Dynamic Data Driven Ensemble for Wildfire Behaviour Assessment: A Case Study

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Abstract. Wildfire information has long been collected in Europe, with particular focus on forest fires. The European Forest Fire Information System (EFFIS) of the European Commission complements and harmonises the information collected by member countries and covers the forest fire management cycle. This latter ranges from forest fire preparedness to post-fire impact analysis. However, predicting and simulating fire event dynamics requires the integrated modelling of several sources of uncertainty. Here we present a case study of a novel conceptualization based on a Semantic Array Programming (SemAP) application of the Dynamic Data Driven Application Systems (DDDAS) concept. The case study is based on a new architecture for adaptive and robust modelling of wildfire behaviour. It focuses on the module for simulating wildfire dynamics under fire control scenarios. Rapid assessment of the involved impact due to carbon emission and potential soil erosion is also shown. Uncertainty is assessed by ensembling an array of simulations which consider the uncertainty in meteorology, fuel, software modules. The event under investigation is a major wildfire occurred in 2012, widely reported as one of the worst in the Valencia region, Spain. The inherent data, modelling and software uncertainty are discussed and preliminary results of the robust data-driven ensemble application are presented. The case study suitably illustrates a typical modelling context in many European areas – for which timely collecting accurate local information on vegetation, fuel, humidity, wind fields is not feasible – where robust and flexible approaches may prove as a viable modelling strategy.

Keywords: Wildfire behaviour, Forest fires, Integrated natural resources modelling and management, Semantic Array Programming, DDDAS.

1 Introduction

Among natural hazards, wildfires cause huge environmental, economic, social damages. In the Mediterranean area, a changing climate toward dryer and hotter

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seasons seriously increases the fire risk. Wildfire information has been collected in Europe for a long time, with particular focus on forest fires. The European Forest Fire Information System (EFFIS) of the European Commission complements and harmonises the information collected by member countries and covers the forest fire management cycle [1]. Analysis and prediction of wildfire propagation is growingly supported by computational modelling. However, accurate wildfire behaviour modelling may require a large number of input data and parameters. The impossibility of reliably measuring all of them along with the numerical modelling complexity, simplifications and uncertainty (data and software uncertainty [2,3]) are critical aspects to address. The transdisciplinary nature of the problem is the key driver for its intrinsic complexity.

The spatial extent of most wildfires involves local scales. However, the aim for the described fire information system to support the variety of conditions at continental scale leads the modelling architecture [4] to cover several transdisciplinary aspects [2] aside the direct life and health risks [5]. Fire-induced geomorphic and ecological transformations [6–8] may cause severe carbon emissions and alter biodiversity [9,10] even due to habitat fragmentation [11–13]. They may also affect landslide susceptibility [14] and soil erosion [15,16] with potential off-site impacts [17,18] on water resources [19] (e.g. on floods [20,21] and water quality [22]). The involved complexity and uncertainty suggested the architecture to be set within the context of integrated natural resources modelling and management (INRMM) [23].

Here we present a case study of a novel conceptualization based on a Semantic Array Programming (SemAP) [24,25] application of the Dynamic Data Driven Application Systems (DDDAS) [26,27] concept. The case study is based on a new architecture for adaptive and robust modelling of wildfire behaviour, proposed in [4]. We focus on the architecture modules for simulating wildfire dynamics under fire control scenarios. Rapid impact assessment of carbon emission and potential soil erosion is also shown. An array of simulations is ensembled considering the uncertainty in meteorology, fuel and software modules.

1.1 The European Forest Fire Information System (EFFIS)

EFFIS is a comprehensive environmental information system covering the full cycle of forest fire management from forest fire prevention and preparedness to post-fire damage analysis. The system provides information to over 30 countries in the European and Mediterranean regions, to the aim of harmonising the prevention and fire fighting [1].

Exploratory research is currently on-going to integrate fire behaviour models, with emphasis on extreme conditions, physical modelling, smoke dispersion and spotting related to forest fire occurrences. Another aspect relates the use of high resolution meteorological data from ENCWF [28] and Meteo France [29].

