Fire Weather Index assessment and visualization

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Abstract. The Fire Weather Index (FWI) is extensively used in Argentina to support operative preventive measures for forest fires management. This index describes the moisture content of three different fuel types and the effect of the wind in the behaviour of fire. During last years our team developed a wildfire simulator with several functionalities requested by firefighters. In this work we report the spatial visualization of the FWI on our simulator, in order to describe the dependence of forest fire risks on FWI and fuel type of Northwest Patagonian forests in Argentina. This additional functionality allows the user to visualize the local spatial configuration of fire risk. The potential of this tool is that it would provide the FWI to be readily used in all fire stations in Argentina. Moreover, it could be taken as input information of a fire propagation model under development. In this sense, the need of modelling the impact of weather on the fuel becomes essential for the accuracy of forest fire simulations.

Keywords: Fire Weather Index, Forest Fire Simulation, GPGPU

1 Introduction

In Argentinian Patagonia, climate has been changing during the last decades, increasing wildfire occurrences and severity. For instance, in the western Andean Patagonia, electric storms are more frequent today, usually causing wildfires if the conditions are favourable for burning. Hot and dry seasons are longer and more frequent. In addition, big wildfires increase global climate change causing a feedback between fires and climate that is important to study [9].

Every year, Argentina is the scenery of several and sometimes huge forest fires. Approximately 18 millions of hectares of native forest, shrubland, grassland and exotic species plantations were burned from 2000 to 2013 in our country [14]. Several lives were lost on January 1994 in a grassland-shrubland fire near Puerto

Madryn, Chubut, Argentina [5].

Due to this situation, in 1996 a National Plan for Fire Management (PNMF in its Spanish acronym) was implemented by the Secretary of Sustainable Environment Development [5]. The first objective within this Plan was to define indicators of fire risk that could be accurately applied to the different geographical regions in Argentina. The Fire Weather Index (FWI), originally published in 1970 by the Canadian Forest Service [1], 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, 5]. 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 [1]. 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. In this department, firefighters combine FWI values with local vegetation information to obtain the local fire risk. This quantity is then categorized in five levels: low, moderate, high, very high and extreme.

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 propper 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 [3] [13] 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.

In this work, we add the computation of the Fire Weather Index (FWI) to our simulator, allowing to display FWI values in a tabular format and fire risk as a coloured map. In this way firefighters will be able to visualize fire risk over large areas of interest and can calculate FWI every time that the availability of updated meteorological data allows it.

Standard weather station outputs are used as inputs for FWI computation: daily temperature, relative humidity, wind speed, precipitation and date. In the following sections we explain how we performed FWI assessment (section 3.1) and visualization (section 4) in detail.

2 State of the art

The FWI is one of the modules of the Canadian Forest Fire Danger Rating System (CFFDRS) developed by the Canadian Forest Services (CFS) [8, 10]. This

System is composed by four modules or subsystems: Fire Weather Index (FWI), Fire Behaviour Prediction (FBP), Fire Occurrence Prediction (FOP), and an accessory fuel moisture subsystem. The FWI relates meteorological conditions, fuel state and fire behavior. Humidification and drying process of fuels are essentially independent of location. In addition, fire behaviour always responds to the same physical factors of fuel, topography and weather [7, 5]. For these reasons, FWI can be successfully applied outside Canada.

