An Ontology for Dynamic Wildfire Simulations

Ioannis Karakonstantis and George Xylomenos Mobile Multimedia Laboratory
Department of Informatics, School of Information Sciences and Technology
Athens University of Economics and Business, Greece
E-mail: jkarakon@aueb.gr, xgeorge@aueb.gr

***Abstract*—This paper argues for a standardized ontological representation of the factors influencing the progress of wildfires, such as weather conditions and landscape characteristics, with the explicit goal of driving dynamic simulations combining pre-existing knowledge and, possibly conflicting, field observations. We review previous work to emphasize the absence of solutions able to cope with wildfire simulations that need to be dynamically rerun as the phenomenon evolves, in the harsh, sparsely connected environments of megafires. We argue that an ontology-based approach for modeling the wildfire's environment is the most suitable one to feed data to a decentralized and dynamic simulator and propose an ontology for this purpose. We also discuss the inevitable issue of inexact and conflicting field-submitted data and their implications for wildfire simulations.**

***Index Terms*—Wildfire, Ontology, Simulation, Geoinformatics.**

I. Introduction

Over the past few years, we have experienced an alarming growth in wildfire activity around the globe. Extreme weather conditions, driven by climate change, are setting the fuse to megafires that can burn out of control, threatening human lives and destroying infrastructure. Even though more and more resources are committed to fighting these megafires, the truth is that existing approaches are not enough. To cope with megafires, the allocation of firefighting resources must prioritize the areas where they are most effective, being more threatened by fire spread. Fortunately, considerable scientific effort has been invested on modeling, understanding and predicting wildfire behavior. Breakthrough research in the 50s and 70s led to key publications describing wildfire spread, like Rothermel's fire spread model [1], [2]. Since then, scientific knowledge has been expanded, and wildfire behavior can now be simulated with increasingly accurate models.

A wildfire behavior prediction model can be an extremely valuable tool, but even the best model can be a giant with feet of clay: it is not the inherent accuracy of the model used, but the use of improper input data that can cause a simulation to fail in its predictions of the actual spread of a fire. Modeling a wildfire's environment is challenging, as it requires both scientific and empirical knowledge. Estimating, validating and processing the factors that influence fire behavior is a process subject to change over time, as the phenomenon is evolving. For example, wind measurements will differ from area to area depending on the surroundings (tree foliage, hills, etc.) and due to fire-induced weather phenomena [3]. Even the composition and mass of available forest fuel can change over time, as it is consumed by the fire. In addition, eyewitness observations of conditions in the field may fail to recognize the exact type of forest fuel, due to the different knowledge backgrounds or other cognitive barriers of the observers [4].

To simulate the spread of a wildfire as accurately as possible, we need to combine pre-existing data (e.g., from GIS systems) and data dynamically generated on the field, either due to the availability of more detailed observations (e.g., drones surveying a hard to reach area, due to a nearby fire) or due to changing conditions (e.g., change of forest fuel as the fire progresses). Such data may be partially conflicting, since different observers at different vantage points may not have a perfect understanding of the underlying situation (due to unknown terrain, smoke, cloud cover, etc.) and may not be available on time (due to partial disconnections from the network in hard to reach areas). What we need then, is a unified way to express all these time-dependent and, possibly, conflicting data, feeding our fire prediction model.

We argue that the best way to achieve this goal is a standardized ontology specifically targeting wildfire simulations; it may be compatible to some extent with existing ontologies, so as to allow data sharing, but it will also have to cover areas where other ontologies are lacking. By standardizing this ontology, we will be able to create tools to manipulate data coming from the field and reconcile them against each other (e.g., conflicting reports on where the fire front is), allowing the simulation to take into account as much data as possible. Furthermore, data produced during a fire will be more amenable to later analysis if they use a standardized ontology, allowing researchers to fine-tune both their models and the tools exploiting them. In this paper we propose such an ontology, which is being co-developed with our dynamic wildfire simulation tools.

The outline of the rest of this paper is as follows. In Section II we motivate our ontological approach and outline the challenges faced, while in Section III we critically review existing ontologies related to the problem area. In Section IV we present our proposed wildfire simulation ontology and the rationale for its development, while in Section V we summarize our contributions and discuss future work.