EFFIS exploits geospatial and computational modelling tools within a modelling paradigm aiming at robustness and semantic transparency [2,3].

Forest fire occurrences are collected both on the basis of hot spots provided by NASA and of fire news inventoried by the operator using the dedicated web application implemented within the EFFIS portal, a tool to easily detect and geoparse the fire news [30]. The satellite images used to detect burnt areas are the daily Moderate-Resolution Imaging Spectroradiometer (MODIS) by NASA's Terra and Aqua satellites [31], of 250m resolution.

The procedure consists in a semi-automated process. Hot spots and FireNews points are displayed on a desktop GIS and drive the operator's attention on possible anomalies distinguishable on MODIS images. Where a possible anomaly is identified, the operator compares the image with MODIS images relative to previous days, in order to reveal the burnt area, visible as a garnet coloured spot. Once a fire is detected, it is digitised as a polygon and updated with all the relative information, e.g. extension, starting date, etc. If the fire is still active the day after, the polygon is updated with the new perimeter. Fire perimeters are stored in the EFFIS database. A fire's record stores burnt perimeters day by day, so as to enable the use for future needs and research purposes.

2 Materials and Methods

The case study applies the modelling architecture proposed in [4]. This architecture is designed to exploit information updates whenever available so as to timely adapt wildfire behaviour modelling to changing conditions (e.g. meteorology).

The Case Study. The analysed event refers to a major wildfire (also served as a benchmark in [32]) occurred near Valencia, the third largest city of Spain. The fire started on June 28 2012 in Dos Aguas and was under control on July 4, burning an area of 32424 ha. Our models' input is the 2nd July recorded burnt perimeter. The spread occurring in 24 hours is simulated.

Applying the Modelling Architecture. The modelling architecture of [4] relies on an adaptive control strategy [33] based on stochastic dynamic programming (SDP), which is widely applied in natural resources management [34–36]. Wildfire behaviour dynamics is spatially distributed. For example, the case study is characterised by highly variable local patterns of slope, aspect, fuel type, wind, humidity and rain. Unfortunately, SDP computational costs are exponential with the size of the vector of states $\mathbf{x}$ representing the environmental system. Since the SDP approach easily becomes intractable, approximated algoritms [37–39] are useful. [4,32] proposed one of those approximate techniques – Partial Open Loop Feedback Control (POLFC) [39] – for integrated wildfire behaviour modelling.

The dynamics of fire events may be represented as a data transformation model (D-TM) accounting for the evolution of the state $\mathbf{x}_t = \{x_{t,c_1}, x_{t,c_2}, \cdots\}$ which describes at time t the fire likelihood and severity for each spatial cell c. The evolution is modelled in the discrete time interval Δt with respect to the anthropogenic control $\mathbf{u}_t$, the disturbances $\xi_{t+\Delta t}$ (wind, humidity, rainfall), and the system characteristics (slope, aspect, fuel distribution, parameterised as θ_t):

$$\mathbf{x}_{t+\Delta t} = \; ::\!\left| \, f(\theta_t, \mathbf{x}_t, \mathbf{u}_t, \xi^{\tau}_{t+\Delta t}) \, \right|^{sem}_{::} \Leftrightarrow \begin{cases} \mathbf{x}_{t+\Delta t} = f\left(\theta_t, \mathbf{x}_t, \mathbf{u}_t, \xi^{\tau}_{t+\Delta t}\right) \\ \Box\, sem(\mathbf{x}_{t+\Delta t}, f, \theta_t, \mathbf{x}_t, \mathbf{u}_t, \xi^{\tau}_{t+\Delta t}) \end{cases} \tag{1}$$

$$\text{where:} \quad \begin{array}{llll} t & \in \mathcal{U}^t & \mathbf{x}_t = \mathcal{U}^{\mathbf{x}}_t & \mathbf{u}_t \in \mathcal{U}^{\mathbf{u}}_t(\mathbf{x}_t) \\ \xi^{\tau}_{t+\Delta t(t,\mathbf{x}_t)} & \sim \phi(\,\cdot \mid I_\tau) & \in \mathcal{U}^{\xi}_t(\mathbf{x}_t, \mathbf{u}_t, I_\tau), \; \tau \in \mathcal{U}^t & \theta_t = \theta(\mathbf{x}_t, \mathbf{u}_t) \end{array}$$

