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Integration of field chemical data in initial risk assessment of forest fire smoke

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Abstract

A risk assessment framework was used to assess the risks of forest fire smoke (ffs) to the exposed communities, critical infrastructures and the environment. The present work is focused on the planning and problem formulation phases of this risk assessment procedure. Specifically, as part of the problem formulation phase, integration of the available ffs chemical data was carried out by answering critical questions regarding the ffs. In this way, critical factors have been identified, which mostly define and characterize ffs as a cause of problems and possible symptoms. The integrated information can be used in order to determine assessment endpoints, conceptual models, and risk hypotheses, as presented in an indicative example referred to a simple risk scenario. This work, enhanced with additional risk scenarios, can be used for the next phases of the risk assessment procedure, such as risk analysis and risk characterization. Future research needs for adequate evaluation of ffs impacts on communities, infrastructures, and the environment are also discussed.

Keywords: Forest fire smoke; Data integration; Field chemical data; Risk assessment; Fire-fighters

1. Introduction

Forest fires are known to have devastating consequences on the affected areas. Thus, actions towards fire suppression and management, as well as forest fire risk assessment have been of significant interest. Specifically, assessment of forest fire risks and management policies, have been conducted by the corresponding organizations (US NPS, 2006; USDA/USDI, 2005; US NWCG, 2004a). A study for assessing the risks and optimising the resource allocation over a considered territory has also been carried out for pre-operational and real-time phases (Fiorucci et al., 2005). An "event-based" approach has been used for risk assessment of wildland fires to human communities (McCool et al., 2006). Furthermore, various fire risk indexes have been used for the prevention of forest fires, or for facilitating the suppression of a forest fire (Hernandez-Leal et al., 2006; Christophe, 1998; Velez, 1998; Viegas, 1998; Wybo, 1998).

In addition to forest fires, the issue of forest fire smoke (ffs) risk assessment is also critical. During large-scale forest fires (e.g. Indonesia 1997), significant

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quantities of smoke are produced, which can maintain in the atmosphere for many days, affecting not only the areas in the vicinity of the flame-front but also areas in the dispersion path of the smoke plume. Ffs as a stressor can cause numerous adverse effects on receptors, such as communities, infrastructures and the environment. More specifically, serious health effects can be caused, such as lung diseases or even death, with the fire-fighters and vulnerable groups (e.g. the elderly, children, asthma patients), being mostly at risk. Smoke also contributes to visibility impairment, leading to irregularities in the operation of critical infrastructures, such as highways, airports, schools, or hospitals. In addition, ffs can contribute to the green house effect, as well as to soil and water pollution.

Until now, studies on the adverse effects of ffs have been conducted by the USDA (Wildland fire on ecosystems: effects of fire on air-2002), the USEPA (Wildfire Smoke Guide for Public Health Officials-2001), the US National Wildfire Coordination Group, Fire Use Working Team (US NWCG) (Smoke Management Guide for prescribed and Wildland fire-2001) and the World Health Organization in collaboration with the United Nations Environment Programme and the World Meteorological Organization (WHO/UNEP/WMO) (Health Guidelines for Vegetation Fire Events-1999). The above guidelines are mainly focusing on smoke management principles, which are available to fire-planners and fire-use practitioners for the management and mitigation of wildland fire smoke. They also provide with useful information on fire-risk assessment and include public advisories in case of forest fires.

However, future research is needed on comprehensive ffs risk assessments in order to evaluate ffs impacts on the fire-fighters and the public (USDA, 2002, pp.63–67). The present work is an effort for initial ffs risk assessment, based on a comprehensive risk assessment framework. More specifically, the USEPA's Ecological Risk Assessment Guidelines (USEPA, 1998), which have already been successfully used in a wide range of other applications (Power and McCarty, 1998), have been selected as framework for the ffs risk assessment. It consists of four phases: *planning, problem formulation*, *analysis* and *risk characterization*. Planning and problem formulation phases will be implemented in this work. The main goal is to integrate field chemical data related to ffs; to provide possible exposure characteristics, to define and characterize the entities and systems potentially at risk, (focusing primarily on communities, infrastructures and the environment) and to identify possible effects, emphasizing on the fire-fighters. In order to achieve this, a number of critical questions regarding the ffs are answered. In addition, an indicative risk scenario is presented, so as to illustrate how those integrated data could be used to define assessment endpoints and conceptual models.

