

-ORIGINAL ARTICLE-

# First Steps Towards a Dynamical Model for Forest Fire Behaviour in Argentinian Landscapes

## Primeros Pasos Hacia un Modelo Dinámico del Comportamiento del Fuego en Incendios Forestales para Paisajes Argentinos

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### Abstract

We developed a Reaction Diffusion Convection (RDC) model for forest fire propagation coupled to a visualization platform with several functionalities requested by local firefighters. The dynamical model aims to understand the key mechanisms driving fire propagation in the Patagonian region. We'll show in this work the first tests considering artificial landscapes. Synthetic maps were created and used to test our RDC model, analysing step by step the effect of every landscape characteristic on fire propagation. Simulation results were in agreement with the expected fire behavior in the presence of heterogeneous vegetation, wind and slope gradients.

The simulator, developed in CUDA C/OpenGL, integrates several layers including topography, weather, and fuel data. It allows to visualize the fire propagation and also to interact with the user in simulation time. The Fire Weather Index (FWI), extensively used in Argentina to support operative preventive measures for forest fires management, was also coupled to our visualization platform. This additional functionality allows the user to visualize on the landscape the fire risks, that are closely related to FWI, for Northwest Patagonian forests in Argentina. Real land coverage, topography and weather maps were used in order to calculate FWI and fire risk. Those maps were used to feed our simulator to show, in a friendly visual way, the fire risk under different possible scenarios.

**Keywords:** Forest Fire Simulation, Graphic Processing Units, Reaction-Diffusion-Convection Model

### Resumen

En este trabajo se presenta un modelo de Reacción-Difusión-Convección (RDC) para la propagación de

incendios forestales implementado en un entorno de simulación y visualización. Dicho simulador posee amplias y útiles funcionalidades las cuales han sido planificadas junto a expertos combatientes del fuego de nuestra región. El modelo presentado intenta comprender los mecanismos claves detrás de la propagación del fuego en la región Patagónica argentina. En este trabajo se exponen los primeros resultados del modelo en escenarios artificiales. Se generaron mapas sintéticos que fueron utilizados para probar nuestro modelo RDC, analizando paso a paso el efecto de cada una de las características del paisaje en la propagación del incendio. Los resultados de las simulaciones concuerdan con el comportamiento esperado del fuego en presencia de vegetación heterogénea, gradientes de viento y de pendiente.

El simulador, desarrollado en CUDA C/OpenGL, integra capas de información que incluyen topografía, meteorología y datos del combustible. Dicho simulador permite visualizar la propagación del fuego y que el usuario interactúe con el simulador en tiempo de simulación. Además, en dicho simulador se implementó el Índice Meteorológico de Peligro de Incendio (FWI: Fire Weather Index). Este índice es muy utilizado en Argentina para dar soporte al manejo y prevención del fuego. El cálculo de este índice en el simulador permite visualizar el peligro o riesgo de incendio para escenarios del noroeste de la Patagonia Argentina. Para la evaluación y uso del Índice Meteorológico de Peligro de Incendio se han utilizado mapas reales de cobertura de vegetación, topografía y meteorología. Dichos mapas se usaron para alimentar el simulador y mostrar en una forma visual amigable, el riesgo de incendio en diversos escenarios posibles.

**Palabras claves:** Modelo de Reacción Difusión Convección, Simulación de Incendios Forestales, Unidades de Procesamiento Gráfico.

## 1 Introduction

Every year, Argentina is the scenery of several and sometimes huge forest fires. Approximately 18 millions hectares of native forest, shrubland, grassland and exotic species plantations were burned from 2000 to 2013 in our country [1]. Several lives were lost on January 1994 in a grassland-shrubland fire near Puerto Madryn, Chubut, Argentina [2].

Approximately 10 millions of hectares were consumed by wildfire in Australia during their last summer season (2019-2020), with more than a thousand million of animal deaths, 2500 burnt buildings and a total of 26 human fatalities. It is estimated that approximately 300 millions tonnes of CO<sub>2</sub> were released into the atmosphere while CO<sub>2</sub> natural re-absorption was reduced due to lost forest areas. From January to September 2019, more than 91 thousand wild fires were reported in the Brazilian Amazonian, more than 20 thousands in Bolivia and more than 14 thousands in Colombia. Amazon rain-forest acts as a filter of CO<sub>2</sub>, one of the global warming sources, releasing oxygen to the atmosphere.

In Argentina, a National Plan for Fire Management (PNMF in its Spanish acronym) was implemented in 1996 by the Secretary of Sustainable Environment Development [2]. The first objective within this Plan was to define indicators of fire risk that could be accurately applied to different geographical regions in Argentina. The Fire Weather Index (FWI), originally published in 1970 by the Canadian Forest Service [3], was one of the indexes chosen to that aim, because is part of a modular system that could be gradually implemented. Also it was proved to accurately represent fire occurrences in different ecosystems all over Argentina [4, 2]. This is because FWI is related to the humidity content of three organic fuel layers where weather has similar impact. Hence, it does not depend on the species composing both the forest floor and hummus. Inputs for FWI calculation are several meteorological variables and it accounts for the effects of fuel moisture and wind on fire behavior [3]. In a previous work ([5]) we presented the main features and implementation of this index within the forest fire simulator. Our team is working in collaboration with the staff of the Fire, Communications and Emergency Department (known in Spanish as ICE) of the Nahuel Huapi National Park (PNNH in its Spanish acronym), in San Carlos de Bariloche city.