II. Why an ontological approach?

Ontologies are a well-established form of information formalism and representation; they have been applied to a variety of domains where knowledge acquisition and sharing is required. The term "ontology" involves the process of explicitly specifying a conceptualization [5]. It signifies a set of concepts

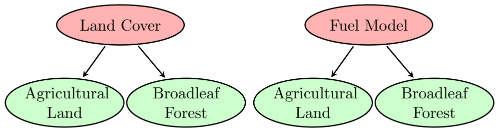

Fig. 1. The same concept may be assigned to different hierarchical structures.

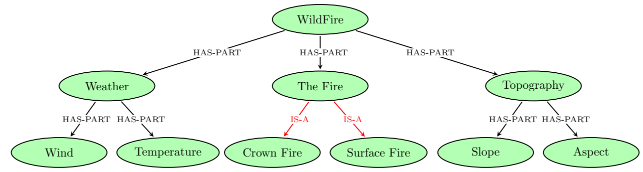

Fig. 2. A hierarchical structure with relationships of different types.

and objects, plus the relationships between them, describing the knowledge of a field, an application or a knowledge base [6]. To ensure that the concepts are clearly and correctly interpreted, a set of ontological commitments (agreements to use a common vocabulary consistently) are specified in [6].

The introduction of a strict formalism and the structures needed to accurately describe the objects involved and their relationships, introduce complexity and may lead to misunderstandings. For example, in the case of SoKNOS [7], the authors mentioned that domain experts (firefighters) found its terminology quite irritating, as it did not match their own perspective and colloquial language. A formalized, hierarchical structure holding ontological information must serve a reasoning mechanism, but in this case it was not aligned with the vocabulary and concepts users were comfortable with.

As an example, when modeling the environment of a typical wildfire, the most crucial entity to identify is the "forest." This term may have different meanings (polysemy) depending on the educational, cultural and legal background of the person using the term. A definition derived from ecological science may be: "a forest is the ecological system consisting of biotic and abiotic elements which interact with it and is covered with trees for more than 20% of its area." An administrative definition approaches the term differently: "forest is the area within the administrative boundaries of a forest service, with or without trees." Finally, a simpler definition can be derived by examining the land cover of an area: "forest is the area with dense cover of trees or other plants." [6] The advantages of one definition over the other are not clear. When a user needs to model a forest in a computer simulator, the most appropriate way to draw its boundaries is to follow the land cover definition, but the point here is that there is no single way to describe the concept, because users are biased by their personal beliefs and knowledge backgrounds.

Simulating the behavior of a wildfire requires not only identifying where a forest is located, but what type of plants and trees it consists of, their height, density, etc., in order to map the area to its corresponding fuel model. A problem arises when we try to implement a hierarchy between concepts, and their corresponding classes, related in a non strictly defined way. For example, Figure 1 (left) depicts a hierarchy between land cover; an alternative hierarchy (right) may be formed between fuel type models. Another common issue when building hierarchical structures of related concepts is mixing subtype-supertype relationships with part-of (part-whole) relationships in the same hierarchy. Figure 2 depicts a hierarchy which mixes these types of relationships between the concepts involved.

According to Kavouras et al [6], the main causes of conceptual and taxonomic misinterpretations are the different perspectives between stakeholders, the different training or methodology applied, cultural and social factors and cognitive diversity. The last factor is related to the personal beliefs, assumptions and biases leading each individual to understand the concepts involved by utilizing knowledge acquired from their previous training. As a result, modeling the multifaceted and complex environment of a wildfire with an ontology is a challenging problem. In this context, we can classify the most fundamental challenges that must be overcome to create a standardized wildfire simulation ontology, as follows.

1) Ontology-related challenges:

- Verifying an ontology-based model: verification requires deep understanding and technical awareness of the knowledge domain that it models.
- Expanding and updating a model: trying to update or expand an ontology may lead to constraint violations or misleading information.
- Unrealistic perspectives of the environment: a model tries to represent the environment, but it is limited by its creator's knowledge barriers and cultural biases.

2) Human behavior-related challenges:

- Terminology and polysemy: stakeholders may interpret the same term with different meanings, or misunderstand a key concept.
- Ambiguous data: when users submit data required by the model (observations), they may provide ambiguous, incorrect, conflicting or noisy data.