In Argentina, the FWI has been used over different regions [5]. For scenarios presented in this work, historical FWI values were computed and its relationship with fire occurrences was studied. In reference [7] the author classified the FWI into 5 different fire risk levels (low, moderate, high, very high and extreme) based on risk classes defined for southeast British Columbia. Results for Chubut (42° 56' S; 71° 09' W, region of Andean Patagonia) show that burned area and fire occurrences increased with fire risk levels, from low to very high levels. For very high and extreme risk levels it becomes necessary to include more accurate inputs. According to Dentoni et. al [5], in all Argentinean scenarios, the seasonal variation of FWI was found to be positively correlated with the monthly variation in burned areas for wildfires between 1999 and 2004. Once FWI was proved to be a useful indicator of fire risk on these Argentinean scenarios, an 8 stage plan was implemented for the FWI computation in our country, including personal for training, daily weather observations, local vegetation studies, etc.
The Argentinean fire management system is based on the Canadian Forest Fire Danger Rating System (CFFDRS) and a very detailed report about its adaptation to Argentina can be found in [7]. This adaptation was possible despite the fact that many Argentinian natural habitats are different from the Canadian ones. It was possible to match Argentinian vegetation with Canadian fuel types in the case of grasslands, native cypress forests and plantations. However it is still necessary to define shrubland models for Argentinian scenarios.
So far, we could not find evidences of development of FWI visualization tools over Argentina. There is however, some developed software for Córdoba Province, Argentina [2], that combines FWI with historical fires to predict fire risk using neural networks.
There are studies that link spatial variations in FWI and fire occurrences. For example [14] linked heat spots detected with the Moderate Resolution Imaging Spectroradiometer (MODIS) and FWI values for the north of Argentina. MODIS data is obtained from Terra and Aqua satellites (Earth Observation System EOS) using the electromagnetic mid-infrared spectrum for detecting focal points of heat. Using historical meteorological data, FWI and Fine Fuel Moisture Content (FFMC, see section 3.1) values were calculated from 2003 to 2012. A correlation analysis made for June to October (the fire season) between MODIS data and FWI showed that, from a given threshold, the occurrence of fire (estimated by the number of heat spots) increases with fire risk. However, given the high variability of collected data, other complementing factors like landscape vegetation cover, energy released, fuel type or burn proposes, should

be also taken into account.
Our simulator couples FWI and fire risk visualization in a geographical domain along with a simulation framework that allows the visualization of fire propagation in case of occurrence. Additionally, the user can navigate in simulation time to change the parameters of fire spreading.

3 Forest fire simulator and FWI implementation

Our application is based on a cellular automata to simulate forest fire propagation [6] [3]. The code was developed on GPGPU (General Purpose Graphic Processing Units) in order to achieve high performance, reducing execution time.

The fire scenario is modeled by a 2D array of cells that can be in one of the following three states: burned, burning or not burned. Moreover, each cell has specific features (topography, weather and vegetation) and the status of a given cell changes according to some probability that depends on the state and features of its 8 nearest neighbours as explained in [3].

In a sequential solution, the cellular automata goes cell by cell, executing the fire spread model across each row and column. Then, if the fire map is NxM (rows x columns), and the fire spread model has time complexity equal to $O(S)$, with S the number of arithmetic operations per site, 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 automata 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.

The first sequential version of this simulator (using SELES and presented through [6]) took 10 days to perform 9 hundred thousands simulations, running on an Intel(R) i7-4770K CPU. Our first version of the parallel simulator takes approximately 12 hours to perform a million of simulations using our CUDA parallel algorithm. More details of this parallel application and a scalability study is presented in [3].

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 [13].

The visualization platform shows the fire spread, and 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, GoogleEarth, ArcGIS, etc). The raster files define the spatial resolution of the underling 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.

The FWI computation and visualization was coupled with the original version of our simulator. As a first step, we implemented the set of equations for FWI in C and CUDA based on [11] and [12]. In a second step local firefighters helped us to define fire risks levels based on surrounding vegetation and local weather.

3.1 Fire Weather Index

The Fire Weather Index (FWI) is assessed with the following standard weather station readings as input: temperature, relative humidity and wind speed at 12h, and accumulated rain during the last 24 hours.

The 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 [11].

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. In Fig. 1 we show the FWI block diagram and FWI required inputs [11] [12].

Codes and indexes of FWI are defined by mathematical functions presented in detail in the Canadian Forest Service technical reports: [11] and [12]. Furthermore, for each code (FFMC, DMC and DC), the drying phase and the rainfall phase equations are described. In particular the report [12] shows implementation procedures, inputs and outputs.