Local FWI is an indicator for fire risk that is defined using the fine fuel humidity content, assessed taking into account meteorological conditions, mainly rainfall and humidity of the last days. This index is categorized in five levels: low, moderate, high, very high and extreme.

Firefighters from ICE, combine FWI values with local vegetation information to obtain the local fire risk.

Once a fire occurs, firefighters mainly make use of their experience to define the best operative strategy to stop fires. Therefore the need of a wildfire simulator tailored for local requirements becomes more evident every day. However, a proper fuel type classification (which is another crucial input for an accurate prediction system of fire behavior) is currently lacking in Argentina.

In previous works we developed a visual forest fire simulator [6] [7] that uses several layers, e.g. topography, weather, and vegetation data, to simulate fire propagation. Our simulator was developed with a High Performance Computing technology and programmed in CUDA C and OpenGL. A cellular automaton computation, landscape and fire progress visualization, as well as user interaction are executed on Graphic Processing Units (GPU) to enhance efficiency. The FWI computation was described in [5]. In the following sections we will introduce the main features of our simulator coupled with the new forest fire model. This physical model will help to identify the physical mechanisms driving fire spreading in our regional conditions of topography, weather, and fuel type.

In this work a Reaction-Diffusion-Convection model (RDC) for wild fire spread is presented. In previous works Reaction Diffusion models were used to describe infectious disease propagation that occurs in a similar way as forest fires [8]. We can make an analogy with such a model by considering fire fuel as the susceptible individuals and burning cells as infected individuals. Additionally in this work we add new convective terms that take into account the effect of wind and slope on fire propagation.

In related work [9] a theoretical continuum-deterministic reaction diffusion model was defined in order to describe the dynamical evolution of the wild fire. This reaction diffusion model, describes the evolution of the system between two homogeneous steady states: the state corresponding to the whole forest green and the state corresponding to the whole forest burned. Both states are connected by a traveling front with a particular speed (which must fulfill some restrictions). The value of  $n$  is the normalized number of burning trees, which changes with time and position. Its evolution is given by the hyperbolic reaction diffusion equation. Distance between trees, capacity of a green tree to be burnt, density of green and burning trees, shape of the fire front, initial number and shape of burning trees are taking into account by the mentioned reaction diffusion model.

The work in [10] presents a numerical method for fire spread simulation modelling. This paper is a contribution to generally applicable models of fire spread through fuel beds, by means of simple models but taking into account radiation, moisture content, wind and slope effects. They proposed a diffusion term in order to avoid the computing cost of a convolution operator that represents the radiation from the flame. They

conclude that numerical examples show the effect of vegetation moisture, decreasing the velocity of the fire front, as well as the effect of wind and slope on fire propagation, increasing the velocity of the fire front in the corresponding direction.

Therefore, related works show different implementations of reaction diffusion models for fire spread equations. However, to our knowledge there are no works on the kind, developed in graphic processing units (GPU's). Our model is developed in GPU's, taking into account its main characteristics in order to develop high performance applications. We created a model that takes into account topography, weather and fuel, in addition to the physics mechanisms involved in fire propagation. High quality of simulations and low execution times are our main goals.

In the next sections we present the two main lines of our research. On the one hand, we expose the FWI implementation and visualization using real maps. On the other hand, we report the first results using RDC model for forest fire spread with synthetic maps.

Our main goal in the near future will be to integrate those two developments in our simulator using real environmental maps to visualize fire spread in real scenarios.

## 2 Forest fire simulator

Our application is based on a parallel cellular automaton to simulate forest fire propagation [11] [6]. The parallel application was developed on CUDA C for NVIDIA GPGPU (General Purpose Graphic Processing Units) to achieve high performance applications.

Landscape is modeled by 2D matrices of the same size, accounting for topography, weather, and fuel. Fire progress is an additional matrix where each cell can be in one of the following three states: burned, burning or not burned. Each cell has specific attributes, e.g. topography, weather, vegetation, and the status of the cell.

The state of a target cell changes according to some probability that depends on the state and features of its 8 nearest neighbours as explained in [6].

In a sequential solution, the cellular automaton goes cell by cell, iterating the fire spread model across each row and column. Then, if the fire map is  $N \times M$  (rows x columns), and the fire spread model has time complexity equal to  $O(S)$ , with  $S$  the number of arithmetic operations per cell, then the simulator time complexity is  $O(NMS)$ . In this work  $S$  is constant in time, given that fire spreading is based on arithmetic operations over a target cell and its nearest 8 neighbors.

Our parallel cellular automaton reduces the time complexity to  $O(S)$ , because loops that iterate over the rows and columns are replaced by a matrix of threads that executes all arithmetic operations simultaneously. However given that an infinite number of concurrent threads is not possible, a more realistic analysis is to

consider  $O(NMS/p)$  where  $p$  is the number of available GPU cores.