A key issue is that users tend to believe that the model and the data they have is a perfect representation of the environment (wildfire) and is not subject to changes, modifications or improvements. This is clearly untrue in a dynamic environment with imperfect knowledge. Our proposed model tackles this challenge by explicitly acknowledging that user observations may be conflicting and time-dependent; this requires combining and merging the diverse individual perceptions to an updated version of the model (see Section IV). Storing multiple independent representations of the same entity allows the use of interpolation techniques (e.g., weighted averaging, consensus modeling, metaheuristic algorithms), to merge user inputs in a statistically robust way. The aggregated geometry is more likely to converge toward the true spatial ground truth, as it integrates the most probable components of each input, rather than prematurely forcing agreement. Additionally, it requires less resources, since new inputs (due to continuous data evolvement) can be compared directly to all prior representations, without requiring a costly re-topologizing of the dataset. In the context of a mobile, decentralized wildfire simulation platform that relies on crowdsourced user data—where uncertainty is inherently present—prioritizing accuracy and replayability over minimal storage constitutes a robust methodological choice and defensible design principle.

III. Related work

Modeling geospatial data is a well-studied field of geoinformatics, with a wide range of real-world practical applications. Under the devastating effects of wildfires, researchers understood that in order to model the complex phenomena involved during a wildfire and help elevate firefighting efforts, a digital geographical representation of wildfire components should be applied. A plethora of GIS-based approaches have been proposed for monitoring and early warning, management of firefighting resources and modeling the wildfire's environment. The technologies utilized for data acquisition and digitization range from simple user entry, accessing remote databases, remote sensing from satellite photographs to, even, crowdsourcing. The majority of the approaches are client-server oriented, while others may rely on other topologies.

Although many proposals exist, we focus below on those that tackle the problem from an ontological perspective. They adopt the approach of not only describing the ontologies involved, but also making cognitive connections between them, which leads to a degree of knowledge extraction. We summarize the proposals covered in Table I.

A. OntoFire

OntoFire [8] is a geo-portal service in which users can both retrieve and publish geospatial information regarding past and active wildfires. Access to the service for publishing is limited to authorized users with a strong scientific background. The key feature of OntoFire is its search and navigation mechanism which implements both traditional spatial and semantic queries. The portal can be accessed via a web interface. To accurately describe a wildfire and its components in OntoFire, a hierarchy of semantically linked classes is introduced, with metadata represented in the ISO 19155 format. At the upper level of the hierarchy, the abstract class "Geo Information Resource" is placed and semantically linked classes underneath it are connected as described in an RDF framework.

B. Onto-Safe

Onto-Safe [10] is a framework for gathering and interpreting information from heterogeneous geospatial data collected from diverse sources, such as social media, sensors and user submitted content. The data is driven through a knowledge base engine and delivered to decision makers in the field or in command posts. A key contribution is gathering user requirements (derived from a fire manager's needs) and mapping them to *Competency Questions* (CQ). The structure of ontology representation and knowledge base engine must support these CQs, since they are crucial in identifying the involved firefighting tactics. CQs include details about weather conditions, the affected area and firefighting mission related information. Knowledge is represented with OWL 2 and the reasoning mechanism is implemented as a set of *Shapes Constraint Language* (SHACL) queries linked with the CQs.

C. SoKNOS

SoKNOS [7] aims to handle natural disaster management. Resources from different sources and services are annotated with ontologies to facilitate interoperability and visualization of data. There is a core ontology and specific domain-based ontologies representing resources, damages, application-specific ontologies, etc. The key contribution of SoKNOS is its mechanism of semantic annotation of the data involved in the implementation of the software. The project implements a dynamic mechanism able to map at run time the corresponding ontological category of a given data object.

D. BeAWARE

The BeAWARE project [11] implements an ontology aiming to support a decision support system for a Crisis Information Management system. In the context of the project, various stakeholders and domain experts expressed their views in order to gather user requirements (mapped to CQs, as in Onto-Safe) and establish a common terminology and format. The ontology developed under BeAWARE represents natural disasters and their associated climate conditions, based on user-entered and sensor data and incident management related data.

E. SIADEX / BACAREX

BACAREX is part of the SIADEX [13] project, implementing an ontology developed especially for forest firefighting. Hence, it can describe not only typical information (like incident coordinates, weather data, etc.) but also operational related metadata, such as the sections of the incident with their respective radio frequency. On the other hand, it covers only a subset of the ontologies developed for general purpose natural disaster incidents. Part of the project is the planning module which can generate an attack plan (chronologically ordered sequence of actions) for the incident.

