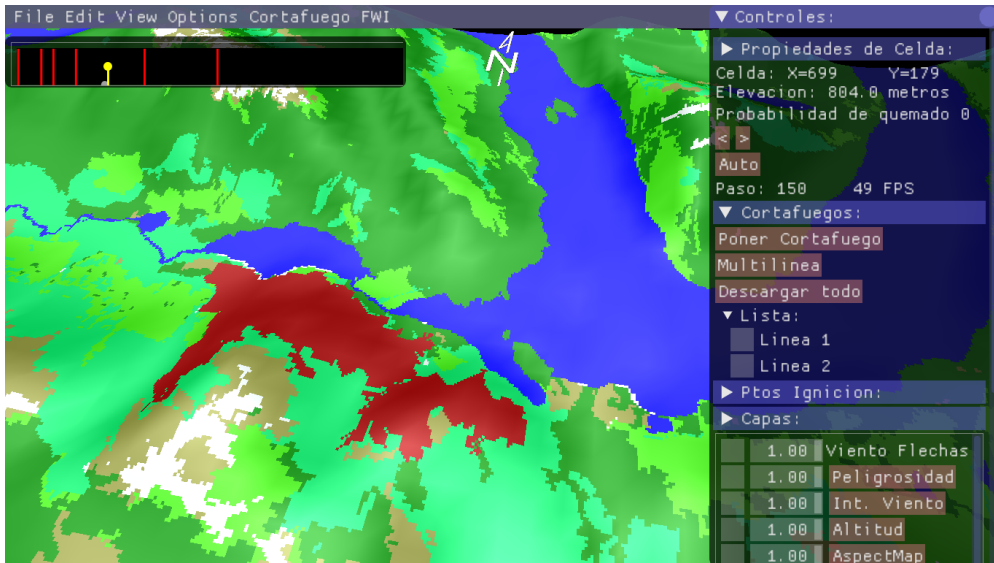


Figure 4: Step 150 of the simulation. The fire area was zoomed and rotated.

this fire 3831 hectares were burnt (Mermoz (2005)). As we see in Figure 7 there is an acceptable agreement between simulations and data (Jaccard coefficient = Intersection sites/ Union sites = 0,53), taking into account that we are comparing with real data, and that we are considering only one set of (arbitrary) parameters. Unfortunately we don't have the temporal information of this fire, but it can be completely reproduced after changing wind direction in simulation time. This behavior will be explored in the near future.

During a simulation, fire progress stops when: a) fire reaches a map edge, or b) when environmental conditions stops the fire. For the CA model, it happens when the ignition probability of a target cell (Eq. 7) is low enough that does not exceed a generated random number (the propagation probability is calculated using the eight nearest neighboring cells). For the RDC model the fire stops when the fraction of burning fuel (I in Eq. 1, 2, and 3) is negligible.

Forest Fire Simulation in Patagonia

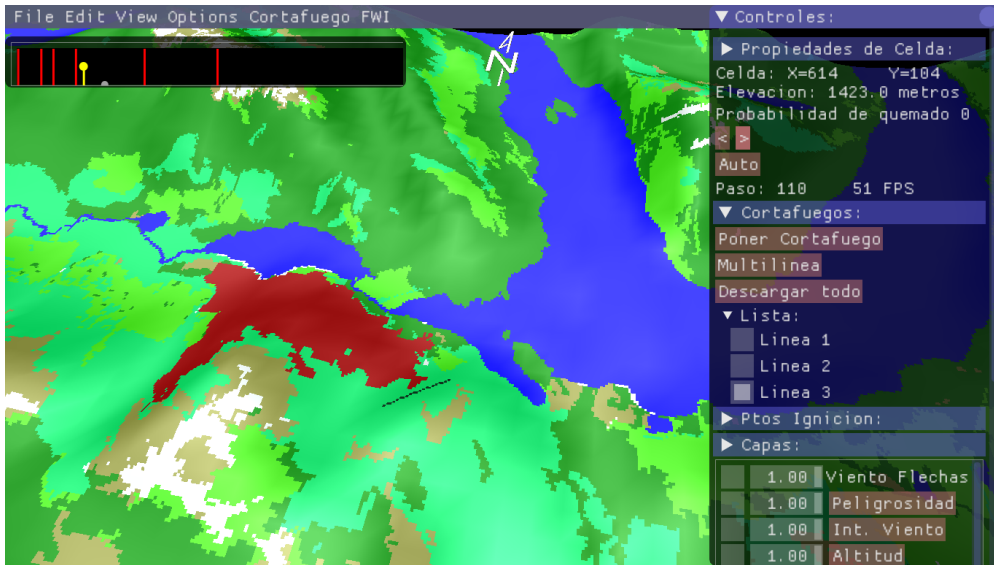


Figure 5: Step 110 of the simulation of Figure 4 (fire was moved backward 40 steps). Afterwards a linear firebreak was set up. Fire area was zoomed and rotated.