Furthermore, visualization of fire progress and user interface was developed taking into account high performance requirements. Visualization of fire propagation landscape, main and secondary menus and layer information, were developed using OpenGL and executed in parallel on the GPU. In addition, user interaction with the simulator is solved with OpenGL and efficiently executed on GPU [7].

The application main view shows fire spread on the landscape and its main features. Moreover, the user can interact with the graphical interface in simulation time. The most important functionalities are: fire-cuts definition, new ignition points setting, zooming, rotating and shifting fire landscape. Our simulator stores the history of fire growth, then fire can go forward and backward. In particular the dual fire spread direction and user customized firecuts are a very valuable tool for firefighters and fire control agencies.

Raster files of vegetation, aspect, slope, wind speed and direction, real fire map (if any) are some of our simulator input layers. The outputs are also raster files, all of them compatible with any GIS (QGIS, ArcGIS, etc). The raster files define the spatial resolution of the underlying cellular automaton. Inspired on GIS layer manipulation, our simulator displays a visual panel where each data layer can be managed. They can be turned on and off by the user. Additionally, layer transparencies can be changed in order to get the best fire landscape view during simulation. For example, fire progress layer transparency and fuel layer transparency can be handle in order to evaluate how the fire spreads over different fuel covering.

Moreover, the FWI computation and visualization was coupled with our simulator. The FWI together with landscape vegetation coverage determine fire propagation risk.

As a first step, we implemented the set of equations for FWI in C and CUDA based on [12] and [13]. In a second step local firefighters helped us to define fire risks levels based on surrounding vegetation and local weather.

The FWI index is made-up of 6 components: the first three are fuel moisture codes that follow daily changes in the moisture contents of three classes of forest fuel with different drying rates. The three last components are fire behavior indexes representing rate of spread, fuel weight consumed, and fire intensity [12].

Those three moisture contents codes are: the Fine Fuel Moisture Code (FFMC) that represents the moisture content of litter and other cured fine fuels, the Duff Moisture Code (DMC), which represents the moisture content of decomposing organic matter and the Drought Code (DC), which represents a deep layer of compact organic matter. For each of these three indexes an additional index is computed, one for wetting

by rain and one for drying.

The two slow-reacting codes (DMC and DC) need date information because they depend on the variation on the day length according to the season.

The three moisture codes are combined with wind to form two intermediate indexes: Initial Spread Index (ISI) and Buildup Index (BUI). ISI is a combination of wind and the FFMC that represents rate of spread without fuel influence. BUI is a combination of DMC and DC that represents total fuel available for fire consumption.

Then, BUI and ISI are combined to compute FWI: the intensity of the spreading fire as energy output rate per unit length of fire front [12] [13].

Codes and indexes of FWI are defined by mathematical functions presented in detail in the Canadian Forest Service technical reports: [12] and [13]. Furthermore, for each code (FFMC, DMC, and DC), the drying phase and the rainfall phase equations are described. In particular the report [13] shows implementation procedures, inputs and outputs. Our last work ([5]) gives several FWI details and how we had embedded this index into our simulator.

In Fig. 1 we show a simulation landscape and the corresponding table of fuel references. This scenery corresponds to a northwest Argentinian Patagonia area of 25 km x 25 km extension (at 41°21'59" S, 71°38'46"W). Simulator inputs are raster files with different layers of information [7].

Using FWI main menu item, the user can select an input meteorological data file (a list of: date, temperature, relative humidity, wind speed/direction, and rainfall). Once the input data file is chosen, FWI equations are executed and subsidiary codes and indexes are computed. Results are presented in a tabular way (Fig. 2).

As shown in Fig. 2 and Fig. 3, the last four columns of the table display one of the 5 levels of fire risk for the corresponding fuel. For our area of interest 7 fuels are considered: lakes or rivers, no fuel, two type of native forest: nothofagus predominant mixed forest and cypress and lenga (*Nothofagus pumilio*) predominant mixed forest (columns BA and BB respectively), exotic plantations (column BI), shrubland (column Ar), and grassland (column Pa).

Then, fire danger or risk is calculated based on ISI, BUI and FWI values combined with fuel of each cell. Following previously mentioned works, fire risk was divided into 5 categories: low, moderate, high, very high and extreme (initials in figures are B, M, A, X, E respectively). These values are calculated for each day registered in the input file. Each risk level is properly coloured on the table. A window appears over the FWI table with the corresponding colours for reference. This windows can be open or closed regardless of the display of the FWI table.

When the layer called "Peligrosidad" (fire risk) is turned on (using the right panel) and a specific day

is selected from the FWI table, the underling map is coloured based on the fire risk of the selected day in combination with the cell fuel (Fig. 2 and Fig. 3). These two figures show the same map when different days are selected in the tabular FWI window.

To perform this test, 30x30 m raster maps were used. The same resolution was used in order to generate raster maps with fire risk information. All these maps can be then managed using GIS systems.

This is the state of the art of our simulator. In the next section we introduce a new fire behaviour model based on reaction, diffusion and convection processes, to simulate fire propagation.