2. Description of the risk assessment phases applied on forest fire smoke

The aim of this section is to describe the phases of "planning" and "problem formulation" according to the USEPA environmental risk assessment framework (USEPA, 1998).

During the planning phase, the management goal, the scope, and the objectives of the risk assessment are defined. In this work, the management goal is to control possible ffs impacts, so as to protect receptors (i.e. communities, infrastructures, environment), from anticipated adverse effects, such as acute and long-term health effects on the fire-fighters or population. In order to interpret this goal, the main objectives will be: 1) to define critical factors, 2) to determine emergency response plans and address corrective and mitigating actions (e.g. personal protective equipment use, evacuation of people in safe places). It should be noted that the scope of this work has been set to match the perspectives of operational agencies for coping with ffs impacts and for that reason more emphasis has been given on forest fire-fighters.

The problem formulation phase begins with the integration of available information; the present work is focused on this phase. The gathered information is interpreted in order to define how a stressor might be associated with numerous adverse effects on the entities/ systems under consideration. Moreover, based on the integrated information, assessment endpoints and risk conceptual models are developed. Assessment endpoints are the valued attributes of ecological or other entities, upon which risk management actions are focused (USEPA, 2003). Three principal criteria can be used to select assessment endpoints: 1) relevance to the entity of concern, 2) susceptibility of the entity to the stressor, and 3) relevance to management goals. In order to define the assessment endpoints, firstly there is a need to identify an entity that is of significant concern and secondly, to define the entity's characteristic value that is potentially at risk or that needs to be protected (USEPA, 1998). The conceptual models can be developed from the information that has been collected about the stressors, the exposure characteristics and the predicted effects to an entity or system of significant concern. The fundamental concept behind the conceptual model is the risk hypothesis that can be either a written document, a diagram (i.e. commonly known as conceptual model diagram), or a combination of both. A risk hypothesis is an assumption – scenario about potential risks.

3. Integration of the available information regarding forest fire smoke

In this section, questions suggested by the USEPA (1998) guidelines will be answered specifically for the ffs, in order to integrate the relevant available information. Characteristics of the source, the stressor and the exposure, as well as possible receptors at risk and consequent effects will be presented and discussed.

3.1. Source and stressor characteristics

3.1.1. What is the source? Is it anthropogenic, natural, point source, or diffuse non-point?

Forest fires can be anthropogenic (e.g. negligence), or natural (e.g. lightning). Non-point sources are considered the pollution sources that diffuse and do not have a single point of origin. Forest fires that are the source of ffs are considered diffuse non-point. As a result, generating risk maps that provide information about areas which are vulnerable to fire can sometimes be an especially difficult task (Hernandez-Leal et al., 2006).

3.1.2. What type of stressor is it: Chemical, physical, or biological?

FFS can be considered as physical and chemical stressor, as long as it consists of components with physical and chemical properties. More specifically, ffs is an aerosol consisting of water vapour, permanent gases, VOCs (Volatile organic compounds), SVOCs (Semi-volatile organic compounds) and particles. Permanent gases include CO_2, CO, NO*x* (Radojevic, 2003; Muraleedharan et al., 2000), SO*x* and NH_3. SO*x* are usually produced in small quantities because generally forest fuel sulfur content is low (Ward and Smith, 2001). However, high amounts of sulfur-based compounds can be produced when sulfur-rich vegetation or soil are burned, such as the Yellowstone National Park fires (Reh and Deitchman, 1992). In savannah fires, the emission ratio of NH_3 relative to CO_2 has been found to be at low levels (Koppmann et al., 2005).