Semantic checks *sem* are imposed as pre-, post-conditions and invariants on inputs, outputs and the D-TM module $f(\cdot)$ itself [3]. $\Box$ *sem* is a modal/deontic logic expression meaning: "it ought to be that *sem*". *sem* is a set of valid array-based semantic constraints following the *semantic array programming* paradigm [24,25] . Straightforward examples of semantic constraints are exemplified in the following as active links **::*constraint*::**. The disturbance vector $\xi^{\tau}_{t+\Delta t}$ represents the uncertain set of forecasted disturbances $\phi(\,\cdot \mid I_\tau)$ and depends on $\mathbf{u}_t$, $\mathbf{x}_t$ and the available data-driven information I_τ. A POLFC control problem is proposed at each time t to mitigate (sub-optimal minimisation) the global fire costs:

$$u^t(\cdot) = \mathop{\arg\min}_{\mathbf{u}\,\in\,\mathcal{U}^{\mathbf{u}}_{t,\,t_{\text{end}}}} \left[\,\mathcal{C}^{\,\text{carbon emission},\,t}\quad \mathcal{C}^{\,\text{soil erosion},\,t}\quad \cdots\quad \mathcal{C}^{\,n,\,t}\right] \tag{2}$$

$\mathbf{u}_{\cdot}$ are planned in the set of possible actions $\mathcal{U}^{\mathbf{u}}_{t,\,t_{\text{end}}}$ along the whole event lifespan $\mathcal{U}^{\,t}$. Since the controls are spatially distributed in wide raster grids, heuristic control options are explored and the uncertainty associated with their predicted effects is assessed with a robust ensemble strategy. Fig. 2 illustrates a simplistic example where the carbon emission and soil erosion costs are highlighted.

Design Diversity: The Meteorological Data. Three wind-forecast scenarios (fig. 1) were utilised as input for the model simulations, to explore the uncertainty associated with the meteorological models. Wind-forecast scenarios were based on a set of operational Numerical Weather Prediction (NWP) models with heterogeneous spatial and temporal resolution:

- The ECMWF (European Centre for Medium-Range Weather Forecasts) operational high-resolution single global deterministic model (ec_{16}), with a horizontal resolution of about 16 km [40–42]. The model is initiated on both the 00 and 12 UTC analysis fields reaching to an 11-hour forecast horizon with an archived time-step of 1 hour;
- The ECMWF EPS (Ensemble Prediction System) global deterministic Control component, with a horizontal resolution of about 32 km (ec_{32}). This single-model deterministic platform is initiated from a truncated analysis of ec_{16} while no errors are introduced to this initial field [43, 44];
- The DWD/Deutscher Wetterdienst (German Meteorological Service) operational single deterministic global icosahedral-hexagonal grid point model with a horizontal resolution of about 20 km [45, 46]. DWD model values have been retrieved at a regular 25x25 km grid (dw_{25}).

The forecasts have been spatially upsampled so as to disaggregate the average values of the coarse meteo-grids to the denser simulation grid.

The interpolation driven uncertainty (IDU) [47] has been explored by comparing an upsampling which preserves the local average invariance (LAI) [24] with an usual non-LAI upsampling (i.e. typically confusing the average value of each coarses-grid cell with the value of the associated centroid).