### 3 Reaction - Diffusion - Convection model

We present the first steps towards a new physical fire propagation model. This RDC model implements physical and chemical processes involved in fire spreading on a landscape, i.e. reaction, diffusion and convection. For instance, reaction represents the combustion in a given cell that produces heat that diffuses to neighbours cells and is transported through convection by wind and slope.

Fire spreads on a 2 dimensional grid from a cell to its 8-neighboring cells. Cells are composed by vegetation (or fuel) that can be in three possible states: not burnt, burning and burnt. The mathematical model is defined by the following equations that are computed for each cell of the grid:

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

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

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

where in each cell with coordinates  $\vec{r}$ , 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.

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

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

the integral of the quantity of fuel over the whole grid is constant. In other words, 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.

Making the analogy with an infectious disease propagation process [8], the susceptible fraction ( $S(\vec{r}, t)$ ) is the vegetation fuel fraction that is susceptible to be burnt. This fraction changes between grid cells in space and time. Besides, each cell has a fuel type that determines the heat transmission rate  $\beta$ ,

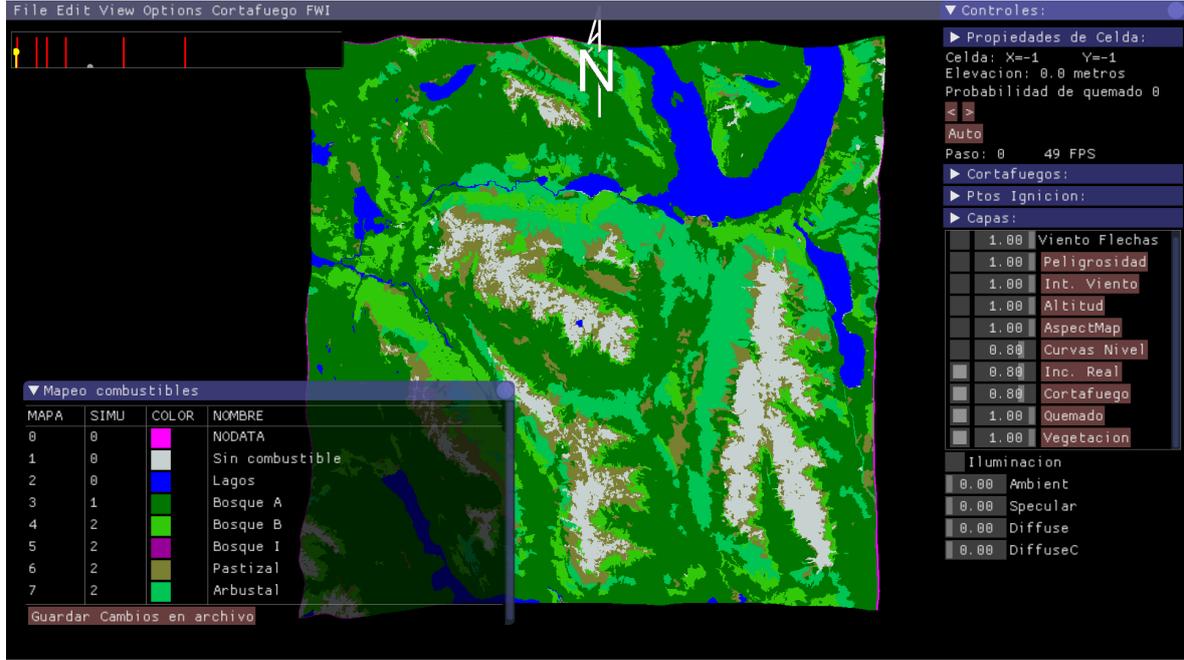


Figure 1: Simulator main panels: landscape top view and table with fuel references. Landscape reflect effects were turned off to emphasize local vegetation categories.

that we consider constant for each grid cell but can change between cells as in [8]. 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  $\beta$  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. 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'll 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'll consider it constant in time, taking the average wind intensity in each cell of the grid. The second term in Eq. (6) is proportional to the height gradient between a cell and its neighbouring cells, and the sign is defined by the fact that fire tends to propagate uphill in the absence of wind.

Finally the last term of Eq. (1) accounts for the fuel that is extinguished, with  $\gamma$  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 RDC model is a deterministic model, therefore in the next sections we'll present a representative simulation with a given set of parameters for each particular scenario.

### 3.1 RDC model implementation details

Our applications are designed and implemented in the context of High Performance Computing (HPC) technology. Our main goals are to obtain simulations of high quality and to minimize total execution time.

The RDC model (Section 3) was implemented in two different ways. These two versions will be exposed in the next paragraphs.