IV. A wildfire simulation ontology

A. Limitations of existing approaches

The ontology-based approaches proposed in the literature share a variety of similarities, but none of them can be used unmodified when nearly real-time data from a fire incident are used to conduct a *mostly accurate* wildfire simulation, especially when stakeholders suffer from limited / poor network coverage. These approaches are designed to tackle problems related to natural disasters and the management of rescue and suppressing missions. Stakeholders, natural risks, meteorological conditions, topological data, and so on, are mapped to classes with corresponding attributes. Semantic information is represented as linked class instances. Authoring of such classes can be done using the *Resource Description Framework* (RDF) and the *Web Ontology Language* (OWL). This has the advantage that we can query RDF data initially stored in flat files using SPARQL [14] in a SQL-like manner.

TABLE I
ONTOLOGY BASED APPROACHES FOR MODELING NATURAL DISASTERS AND/OR WILDFIRES.

Publication	Main Purpose	Retrieval / Reasoning	Ontology Language	Architecture
OntoFire [8]	Geo portal	RQL [9]	RDF / ISO 19115	Client-server (WEB)
Onto-Safe [10]	Forest fire fighting	SHACL	OWL 2	Generic Framework
SoKNOS [7]	Incident management	JQE / F-Logic	DOLCE / OWL	Generic Framework
BeAWARE [11] [12]	General purpose crisis management	SPARQL	OWL 2	Generic Framework
SIADEX / BACAREX [13]	Forest fire fighting	HTN planning	Protégé (OWL)	Client-server (WEB)

However, these solutions are not intended for a simulation environment, therefore they do not meet some simulation-specific requirements, especially for dynamic simulations. One important problem in a wildfire context is that the data gathered in the field are subject to a user's judgment and personal knowledge about the evolving phenomenon. Poor judgment, fragmentary knowledge, and lack of experience may lead to datasets of poor quality, with limited value to simulation software. Therefore, the ontology must take into account that *data entered in the field can be contradictory*.

Another problem is that a wildfire is a natural phenomenon which evolves dramatically over time. Even minor changes to parameters (such as wind direction) may have a huge impact in the final outcome. Due to the phenomenon's fast-changing nature, any information gathered is subject to regular updates over time. For example, areas with vegetation (combustible fuels) are displaced by burnt areas, fuel humidity declines due to radiation from flames, fuel discontinuities may be formed from firefighting activities, etc. Therefore, the ontology must take into account *the time of each observation*.

Finally, the client-server architecture adopted by most solutions is a limiting factor when we need to exploit the collective knowledge of users deployed in the field. Not only the connectivity in the wildfire area is questionable, but each individual stakeholder cannot interpret and model the incident and its surroundings at their full extent. Firefighters deployed in the field have the experience, the knowledge and the proximity to identify, describe and model the required parameters, unlike in previous solutions where information is spread top-down by a small group of experts or stakeholders. This implies that updated information must spread to other nearby users quickly; but, due to the evolving connectivity of users, *each user may have only partial knowledge of the situation*.

B. Proposed approach

We approach the problem of representing semantic information regarding wildfire behavior from the perspective of its utilization for dynamic simulations. This imposes additional requirements regarding sharing, relaying, reusing and integrating that information to a variety of platforms and devices used during the simulation. In the literature we find two different modeling approaches. At a "higher ontological level," creators aim to represent the real world as accurately as possible. At a "lower ontological level," creators focus on data processing, linking and standardizing the data involved in a formal and well-defined way. Due to the inevitable limitations introduced by the nature of mobile phones, which we intend to use as the main platform for gathering data, exchanging data and running simulations, we adopt a low-level approach, focusing on simplicity and reusability of data.

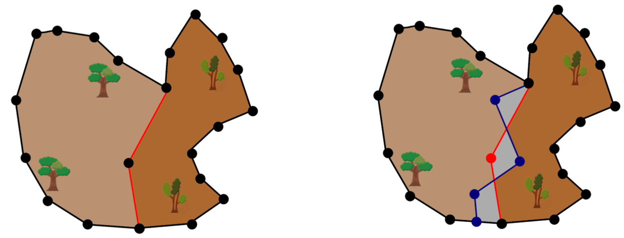

Fig. 3. Digitization of the same forestry area by different users.