VOCs, include methane (Miranda, 2004; Heil and Goldammer, 2001; Ward, 1999) and other hydrocarbons, which can be aliphatic (alkanes, alkenes, alkynes), such as ethane, heptane, decane, propene, 1-nonene, 1-undecene, acetylene (Statheropoulos and Karma, 2007; Shauer et al., 2001; Ward and Smith, 2001; McDonald et al., 2000), or aromatic hydrocarbons (e.g. benzene, alkylbenzenes, such as toluene, xylene, ethyl–benzene) (Statheropoulos and Karma, 2007; Muraleedharan et al., 2000; Reh and Deitchman, 1992). In addition, VOCs can include oxygenated compounds, such as alcohols (e.g. phenol, m-cresol, p-cresol, guaiacol) (Statheropoulos and Karma, 2007; Shauer et al., 2001; Ward and Smith, 2001; McDonald et al., 2000), aldehydes (acetaldehyde, formaldehyde, furfural, acrolein, crotonaldehyde, benzaldehyde) (Statheropoulos and Karma, 2007; Reinhardt and Ottmar, 2004; Shauer et al., 2001; Reh and Deitchman, 1992; Kelly, 1992a), ketones (e.g. acetone, 2-butanone) (Statheropoulos and Karma, 2007; McDonald et al., 2000), furans (e.g. benzofuran), carboxylic acids (e.g. acetic acid), esters (e.g. benzoic acid, methyl ester) (Statheropoulos and Karma, 2007; Ward and Smith, 2001; McDonald et al., 2000; Muraleedharan et al., 2000; Reh and Deitchman, 1992). In addition, halogenated compounds, such as chloro-methane have been detected in the ffs (Statheropoulos and Karma, 2007; McDonald et al., 2000). SVOCs can be polyaromatic hydrocarbons (PAHs), such as benzo(a) Pyrene (Booze et al., 2004; Muraleedharan et al., 2000; Ward, 1999; Reh and Deitchman, 1992; Kelly, 1992a).

Particles can be coarse ($>PM_{10}$) or fine ($PM_{2.5}$, PM_1, $PM_1<$), depending on their size. The major amount of particles produced in a forest fire, (over 90%), are 10 μm or less in diameter (Johnson, 1999). They can be primary, released directly to the atmosphere due to the incomplete combustion, or secondary, formed through physical or chemical transformations (CEPA, 1999). Primary particles can be elemental carbon (soot), or organic carbon particles. The latest can also be generated secondary, by condensation of hot vapours (tars) and also nucleation of atmospheric species (CEPA, 1999). Additionally, trace elements are known to concentrate in the fine fraction. According to the literature, particles produced from forest fires were found to contain trace elements, such as Na, Mg, Al, Si, Cd, P, S, Cl, K, Ca, Ti, Mn, Fe, Zn, Rb, Sr, V, Pb, Cu, Ni, Br, Cr (Radojevic, 2003; Muraleedharan et al., 2000; Ward and Smith, 2001; Reh and Deitchman, 1992). This issue is of significant concern, especially when heavy and toxic metals, such as Pb and Hg are contained in the ffs fine particles (e.g. the Los Alamos fires) (Popp et al., 2000).

3.1.3. What is the forest fire flame-front path (complexity of ffs)?

Forest fires are usually characterized by dynamic phenomena and changes in the wind velocity and direction. As a result, the flame-front produced can expand to different directions and pass through rural fields, rural/

urban constructions, or landfills. In such cases, wood, plastics, fertilizers, pesticides, fungicides, wastes can also be burned and hence, some of the ffs components can have a different origin than that of the forest fuel (Statheropoulos and Karma, 2007). The smoke produced might be even more complex, including hazardous compounds, such as Dioxines (Polychlorinated Dibenzo-*p*-Dioxines/ Polychlorinated Dibenzo-Furans PCDDs/PCDFs). Moreover, it has been reported that when radioactively contaminated vegetation was burned redistribution of radionuclides took place, such as the long-living radionuclides caesium ($_{137}$Cs), strontium ($_{90}$Sr) and plutonium (239Pu) (WHO/UNEP/WMO, 1999, pp. 29). Possible scenarios of the flame-front expansion and the potential chemical composition of the generated smoke can be integrated in a road-map for air quality assessment (Statheropoulos and Karma, 2007, 2005).