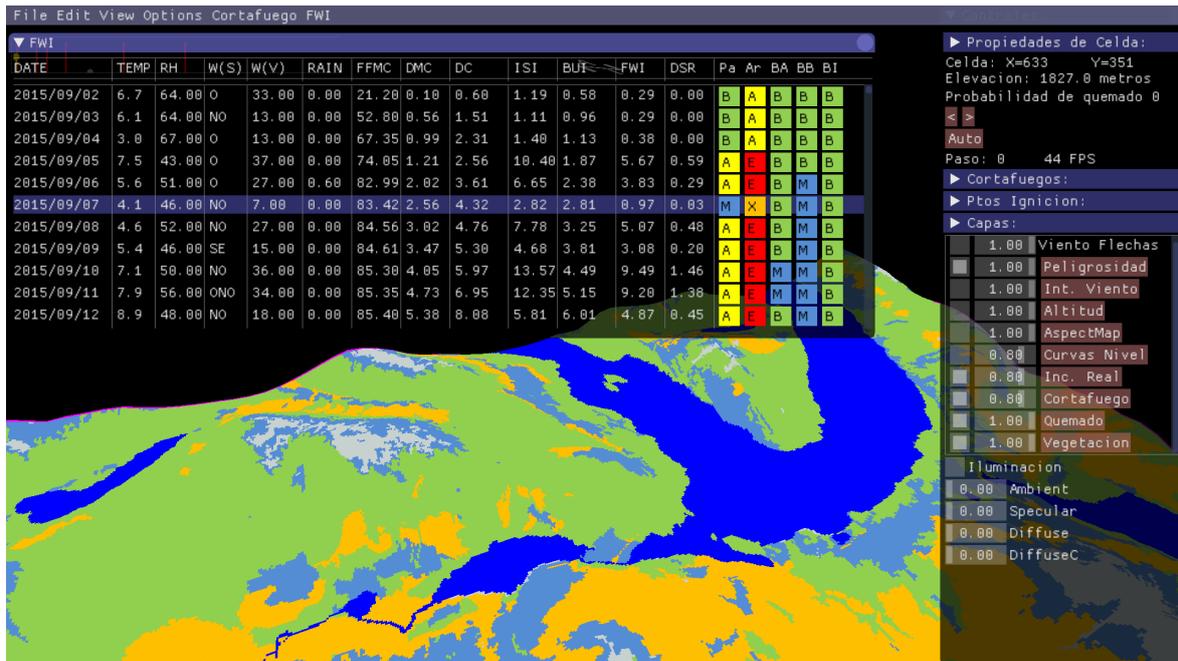


Figure 2: Effect of selecting a specific day (2015/09/07). Map is coloured according to fire risk level. In this figure landscape was zoomed and rotated in order to focus on Mascardi Lake area.

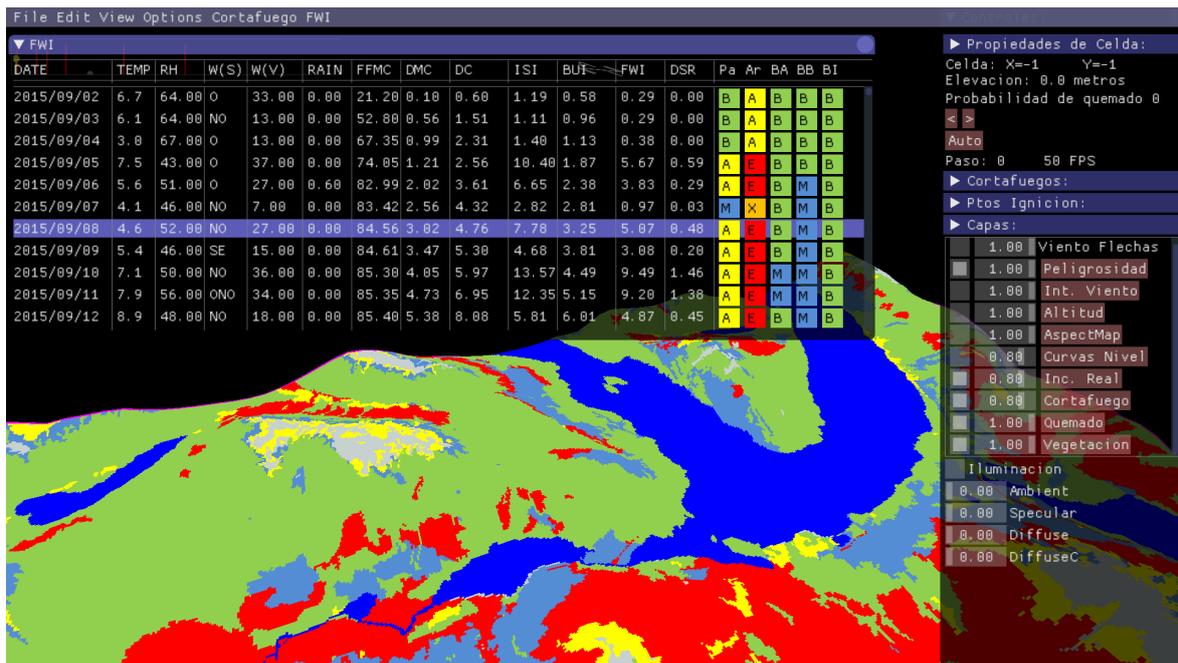


Figure 3: Effect of selecting a specific day (2015/09/08). Map is coloured according to fire risk level. In this figure landscape was zoomed and rotated in order to focus on Mascardi Lake area.