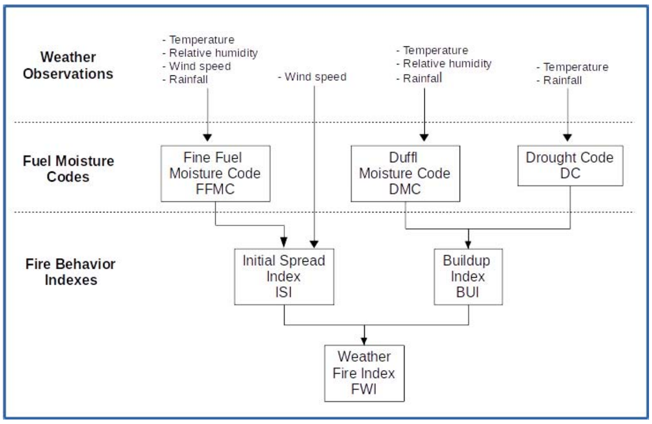


Fig. 1. Fire Weather Index block diagram.

An optional additional component of the FWI is the Daily Severity Rating (DSR). Severity rating provides a measure of wildfire control difficulty. The FWI itself is not considered suitable for averaging and should be used as its single daily value only. Any averaging (spatially over a number of station on a given day or at a single station over any period of time) is better accomplished using DSR [11].

4 FWI embedding in our Simulator

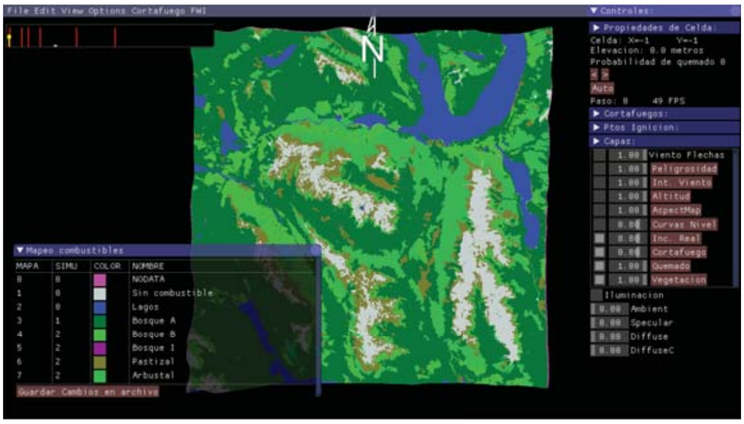
Our first FWI version was programmed in plane C language. It was based on the translation of FWI equations implemented in a spreadsheet to a more robust and solid application in C language. That initial implementation was based on [11] and [12].

It calculates the FWI for one day, or for a number of days, using an input file with weather stations data. Data input is date, temperature, relative humidity, wind and rain plus FFMC, DMC and DC of previous a day, and the outputs are: FFMC, DMC, DC, ISI, BUI and FWI.

Once this FWI implementation was sufficiently tested, the FWI computation was added to our visual parallel simulator as a new functionality. User can choose the input meteorological data file for FWI computation, including intermediate contents and indexes (FFMC, DCM, DC, ISI, BUI and DSR).

In Fig. 2 we show a simulation landscape and the corresponding table of fuel references. This scenery corresponds to a northwest Argentinian Patagonia area of 25km x 25km extension (at $41°21'59''$ S, $71°38'46''$W). Simulator inputs are raster files with different layers of information [13].

Using FWI main menu item, the user can select an input meteorological data file (e. g., a list of: date, temperature, relative humidity, wind speed and direction and rainfall). Once the input data file is chosen, FWI equations are executed and



Celda: X=-1 Y=-1
Elevacion: 0.0 metros
Probabilidad de quemado 0
Paso: 0 49 FPS

1.00 Viento Flechas
1.00 Peligrosidad
1.00 Int. Viento
1.00 Altitud
1.00 AspectMap
0.00 Curvas Nivel
0.00 Inc. Real
0.00 Cortafuego
1.00 Quemado
1.00 Vegetacion
Iluminacion
0.00 Ambient
0.00 Specular
0.00 Diffuse
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MAPA	SIMU	COLOR	NOMBRE
0	0	🟪	NODATA
1	0	⬜	Sin combustible
2	0	🟦	Lagos
3	1	🟩	Bosque A
4	2	🟩	Bosque B
5	2	🟪	Bosque I
6	2	🟫	Pastizal
7	2	🟩	Arbustal

Fig. 2. Simulator main panels: landscape top view and table with fuel references. Landscape reflect effects were turned off to emphasize local vegetation categories.