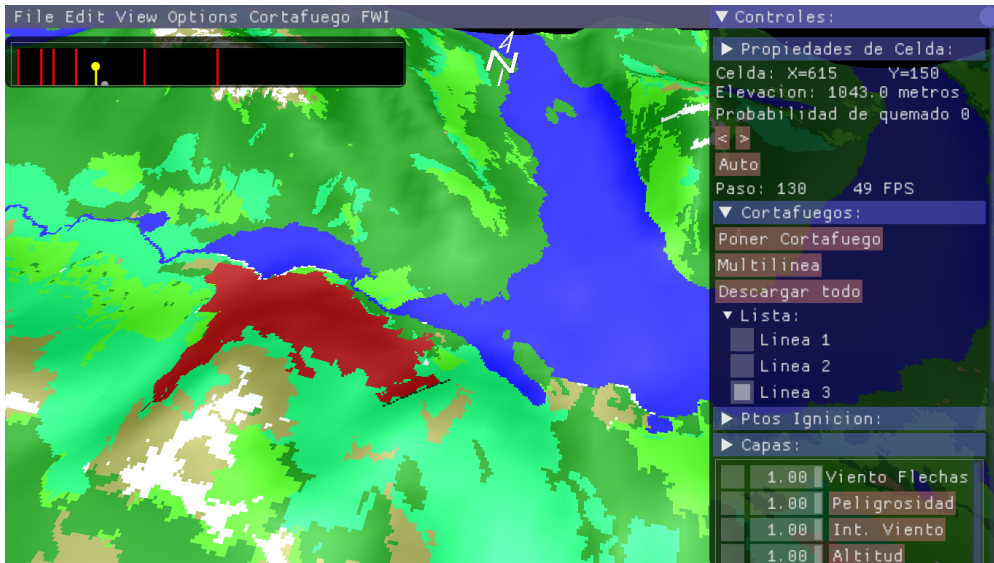


Figure 6: Simulation is again moved forward (step 130 of the simulation). As expected, the firebreak stops fire propagation.

The Canadian Fire Weather Index (FWI from now on) (Government of Canada (a); Taylor, Pike and Alexander (1996); Van Wagner C. E. and Pickett T. L. (1985); Van Wagner C.E (1987)) quantifies the effects of fuel moisture and weather conditions on fire behavior. In spite that the FWI was developed for Canadian landscapes, it was proved to accurately represent fire occurrences in some ecosystems all over Argentina (Zacconi (2018); Dentoni, Muñoz and Marek (2015); Dentoni, Muñoz and Epele (2007)). In Patagonia it is daily used by the forest fires brigade to asses fire danger. This is because FWI is related to the humidity content of three organic fuel layers where weather has a similar impact, independently of the forest floor and hummus composition. Therefore, the FWI was included in our simulator (Waidelich, Laneri and Denham (2018); Waidelich, Zimmerman, Laneri and Denham (2019)) and the user can select and upload a meteorological data input file. The FWI value is calculated for each day in that input file. Afterwards the user can choose a specific day to visualize the fire risk over the landscape, that is calculated based on the FWI and the