The first RDC model version was implemented using CUDA-C, in order to evaluate all terms of the differential equations (Eq. (1) and Eq. (2)). For each cell, values of  $S$ ,  $I$  and  $R$  were updated in parallel, using the Thrust Library, a high level library based on the Standard Template Library (STL). Using device and host vectors, iterators and transform Thrust functions, a simple and efficient CUDA-C

implementation of the RDC model was obtained. An operator function was implemented to update  $S$ ,  $I$  and  $R$  fractions every time step for the whole grid using high performance functions in parallel. Thrust selected the most efficient implementation automatically for our data structures and available hardware.

First results with that previous version had showed

the feasibility of the model implementation and supported the idea of coupling the RDC model to the visual interface.

For visualization purposes, a second version was implemented using C++ and GLSL language. This version implements all involved RDC equations in GLSL shaders. A shader is a little program that rests on the GPU. Each shader receives an  $uv$  coordinate which corresponds to a cell on the landscape map. Through each shader, the differential equations are calculated and new values for  $I$ ,  $S$  and  $R$  variables are obtained.

Shader output is a vector with RGB and alpha values for the cell, which is used in a final texture that will be drawn on screen when frames are updated. Colors chosen for the different fractions were: green for the susceptible fraction ( $S$ ), red for the fraction that is burning ( $I$ ) and black for the burnt fraction ( $R$ ). Screen refreshment is done after a given number of iterations because we are not able to notice frame actualization when all of them are performed.

Next section figures were obtained using the GLSL version of the model.

#### 4 Simulation results using synthetic maps

This section will expose the initial tests using the RDC model. Synthetic maps of 801x801 (rows x columns, squared cells) were constructed for testing purposes, so the effect of each of the terms in equations (Eq. (1), Eq. (2) and Eq. (3)) were studied as separated cases.

In the following sections we'll show fire propagation results, initially considering an homogeneous vegetation landscape with reaction and diffusion. Afterwards we add one by one vegetation heterogeneity, as well as convection wind and slope terms.

The graphical interface exposed in previous sections was adapted to be used with those artificially generated landscapes, to easily visualize the fire front for each scenario.

All maps have the same dimensions and the ignition point was situated at the same coordinates for all cases. These tests with synthetic maps will serve as a previous step before the use of real landscape maps for fuel, elevation and weather conditions. In this way, we can understand how the model works under controlled conditions before applying it to a real fire propagation scenario.

##### 4.1 Reaction and diffusion in homogeneous landscapes

As a first step we tested the RDC model with the first two terms of Eq. (1), i.e. only considering reaction and diffusion processes.

We generated some fuel synthetic maps with an

homogeneous substrate layer to perform the initial tests. Simulations show a circular fire progress, as expected if fire propagates on a unique vegetation type field in the absence of wind and slope (Fig. 4).

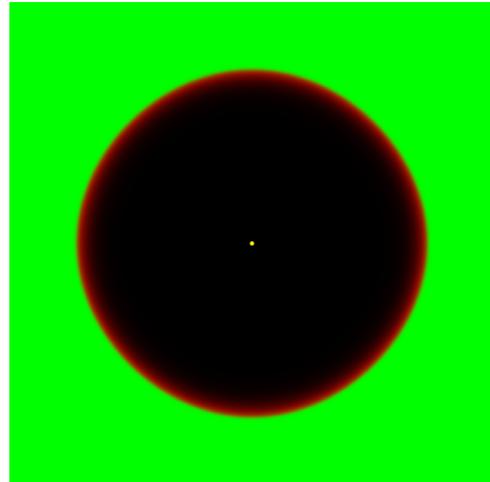


Figure 4: Simulation with reaction and diffusion terms on an homogeneous substrate all composed by one vegetation type ( $D=0.7$ ,  $\beta = 0.7$ ). The yellow point indicates the ignition position.

The fire front, shown in red in Fig. 4, is circular and symmetric around the ignition point (yellow). This behavior is expected given that diffusion occurs with the same intensity in all directions. Black cells are the ones that were already burnt and can not be burnt again, while green cells represent vegetation cells susceptible to be burnt.

##### 4.2 Heterogeneous vegetation substrate

Fire propagation in a non-homogeneous vegetation substrate is shown in Fig. 5. The artificial vegetation landscape was constructed with the following layer values that represent 8 different fuel types (from bottom to top): 0 ( $D = 0.0$ ,  $\beta = 0.0$ ), 1 ( $D = 0.1$ ,  $\beta = 0.1$ ), 2 ( $D = 0.2$ ,  $\beta = 0.2$ ), 3 ( $D = 0.3$ ,  $\beta = 0.3$ ), 4 ( $D = 0.4$ ,  $\beta = 0.4$ ), 5 ( $D = 0.5$ ,  $\beta = 0.5$ ), 6 ( $D = 0.6$ ,  $\beta = 0.6$ ), 7 ( $D = 0.7$ ,  $\beta = 0.7$ ). Therefore the propagation rate in each vegetation strip increases from dark green to light green (Fig. 5).

The values of the diffusion coefficient ( $D$ ) and the reaction rate  $\beta$  are arbitrary, but the relative values mimic real vegetation types that propagate fire with different velocities. Tests show that the model responds correctly for different land coverage, given that fire spread velocity increases, as expected, from bottom to top in Fig. 5.