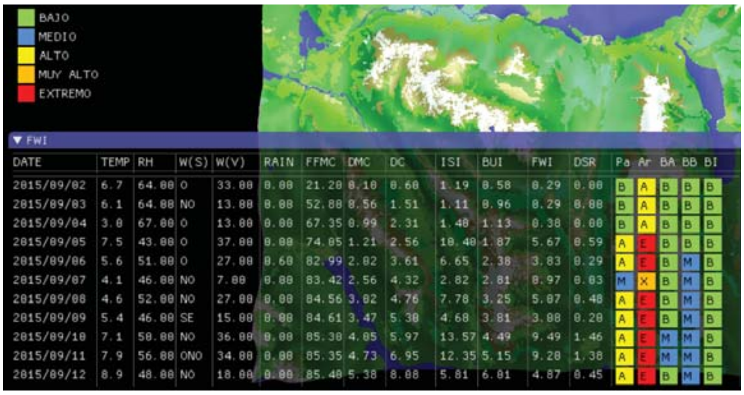
subsidiary codes and indexes are computed. Results are presented in a tabular way (Fig. 3).

As shown in 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 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 (Fig. 3). 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. 4 and Fig. 5). These two figures show the same map when different days are selected in the tabular FWI window.

To perform this test, 30x30m 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. Nowadays daily FWI is calculated, but this temporal frequency can be increased in order to obtain hourly FWI results.