3.1.4. *What are the possible secondary products of the smoke plume?*

Photochemical reactions can take place under sun radiation, and therefore secondary products can be produced in the smoke plume. VOCs and the CO have been described as precursors to ground level ozone, especially when NO_2 is present (Hogue, 2005). Field observations by aircraft measurements have shown elevated ozone at the edge of ffs plumes far downwind (Stith et al., 1981). More recent observations (Wotawa and Trainer, 2000), suggested that high concentrations of ozone were found in forest fire plumes that were transported to significant distances, across international boundaries. It has also been reported that Canadian forest fires changed the photochemical properties of air masses over Tennessee on days with strong fire influence (USDA, 2002, pp. 41).

In addition, the smoke plume can pass over urban and industrial areas. Urban and industrial pollution can interact with ffs (Quiterio et al., 2004; US PNW, 2004; Cincinelli et al., 2003; Lee et al, 2002; Caricchia et al., 1999). FFS components, when mixed with urban and industrial pollutants may have additive, or even synergistic results. According to the literature, the net production of ozone occurs either in the original plume, or as a result of the plume mixing with the regional atmosphere (USDA, 2002, pp.42).

3.1.5. *What is the intensity of the ffs stressor (e.g., the dose, or concentration of a chemical)? How is it related to the intensity of exposure?*

Intensity-concentration of the smoke components plays a critical role in the resulted problems and symptoms. During a forest fire, high values of peak concentrations are observed, especially near the flame-front. Table 1 shows the mean concentrations measured in smoky conditions in the field (sampling duration 20–30 min) and also the respective short-term limits, recommended by the National Institute for Occupational Safety and Health (NIOSH).

The intensity of the stressor is straightly correlated to the intensity of the exposure, especially for the front-line personnel (fire-fighters). Concentrations of PM_{10} as high as, 47 600 μg m^{-3} have been identified in smoky conditions (Reh and Deitchman, 1992), whereas the exposure limit for 24-h given by the American Conference of Governmental Industrial Hygienists (ACGIH) is 150 μg m^{-3}. Moreover, peak $PM_{2.5}$ level measured in the field at a distance of approximately 70 m from the flame-front was estimated to be 49 500 μg m^{-3} (Statheropoulos and Karma, 2007), whereas the respective ACGHI 24-h limit is 65 μg m^{-3}. According to Reinhardt et al. (2000, pp. 34–35), the exposure of fire-fighters to CO and formaldehyde can occasionally exceed legal and short-term exposure limits; for example, the CO level exceeded the 200 ppm ceiling of NIOSH in smoky conditions. Carbon monoxide is known to displace oxygen from hemoglobin in the blood to form carboxyhemoglobin (COHb); it can have acute health effects, which may range from decreased work capacity to acute nausea and severe headache, or it can even lead to death during extreme exposure levels (Reinhardt et al., 2000). It has been reported that generally a level of 5% COHb results from 3–4 h of exposure to CO concentrations of 35 ppm (Ward, 1999). Estimation of COHb level can be made by using the CFK (Coburn, Foster, Kane) equation, which takes into consideration variables, such

Table 1
Mean concentrations measured in smoky conditions in the field and short-term occupational exposure limits

Compound	Concentration	Short-term exposure limits (NIOSH) (U.S. 1997)
CO [a]	54 ppm	200 ppm
CO_2 [a]	350 ppm	30000 ppm
Benzene [a]	0.22 ppm	1 ppm
Toluene [a]	0.12 ppm	150 ppm
Xylene [a]	0.08 ppm	150 ppm
Acroleine [b]	0.071 ppm	0.3 ppm
Formaldehyde [b]	0.468 ppm	0.1 ppm
Benzo(a)Pyrene (BaP) [c]	7.1 ngm^{-3}	–
$PM_{2.5}$ [a, d]	7000 μgm^{-3} [a] 2300 μgm^{-3} [d]	65 μgm^{-3} (24-h) [e]

[a] Statheropoulos and Karma, 2007.
[b] Reinhardt et al., 2000.
[c] Pinto and Grant, 1999.
[d] Miranda et al., 2005.
[e] ACGIH.

as the duration of the exposure, the lung ventilation rate, the rate of endogenous CO production, the diffusion rates in the lung, the blood volume, the barometric pressure and the partial pressure of CO and oxygen in the lung (Reh and Deitchman, 1992). Regarding the concentrations of smoke particles, it has been reported that in a two months period during the 1997 large-scale forest fires, about 20 million people in Kuching region in SE Asia were exposed to ambient concentrations of PM_{10} that exceeded the USEPA's 24-h National Ambient Air Quality Standard of 150 μg m^{-3}; in some days, PM_{10} reached 24-h peak concentrations of 852 μg m^{-3}, exceeding the USEPA's 24-h hazardous level of 500 μg m^{-3} (Mott et al., 2005).