Fire almost does not propagate towards the bottom direction because for those layers propagation velocity is very small. However propagation to the top is very fast which is consistent with layers with higher fire spread rates.

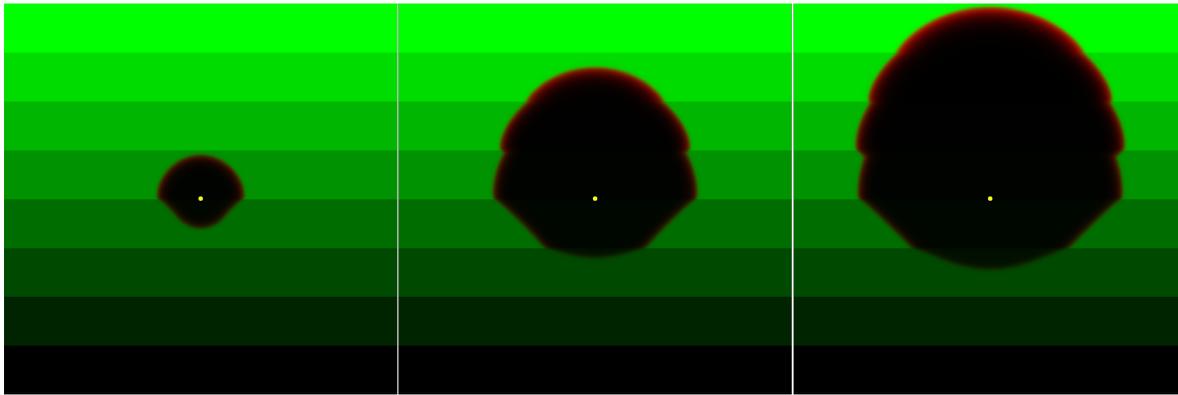


Figure 5: Simulation snapshots of one fire propagating on a stratified vegetation landscape. Fire starts at the yellow point. Vegetation susceptible cells (green), burnt cells (black), burning cells (red). Propagation rate increases from 0 (bottom dark green strip) to 0.7 (top light green strip). Left: fire propagates faster towards the top. Center and right: fire propagates mostly to the top through several vegetation strips, increasing its radius as spread rate increases.

### 4.3 Wind effect on fire spread

In this section we show simulations adding the wind convection term, i. e. the third term in Eq. (1) but considering only the first term of Eq. (6).

Wind velocity is represented by a vector, with a direction and a modulus or intensity. In order to test RDC model, we set a wind direction of  $45^\circ$  to the bottom-left (Fig. 6).

In Fig. 6 we show the ignition point, followed by two snapshots of the fire spread progression. As expected, the maximum velocity of the fire front occurs in the direction of maximum wind intensity.

Therefore in absence of slope, but in presence of reaction and diffusion, wind defines the fire spread direction. To show the effect of wind on propagation, fire intensity was set at an arbitrary value chosen to make the effect more noticeable. In the future, wind intensity and direction will be set up by real wind maps that will allow to study fire behaviour under variable wind conditions.

### 4.4 The effect of slope on fire spread

In this section we show simulations that are the result of adding the slope term in Eq. (1), i. e. the third term of Eq. (1) combined with the second term of Eq. (6). Model tests shown in this section were done with an homogeneous vegetation substrate, considering diffusion and conduction, without wind but with slope. Slope raster maps were made for testing, choosing arbitrary slope values that increase from the bottom to the top of Fig. 7.

As expected, fire spreads faster in the uphill direction, as can be seen comparing Fig. 4 with Fig. 7. In the first of the figures the fire front is a circle centered in the ignition point, that increases its radius with time (Fig. 4). By contrast the fire front in Fig. 7 is elongated in the uphill direction and not symmetric with

respect to the ignition point.

As expected, maximum fire front velocity occurs in the uphill direction. Towards the bottom of the graph propagation slows down abruptly given that occurs downhill.

## 5 Conclusions and Open Lines

Guided by the needs of our collaborators from ICE and the historical development of the fire management system in Argentina, we coupled to our forest fire simulator a tool for the assessment and visualization of the FWI. This computational tool was designed to be used by firefighters and is expected to be useful for fire management, training and communication. It was developed on graphic processing units to meet the requirements of a high performance real time application, with a friendly graphical interface.

We presented a new model for fire propagation based on RDC differential equations. As opposed to previously implemented statistical models [11], this new model aims to understand the physical processes that drive fire propagation in our region. The model performs well when tested for artificially generated homogeneous scenarios in terms of diffusion and conductivity. More tests performed with synthetic non-homogeneous vegetation maps, as well as with wind and slope maps behave also as expected showing that the RDC model is ready to be used with real environmental conditions maps. The next steps will include simulations for real landscapes.