Design Diversity: The State Transition Function. An ensemble approach is proposed for mitigating the software uncertainty [2,3] associated with the state transition function (eq. 1). Although two particular free software simulators [32] are described, the proposed method is general and applicable to other simulators:

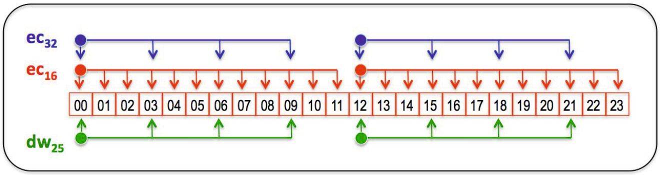

Fig. 1. Graphical representation of model analysis updates during a typical 24-hour interval. Number of dots corresponds to the number of updates, while arrows correspond to various time-steps utilized by model platforms.

- FireSim implements the library FireLib [48] and the Rothermel model [49] by means of a cellular-automata simulator. FireSim is a deterministic parametric and discrete event type simulator structured as a sequential set of D-TMs with a pipeline structure of four stages.
- The second simulator is implemented in GRASS GIS [50]. The spread function is based on the least cost path algorithm and simulates the elliptically anisotropic spread. It is implemented in the function *r.spread* [51], which takes as input the rate of spread (ROS) generated by the function *r.ros* [52]. This latter computes the ROS following the Rothermel model [49] and is based on the Fortran code by [53]. The direction of the maximum ROS is the vector sum of the forward ROS in wind direction and that in upslope direction. The obtained raster map layers serve as inputs for *r.spread*.

Both simulators take in input the standard fuel models defined by [54]. Fuel information was derived from the fuel type map of Europe developed by JRC [55]. The classification scheme adopted for the fuel map encompasses 42 fuel types representing the variety of fuel complexes found in the European landscapes. A cross-walk to the original set of 13 fire behaviour fuel models tabulated by [54] was also developed in order to obtain standard fuel parameters as input to the Rothermels fire spread model [56]. Because of the uncertainties in fuel model attributions and the non-univocal correspondence between fuel types and fuel models, multiple assignments were allowed. The expected proportions of fuel models extent within each fuel type were assigned based on expert knowledge. Equiprobable fuel maps have been generated for each run of the ensemble.

The two simulators are deterministic instances of eq. 1. For each spatial cell c and time t, the state $x_{t,\,c}$ simulated by an instance's run is converted to be a **::binary::**[1] flag to register whether c is burnt. Uncertainty analysis is implemented by ensembling multiple instance runs for different scenarios. Instances expect slope and wind speed input as **::nonnegative::**[2] layers while aspect and wind direction as **::angle::**[3] values. The weighted-quantile analysis of the ensemble

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[1] `http://mastrave.org/doc/mtv_m/check_is#SAP_binary`

[2] `http://mastrave.org/doc/mtv_m/check_is#SAP_nonnegative`

[3] `http://mastrave.org/doc/mtv_m/check_is#SAP_angle`

requires all output **::matrix::**[4] layers to have the **::same_size::**[5] for generating a **::sortable::**[6] 3-dimensional array **::3-array::**[7].

3 Rapid Assessment of Wildfire Impacts

As stated in [4] wildfires are associated with high carbon emission and alteration of ecosystems and soil properties. Hydrology, land cover and soil characteristics are the factors that mainly influence the fire - geomorphic processes connection.

Wildfires can increase soil erosion rate by orders of magnitude. Wildfires can totally remove the protective surface layers, as the litter, and increase the hydrophobic condition at or below the ground surface [57–60].

For the rapid assessment of carbon emissions, soil erosion and other post-fire impacts as landslide susceptibility, a robust computational modelling is required [4, 14]. Within the present study a quick assessment of post-fire carbon emissions and soil erosion was carried out. The e-RUSLE model [15, 16] was applied in Dos Aguas for estimating post-fire soil erosion changes.

Combustion Carbon Emissions. Combustion in wildfires and associated carbon emissions vary depending on the local fire intensity and the characteristics of fuel (fuel moisture, share of dead and live fuel, share of woody and herbaceous fuel, ...) [61]. Specific burning efficiency and emission factors can be associated to classes of fuel and typology of fire (flaming or smoldering) so as for fuel models to be associated with static factors. However, the actual available fuel load is an essential information for a realistic carbon emission assessment. At European scale, a harmonised map of living forest carbon stock has recently been improved the standard methodology for IPCC Tier 1 level [62]. This map served as input for a preliminary, exploratory spatialisation of the carbon emission assessment.