Forest Fire Simulation in Patagonia

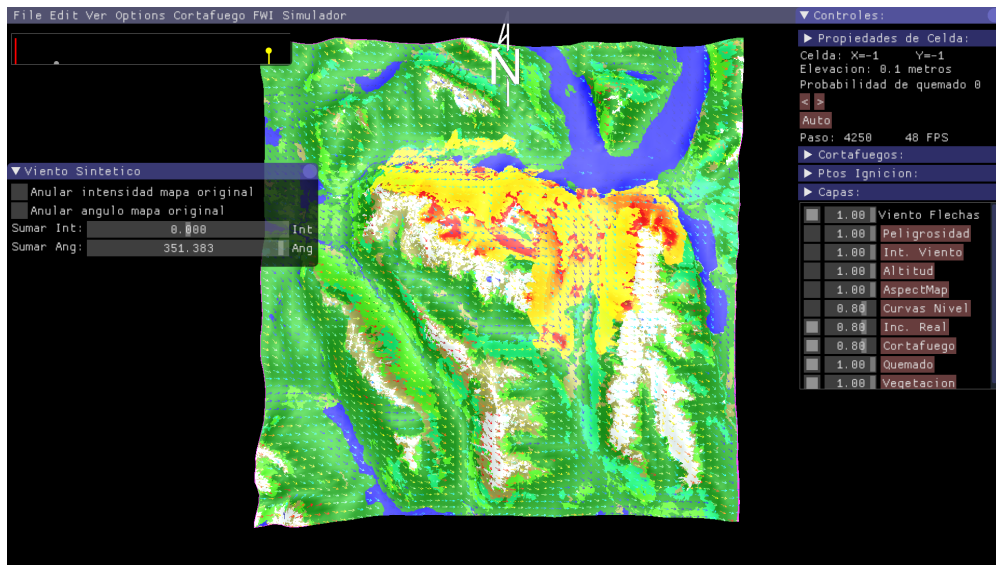


Figure 7: Simulations performed with the RDC model (red) overlapped with real fire scar (yellow) using (arbitrary) suitable parameters.

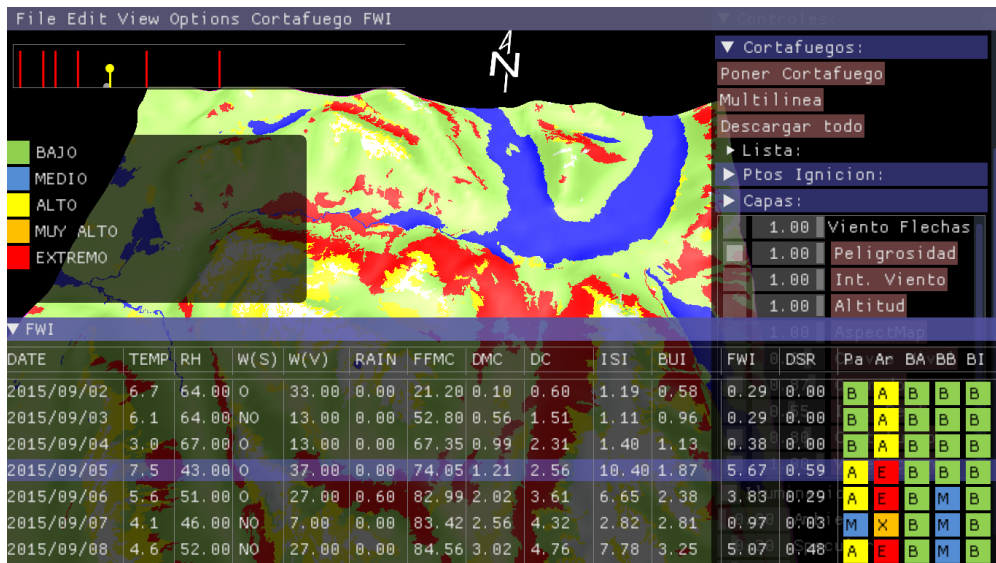


Figure 8: FWI embedded into the *SIP* simulator. Once FWI is calculated, the user can choose a day of the list to visualize the risk map. Color categories are: low risk (green), medium (blue), high (yellow), very high (orange), and extreme risk (red).

fuel of each cell. In Figure 8, each map cell is coloured according to the fire risk based on FWI and cell vegetation type. The fire risk is derived from the FWI combined with local vegetation abstractions (previously described) and is tabulated in (Government of Canada (a); VanWagner (1987); Pickett (1985)). The FWI is composed by the Build Up Index (BUI) and the Initial Spread Index (ISI). The previously mentioned table assigns the combination of ISI, BUI and vegetation abstraction to one of the five classes of risk: low, moderate, high, very high, and extreme. This risk assessment is used by firefighters at ICE (Administración de Parques Nacionales (2022)) in the Nahuel Huapi National Park.

Table 2

Comparison of GTX 1080 and GTX 1080Ti architectures and NVIDIA Jetson Nano. *Last row prices in US dollar correspond to official exchange value during 06/08/2022 in Argentina (1 US\$ = 126.25 \$ar)

	GeForce GTX 1080	GeForce GTX 1080Ti	Jetson Nano
#CUDA Cores	2560	3584	128
Microarchitecture	Pascal	Pascal	Maxwell
Memory (GB)	8	11	4
GFLOPs (Simple Precision)	8228	10600	472
USA Launching price (US\$)	599	699	99
Argentina's price (ar\$)	210000	266000	40000
Argentina's price (US\$)*	1663.36	2106.93	316.83

4.3. NVIDIA Jetson Nano for SIP execution

The NVIDIA Jetson Nano (NVIDIA (2019)) is a small and powerful computer suitable for IA, neural networking, and parallel CUDA programs. The main characteristics are listed in Table 2. The dimensions of the Jetson Nano are: 100mm x 80mm x 29mm and it's cheaper than GPUs for desktop PCs or laptops.