We are also studying the link between the physical processes described by RDC model and FWI, to include some of its components in the model, so at least part of the input will be measurable quantities already familiar to people involved in fire management. For example for management purposes, one can start one or more fires in high level risk areas using the

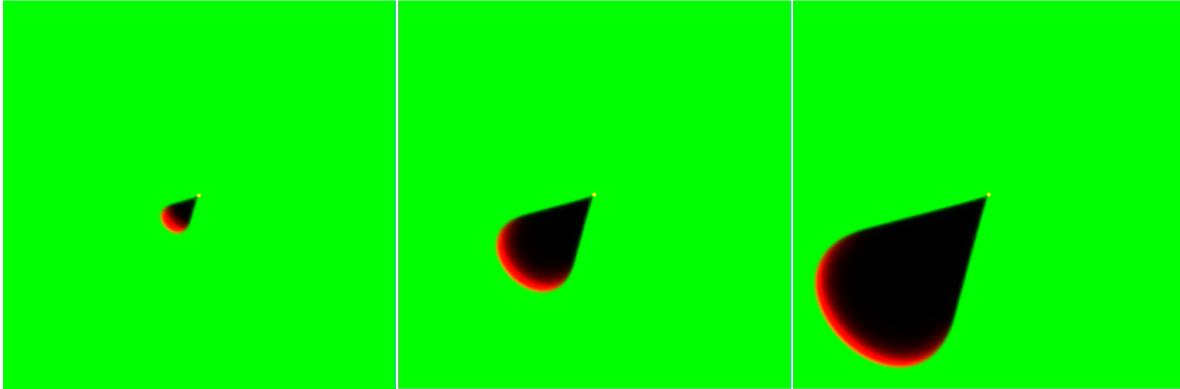


Figure 6: Simulation snapshots of a fire spreading on an homogeneous vegetation landscape without slope and constant wind. Fire starts at the yellow point. Susceptible cells (green), burnt cells (black), burning cells (red). Wind was set at  $45^\circ$  to the bottom-left direction, and wind intensity was equal for every cell of the grid. The output of one representative simulation is shown.

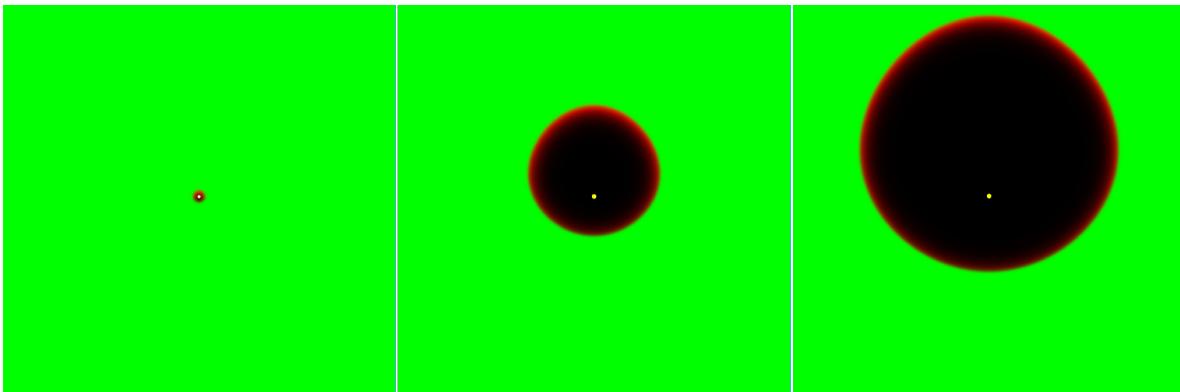


Figure 7: Simulation snapshots of a fire propagating on an homogeneous vegetation landscape with slope. Fire starts at the yellow point. Susceptible cells (green), burnt cells (black), burning cells (red). In all graphs slope increases from the bottom to the top. The output of one representative simulation is shown.

implemented visualization of fire risk and see the final burned area. Some useful application in this direction, could be the prediction of fire propagation in some region of interest. To that aim it will be necessary to fit the models to real fires and find the corresponding physical parameters that reproduce data, by performing a huge number of computer simulations. By using a Bayesian statistical framework it would be possible to obtain a biological plausible set of parameters associated to each of the terms of Eq. (1) and a posterior probability distribution for those parameters. Using different possible scenarios in terms of wind and vegetation, for example, it might be possible to predict fire behavior using the fitted model.

Stochasticity will be also part of the models when real data will enter into the model, given that weather input is not deterministic. The study of the different possible outputs for fire propagation in those scenarios will be one of the open lines. Wind variability and its inclusion will be another very challenging open line. In this direction we can consider wind data from meteorological stations in real time, in which case

we will need an application that respond to the real time requirements for simulations. Alternatively we can use models for wind assessment in which case we will need to couple our model to wind simulator, also needing to improve to the maximum our model performance to reduce simulation times.

Finally the possibility of extending the use of these tools for other regions in Argentina will certainly represent a formidable challenge for the future.

### Competing interests

The authors have declared that no competing interests exist.

### Authors' contribution

KL defined and implemented the RDC equations model, conducted the experiments, analyzed the results and wrote the manuscript. SW implemented the visual interface of the simulator. VZ implemented FWI equations in C language and created artificial maps. MD conducted the implementation, conducted the experiments, analyzed the results and wrote the manuscript. KL and MD conceived the general idea. All authors read and approved the final manuscript.

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