Soil Erosion. The e-RUSLE approach is based on the joint use of a low data requirement model and an innovative technique for model inputs estimation.

The model's architecture is based both on semantic array programming [24, 25] and computational reproducibility [15], easing the integration of natural resources models. Furthermore the family of models to which e-RUSLE belong provide long term erosion averages and have been applied in many different climatic and environmental conditions all over the world [63–65].

Public available electronic datasets – European Soil Geographical Database (ESGDB) [66], Harmonized World Soil Database (HWSD) [67], Shuttel Radar Topography Mission (SRTM) [68], CORINE Land Cover (CLC) [69] and ENSEMBLES Observations gridded dataset (E-OBS) [70] – has been used for calculating the pre and post-fire soil erosion maps in the study site. Electronic archives are one of the main data source for research community, allowing accessibility to large volumes of data and having the capacity to preserve historical data [71]. The e-RUSLE factors have been calculated following the approach presented in [16, 72].

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[4] `http://mastrave.org/doc/mtv_m/check_is#SAP_matrix`

[5] `http://mastrave.org/doc/mtv_m/check_is#SAP_same_size`

[6] `http://mastrave.org/doc/mtv_m/check_is#SAP_sortable`

[7] `http://mastrave.org/doc/mtv_m/check_is#SAP_3-array`

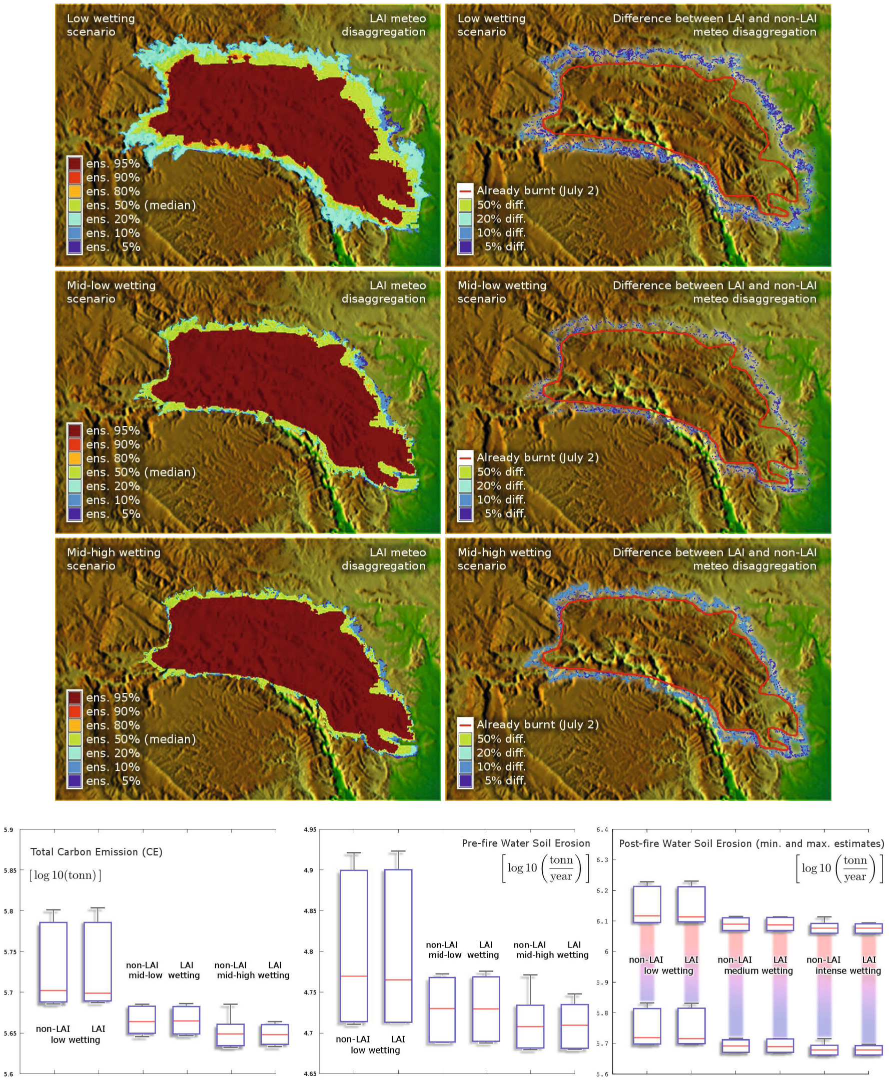

Fig. 2. Dos Aguas, Valencia – Spain. Wildfire behaviour simulations with ensemble prediction (July 3 2012). To illustrate, simplistic fire control scenarios are shown: low wetting (*top*); mid-low wetting (*middle*) and mid-high wetting (*bottom*). Interpolation driven uncertainty (IDU) is also assessed. Meteorological forecasts have been spatially disaggregated by either imposing local average invariance (LAI) [24] (*left*) or not (usual non-LAI disaggregation). The difference is shown at *right*. Below: rapid assessment of wildfire impacts. Total carbon emission and soil erosion by water (pre- and post-fire) have been estimated for each ensemble simulation of each scenario. Box-plots: box with quartiles 25%, 50% (red line), 75%; wiskers with 5% and 95% quantiles. Although the assessment considers the whole burnt area and not only the one which would have been burnt in the simulated day under the different scenarios, the non-LAI induced component of IDU is nonlinear and even its one-day effects may occasionally be non-negligible for the impact assessment of the whole burnt area.