3.2. Exposure characteristics

3.2.1. What is the frequency of the exposure (e.g., is it isolated, episodic, or continuous?

The frequency of the exposure to ffs components is critical for risk assessment. Population's exposure to ffs can be isolated or episodic, whereas for the fire-fighters it can be a seasonal or continuous situation. However, fire-fighters' exposure can differ significantly depending on the fire suppression strategies and work-shifts, due to the nature and specific characteristics of the fire (e.g. duration, extension). According to the NIOSH investigators (Kelly, 1992b), direct attack activities in wildland fires are believed to result in the most significant exposure compared to other fire-fighting activities. It has also been reported that "fireline holders" and "attack crew" fire-fighters are more frequently exposed to high carbon monoxide levels due to the denser smoke (Fowler, 2003). During a forest fire, fire-fighters work-shifts might be exceeded to 12 h or even more, depending on the situation (Reh and Deitchman, 1992). For estimating the Time-Weighted Average (TWA) exposures of the fire-fighters, over the duration of a work-shift and while on the fire-line, an equation has been proposed; comparison of the calculated TWA with the respective exposure limits that are given by health organizations, informs on work-shifts changes (Reinhardt et al., 2000, pp.6). In addition, for evaluating the compliance of non-traditional work-shifts with the 8-h PELs, Occupational and Safety Health Administration (OSHA) uses a specific equation; an exposure limit reduction factor is calculated, which is depended on the duration of the extended working hours (Reinhardt et al., 2000, pp. 6–7).

3.2.2. What is the periodicity of the exposure?

Periodicity of receptors' exposure, which is related to the periodicity of forest fire smoke episodes, is also important for ffs risk assessment. Most of the smoke episodes usually occur when low RH% (<25%) and high temperatures (>30 °C) exist. According to the literature, burning of forests and savannahs in SE Asia is more intensive in the northern hemisphere from November to March, whereas in the southern hemisphere from June to September (WHO/UNEP/WMO, 1999, pp.27). Moreover, Heil and Goldammer (2001) reported that periodic fire-related regional air pollution episodes have been occurred in SE Asia since the 1970s. However, US fire seasons vary significantly; in the Western US, fire season is normally during April to September (Hostetler et al., 2005), whereas in the Eastern US, it is normally during November to March (NOAA, 2006).

3.2.3. What is the stressor duration? How long does it persist in the exposed receptors (human body, environment)?

Persistence of the ffs in the exposed receptors, (e.g. human body, environment), plays critical role for the resulted adverse effects. FFS persistence as a stressor depends on its physical and chemical properties. Among the physical properties, the most important are the smoke particles size, their ability to absorb chemicals and their shape. More specifically, fine ($PM_{2.5}$, PM_1<) and aerodynamic particles can be transferred in long distances; they can also penetrate more easily the respiratory system, causing severe health effects. Among the chemical properties, alkalinity and acidity are essential; alkaline pH of particles is known to cause nose and chest irritation. In addition, vapor pressure of ffs components is correlated with their ability to persist in the environment (e.g. degradation in water, air). Another parameter is Henry's low constant, which provides additional information regarding how compounds are distributed between gas and liquid phase; high Henry's low constant value means that the compound tends to remain in gas phase. Moreover, chemical's octanol-water partition coefficient gives information regarding compound absorption efficiency from human body. In addition, organic carbon sorption coefficient of compounds characterizes the ability of special filters to absorb a compound and hence, indicates indirectly filters for personal protective equipment (PPE) (Hogue, 2006).

It should be noted that CO, which is a hazardous ffs component, has half-life in the human body of about 4–5 h (Baselt, 2000; Reinhardt et al., 2000, pp.3; Kerndt et al., 1986). However, if 100% oxygen is administered and no further exposure occurs, the half-life is reduced to 80 min (Kerndt et al., 1986).