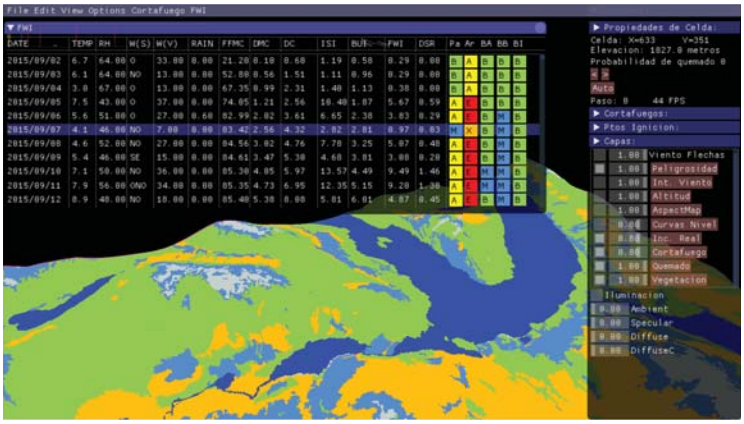


DATE	TEMP	RH	W(S)	W(V)	RAIN	FFMC	DMC	DC	ISI	BUI	FWI	DSR	Pa	Ar	BA	BB	BI
2015/09/02	6.7	64.00	O	33.00	0.00	21.28	0.10	0.60	1.19	0.58	0.29	0.00	B	A	B	B	B
2015/09/03	6.1	64.00	NO	13.00	0.00	52.88	0.56	1.51	1.11	0.96	0.29	0.00	B	A	B	B	B
2015/09/04	3.0	67.00	O	13.00	0.00	67.35	0.99	2.31	1.40	1.13	0.38	0.00	B	A	B	B	B
2015/09/05	7.5	43.00	O	37.00	0.00	74.05	1.21	2.56	10.40	1.87	5.67	0.59	A	E	B	B	B
2015/09/06	5.6	51.00	O	27.00	0.60	82.99	2.02	3.61	6.65	2.38	3.83	0.29	A	E	B	M	B
2015/09/07	4.1	46.00	NO	7.00	0.00	83.42	2.56	4.32	2.82	2.81	0.97	0.03	M	X	B	M	B
2015/09/08	4.6	52.00	NO	27.00	0.00	84.56	3.02	4.76	7.78	3.25	5.07	0.48	A	E	B	M	B
2015/09/09	5.4	46.00	SE	15.00	0.00	84.61	3.47	5.38	4.68	3.81	3.88	0.28	A	E	B	M	B
2015/09/10	7.1	58.00	NO	36.00	0.00	85.38	4.05	5.97	13.57	4.49	9.49	1.46	A	E	M	M	B
2015/09/11	7.9	56.00	ONO	34.00	0.00	85.35	4.73	6.95	12.35	5.15	9.28	1.38	A	E	M	M	B
2015/09/12	8.9	48.00	NO	18.00	0.00	85.40	5.38	8.08	5.81	6.01	4.87	0.45	A	E	B	M	B

Fig. 3. FWI computation using a meteorological data as input. For each register through meteorological input file, FFMC, DMC, DC, ISI, BUI, FWI and DSR values are obtained. Then, fire risk levels are defined by the combination of local vegetation and FWI value.

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 are now developing a new model for fire propagation based on reaction-diffusion-convection differential equations. As opposed to previously implemented statistical models [6], this new model aims to understand the physical processes that drive fire propagation in our region. We are therefore studying the link between those physical processes and FWI, to include some of its components in our model, so at least part of the input will be measurable quantities already familiar to those involved in fire management. For example, from the implemented visualization of fire risk, one can start one or more fires in high level risk areas and see the final burned area. Stochasticity will be part of the models 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, specially regarding the real time requirement for simulations. Finally the possibility of extending the use of the systems for other regions in Argentina will certainly represent a formidable challenge for the future.



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Celda: X=633 Y=351
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Probabilidad de quemado 0
Paso: 0 44 FPS

1.00 Viento Flechas
1.00 Peligrosidad
1.00 Int. Viento
1.00 Altitud
1.00 AspectMap
0.00 Curvas Nivel
0.00 Inc. Real
0.00 Cortafuego
1.00 Quemado
1.00 Vegetacion
Iluminacion
0.00 Ambient
0.00 Specular
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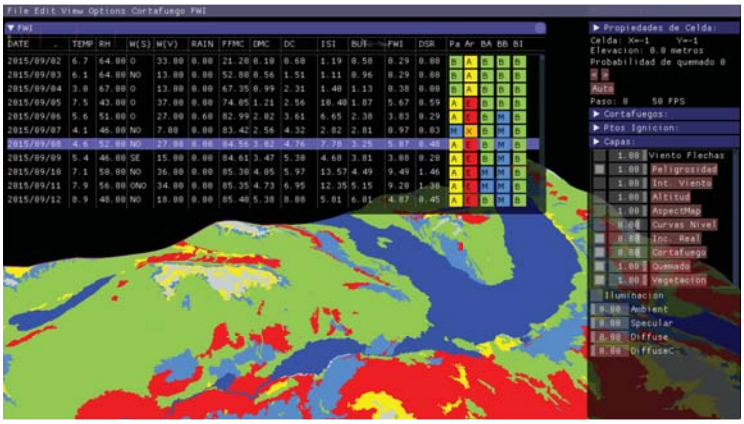
Fig. 4. Effect of selecting a specific day. Map is coloured according to fire risk level. In this figure landscape was zoomed and rotated in order to focus on Mascardi Lake area.



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Celda: X=-1 Y=-1
Elevacion: 0.0 metros
Probabilidad de quemado 0
Paso: 0 58 FPS

1.00 Viento Flechas
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0.00 Specular
0.00 Diffuse
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Fig. 5. Effect of selecting a specific day. Map is coloured according to fire risk level. In this figure landscape was zoomed and rotated in order to focus on Mascardi Lake area.

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