Within the model, the Cover Management factor (C factor) and the soil erodibility factor (K factor) are strongly influenced by high-severity burns. In severe, slow-moving fires, the combustion of vegetative materials creates a gas that penetrating the soil profile causes the soil to repel water. This post-fire hydrophobic condition, reducing the soil permeability, is considered as one of the main causes of the increasing in runoff after a fire [17, 58].

A rapid assessment of post-fire soil erosion is provided applying the DerBos nondimensionalised equation [4]. It describes a RUSLE based lower- and upper-bound for the expected soil erosion.

As stated in Larsen and McDonald [59], the algorithm for calculating K values are not consistent with our current understanding of erosion processes. High severity burns can increase sediment yields of 2-3 orders of magnitude [17] but considering the changes in soil permeability and organic matter content the maximum increase in K factor is around 100%. Despite the evident underestimation, we incresed the K factor passing from K_c^{pre} to K_c^{burnt} [4] of 100%. Because of the lack of information regarding post-fire C factor values and the link with fire intensity, we considered only the case of high severity burns. For C_c^{α}, C_c^{β} and C_c^{γ} we applied equispaced values in the range from 0.5 to 0.2 [59,73,74], representing the maximum and minimum degradation of the cover factor due to the fire.

4 Conclusions

A real case study (Valencia region, Spain) is presented applying the modelling architecture proposed in [4] as a new conceptualization for wildfire prediction [75]. The methodology constitutes an exploratory investigation for possibly expanding the ability of the European Forest Fire Information System (EFFIS) to support wildfire behaviour analysis and management. Transdisciplinary modelling integration – required by the EFFIS continental scale – has been exemplified by means of the rapid assessment of pre- and post-fire potential soil erosion along with carbon emissions. First results are presented on a robust ensemble for mitigating the deep uncertainty [4] associated with static information (fuel mapping), dynamic data forecast (provided by external meteorological models) and software uncertainty [2, 3] (internal modules for simulating the wildfire behaviour). Design diversity has been applied to meteo forecast models (exploiting three different models for wind-forecast scenarios) and fire propagation models (ensembling the predictions of two independent implementations of the Rothermel model). The case study illustrates the preliminary feasibility of real time and robust rapid assessment of wildfire impacts under varying management options.

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