While choosing a standardized format (RDF / stRDF) to store and process geospatial data (utilizing SPARQL / stSPARQL queries) is the preferred approach in the literature [15], we argue that a less resource-intensive approach will be more appropriate for our scenario. We propose instead a GeoJSON representation of the ontologies as the simplest, most resource-inexpensive and easy to implement approach. Although the most obvious solution would be to use a topological structure holding the required ontologies, we claim that a *spaghetti vector* model is a more appropriate way to incorporate the uncertainty introduced by human inputs. Specifically, in a typical vector model representation, a polygon depicting a forestry area is described by the same edges as adjacent polygons. On the other hand, the same polygons in a spaghetti vector model, even if they share the same edges, will have them listed twice. While this requires more storage and processing, it allows diverging user inputs for each area, which can then be aggregated, leveraging the introduced uncertainly.

C. Managing ambiguous data

As mentioned before, the proposed implementations in the literature assume that one or a few stakeholders map the real world to the corresponding ontologies. We introduce instead a decentralized architecture, in which any user can contribute and distribute new knowledge to other users. As a consequence, we expect that the same ontology (let us assume a forestry area with a given type of vegetation) will be modeled by different users with different experience, knowledge and even under different time frames. Hence, user inputs will probably be ambiguous, but not necessarily incorrect. That also introduces an additional problem to deal with: we cannot map the same ontology 1-to-1 to all users involved. Poor human judgment, poor GPS accuracy and fast changing conditions may all lead to different representations of the same area.

Let us examine the case where two users (e.g., firefighters) deployed in the field submit, by drawing polygons on a mobile

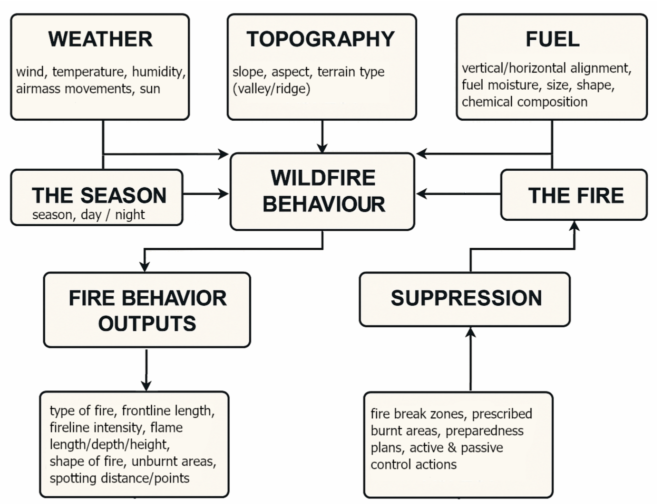

Fig. 4. Wildfire behavior factors, adapted from: [16]

map, two forestry areas with different fuel types, to feed the simulation engine. Chances are that the final polygons submitted will not be the same, leading to conflicts. For example, Figure 3 shows the first user observation (red line) on the left side; the second user observation (blue line) is added on the right side, leading to some unclear areas (silver polygons). The final representation of the area will be an aggregation of the two inputs, which will lead to a more accurate modeling of border areas, with no clear classification and boundaries. As more user observations are collected, the model will become more accurate. Assuming that most users submit correct data, good quality inputs will outvote poor ones by aggregating and interpolating the resulting dataset.

Since different observations of the same area can be submitted by users, we must determine if two observations refer to the same object or a different one; if they refer to the same object, we must decide which object parameters will be used in the simulation, therefore an efficient and lightweight (due to the use of mobile devices) method of interpolation is needed. We have recently proposed ant colony optimization based algorithm that normalizes the fuzziness of user's inputs and generates the geospatial primitives required for the simulation [4]. Our algorithm also takes into account the recency of each observation, since in an evolving phenomenon like a wildfire, objects are bound to change over time (for example, the fireline moves and areas are burnt).

D. A minimal ontology

An in-depth analysis of the literature was required in order to understand the mechanism and the environmental conditions responsible for the behavior of the wildfire. The factors involved in the wildfire spreading mechanism can be seen in Figure 4 [16]. However, the minimum set of parameters, measurements and observation required is heavily dependent on the wildfire simulation model used, with each model being applicable to certain conditions (wind tolerance, fuel types, crown fire behavior, etc.). That mutual dependency between measurements and applicable models raises the need to collect as much data as possible, starting with a limited subset and re-running the simulation when more data are available.