The NVIDIA Jetson Nano developer kit allows a simple Operating System installation and the use of CUDA libraries for parallel programs (including libraries with graphical purposes).

Even though NVIDIA Jetson Nano hardware is simple and it has not the high computational power of others GPUs, our simulator runs in a suitable way in that architecture under all tested scenarios. The FTRT requirements are also maintained using the Jetson Nano architecture. Different features like simulation run times, user interaction and different input data sizes (depending on the scenario) were successfully tested. Using *SIP* simulator in the Jetson Nano device has the following advantages (see Table 2):

1. The Jetson Nano is a full computer itself. It has a CPU and a slot for a microSD unit for permanent storage. In addition, 128 CUDA cores for parallel processing and it's convenient for carrying purposes, having in mind its use in the field.
2. Hardware performance. Despite the low number of CUDA Cores, its performance is acceptable taking into account the cost per FLOP.
3. Hardware costs. Table 2 shows GeForce GTX 1080, GeForce GTX 1080Ti and Jetson nano prices. The difference between prices is significant. It is important to take into account that in Argentina low budget is assigned to institutions related with wildfire control and mitigation.
4. Low weight hardware and small dimensions.

Prices, dimensions, and weight result in a suitable computer for the *SIP* simulator. The easy of transport and operation could open the door to many possible applications. For instance, after mounting it on a drone, the input of some data in real time (like a local change in wind direction or intensity) could enhance simulation and prediction accuracy of the local fire propagation front. The comparison was made using GeForce GTX 1080 series due to this architecture is available nowadays in Argentina. NVIDIA RTX 30 series are available too but the prices are noticeable more expensive.

5. Conclusions and open lines

Computational tools related to wildfires are necessary to improve the decision-making process or to increase knowledge about forest fire behaviour in an area of interest.

We developed a High-Performance forest fire simulator that was implemented in CUDA C and OpenGL to be executed on graphic cards achieving HPC requirements. The GPUs are used to execute the underlying fire propagation mathematical model as well as the interactive user interface. This user interface allows a friendly interaction using mouse and keyboard, also solved on the graphic cards. Therefore, the execution times are short, fulfilling the requirements of Faster Than Real Time.

Using our *SIP* we can perform computer simulations with different mathematical models and visualize the fire propagation probability on the field under a specific scenario of interest. This can be helpful to design plans for fire

control and mitigation, to set up firebreaks, or to plan evacuation strategies. All these actions increase the efficiency of fire-fighting, reducing damage and loss provoked by the fires.

The simulator was provided with several functionalities, most of them discussed with fire-fighters of the *Parque Nacional Nahuel Huapi* in Argentinean Patagonia. Our communication with these experts allowed us to create an application tailored for the local needs and landscape characteristics, to be used for wildfire prevention, control, and mitigation.

The most important functions implemented on *SIP* are: a) the landscape setting, using raster maps where fire spreading will take place e.g., topography, weather, and fuel data b) ignition points that can be set by the user in any cell of the landscape c) advance and rewind of fire propagation, being the fire history stored with a specific frequency of model steps, so the user can go back to a certain state of the fire in the past d) to set firebreaks and test how fire propagates with a new layout of fuel and firebreaks e) to set transparencies for each layer of information, so the user can turn on and off each layer or modify its transparency. In this way it is possible to overlap different layers and customize the information visualization f) another useful feature of our simulator is the assessment and visualization of the Fire Weather Index. This index is useful in order to assess the risk of fire propagation. g) the possibility of changing the underlying mathematical model for propagation.

The last feature allows the user to choose between two fire propagation models. One of them, the RDC model aims to describe the physical mechanisms that produce fire propagation. This model has to be validated by fitting it to data, something to be done in the near future. A procedure similar to the one performed in (Denham and Laneri (2018)) to validate the statistical model, will be done using the RDC model. The combination of genetic algorithms with Bayesian computation to fit model to data, will result in a suitable set of parameters that will give us a better idea of local propagation e.g., average propagation velocity, fire front width or heat of ignition. Also with the RDC model the temporal dimension could be assessed by the study of the fire front depth and its relation with the fire front velocity.

The *SIP* simulator was developed in Argentina thinking about its use for local geographical scenarios, but under an open source philosophy that opens the possibility of adapting the code for other regions of the world.

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CRedit authorship contribution statement

Monica M. Denham: Conceptualization of this study, Methodology, Software, Writing - Original draft preparation.
Sigfrido Waidelich: Software. **Karina Laneri:** Conceptualization of this study, Methodology, Software, Writing - Original draft preparation.

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