After reviewing the corresponding literature, we assembled a set of variables that are required for the majority of the simulation models. It should be understood that perfect knowledge of all variables in the required timeframe is unlikely, but chances are that most of them can be acquired from a variety of sources like weather forecasts, macroscopic observations, historical data, in field measurements, etc. A mapping of the involving ontologies and their corresponding properties is presented in Table II. It is easy to see that while data referring to the topography of the area can be acquired before the ignition of the wildfire (e.g., from satellites) due to their negligible time variation, the majority of the remaining factors are highly time-variant and their accurate prediction without access to in field data is at least challenging; updating the model with new observations and re-running the simulation is the best way to always have the most accurate predictions.

V. Conclusions and future work

We have proposed a standardized ontology for wildfires, intended to drive dynamic simulations combining pre-existing knowledge with observations gathered in the field, which may be inconsistent and time-dependent. Building a standardized collection of observations for an active wildfire provides a significant edge to the simulation: not only does it hold the most accurate and updated information, it can also provide a common framework in terms of phraseology and measurements units. For example, it is common for wildfire spread models developed in North America to use imperial rather than metric units; a standardized ontology allows for automated conversions to each user's locale. Finally, gathering data in a standardized format allows post-processing them to improve the static models of the affected area.

Our future work focuses on completing our decentralized mobile platform for wildfire simulation, based on our previous work [17]. The objective is not to implement the best simulation model–the literature abounds with wildfire simulators–but to adapt the simulation to incorporate user-submitted content, while distributing locally obtained knowledge to nearby nodes for further local simulation. Our work in this area is at the prototyping stage: we have built a quick simulation engine that is updated as new observations are entered.

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TABLE II
PROPOSED WILDFIRE SIMULATION ONTOLOGY ELEMENTS.

Ontology	Properties	Geometry	Data acquisition	Units	Time variable
Weather	Wind direction	point	In field	degrees	extremely
	Wind speed	point and elevation	In field	m/s	extremely
	Temperature	point	In field / forecast	degrees	very
	Humidity	point	In field / forecast	%	very
	Precipitation	point	Historic data	mm	moderate
	Day/Night	-	-	-	moderate
	Season	-	-	-	no
	Air mass stability	point	In field	stable / unstable	very
Forestry fuel	Fuel type	polygon	In field / Satellite data	-	no
	Fuel moisture	polygon	In field /simulation	%	very to moderate
	Dead/live fuel	polygon	In field	tn/ha	moderate
	Understory / overstory composition	polygon	In field	-	moderate
	Fuel shape (diameter, height)	polygon	In field / Satellite data	-	moderate
	Vertical alignment	polygon	In field / Satellite data	-	moderate
	Horizontal alignment	polygon	In field / Satellite data	-	moderate
	Compactness	polygon	In field / Satellite data	tn/ha	moderate
	Chemical composition	polygon	In field / Satellite data	-	moderate
Topography	Slope	points, elevation	Satellite data	%	no
	Aspect	polygon	Satellite data	degrees	no
	Terrain type	polygon	Satellite data	valley/ridge/open	no
Fire behavior	Ignition point(s)	point	In field	-	no
	Type of fire	polygon	In field	crown/ground/surface	very
	Speed and direction of spread	point	In field / simulation	m/s, degrees	extremely
	Frontline length	line	In field / simulation	m	extremely
	Frontline intensity	line	Simulation	kW/m	extremely
	Flame length	point	In field / simulation	m	extremely
	Flame height	point	In field / simulation	m	extremely
	Flame depth	point	In field / simulation	m	very
	Shape of fire	polygon	In field / simulation	-	very
	Spotting	point point	In field / simulation	-	very
	Spotting distance	point	In field / simulation	m	very
	Unburnt areas	polygon	In field / simulation	km^2	moderate
Historic knowledge	Burnt areas (past fire)	polygon	In field / historic data	km^2	moderate
	Prescribed burnt areas	polygon	historic data	km^2	moderate
	Firebreak zones	line	historic data	m	moderate
Suppression activities	fireline	line	In field	m	very
	attack points (land crews)	point	In field	-	very
	attack points (aerial)	point	In field	-	very

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