Regarding the environment, chemicals with low solubility in water tend to be found in soil layer, rich in organic carbon (USEPA, 1998, pp.70).

3.2.4. What is the timing of the exposure? When does it occur in relation to critical organism life cycles or ecosystem events?

Timing of the exposure, related to critical organism life cycles or ecosystem events, is a critical factor for environmental symptoms assessment. It has been reported that photosynthesis in three tree species was reduced by the smoke-haze of 1997 in Indonesia, due to elevated aerosol and atmospheric pollutant levels (Davies and Unam, 1999).

3.2.5. What is the spatial scale (magnitude) of exposure? Is the extent or influence of the stressor local, regional or global?

Cross boarder transfer of ffs defines the number of population that will be exposed to the smoke plume (spatial scale). Depending on the fire dimensions, the extent of exposure to ffs can be local, regional, or global. For example, during the large-scale forest fires of 1997 in Indonesia, over 12 000 000 of people were affected in Indonesia provinces, together with the population affected by the cross border transfer of smoke (Dawud, 1999). Spatial scale of exposure defines the dimensions of symptoms, and therefore characterizes the type of measures and scale of operations for countering possible impacts. Moreover, it defines the cost and the possible services that have to be involved for coping with ffs, such as the number of means needed for the control of fire and smoke (e.g. ground and aerial use of chemical retardants), number and type of protection means.

3.2.6. What is the distribution? How is the stressor transferred through the environment?

Distribution of ffs depends on the meteorological data, such as the wind speed and direction, the temperature, the relative humidity (RH %). Usually, fine particles can be transported to long distances (cross border transfer), whereas the coarse particles deposit on surfaces (e.g. soil, streams). In Table 2, a number of forest fire pollutants such as, CO, CO_2, O_3, NO_2, Benzene, PAHs, PM_{10}, $PM_{2.5}$ and how they can be transferred through the environment are presented (Brauer, 1999; Heil, 1998). Polyaromatic hydrocarbons (e.g. Benzo(a)pyrene), are usually condensed or adsorbed onto the surface of fine particles (PM_{10}<); they can also form small particles themselves with average diameter of 1 μm (Heil, 1998). During the haze from forest fires in Indonesia 1997, Benzo(a)pyrene content of PM_{10} was found 11 ng per mg of particulate (Heil, 1998). According to the same study, the particulate-bound PAHs-concentration seemed to decrease with the distance from the forest fire, due to photochemical degradation processes.

Table 2
Indicative ffs compounds and how they are transferred through the environment (Brauer, 1999)

Compound	Example	Notes
Permanent gases	CO, CO_2	Transported over distances.
	O_3	Only present downwind of the forest fire. Transported over distances.
	NO_2	Reactive. Concentrations decrease with distance from the forest fire.
Hydrocarbons	Benzene	Some transport. Also react to form organic aerosols.
PAHs [a]	Benzo[a] Pyrene	Usually condense or absorbed onto fine particles. Evidence that particulate-bound PAHs-concentration decreases with the distance from the forest fires, due to photochemical degradation processes.
Particles	PM_{10}	Coarse particles are usually deposited. They contain mostly soil and ash.
	$PM_{2.5}$	Fine particles are transported over long distances.

[a] Heil, 1998.

During the 1997 episode in Southeast Asia, the smoke-haze layer covered an area up to 10 million km^2 (Nakajima et al., 1999). In 1992, severe wildfires in the Gomel Region (Belarus) were spread into the 30-km radius zone of the Chernobyl Power Plant; research revealed that radionuclides were lifted into the atmosphere and that within the 30-km radius zone the level of radioactive caesium in aerosols increased 10 times (WHO/UNEP/WMO, 1999, pp.29–30). Moreover, during the Canadian forest fires in a province of Quebec in 2002 affected the PM levels of Baltimore, located hundreds of kilometers from the source (Sapkota et al., 2005). Fires in Canada were also found to cause high concentrations of carbon monoxide and ozone over a period of two weeks in the Southeastern United States and across the Eastern seaboard, during the summer of 1995 (Wotawa and Trainer, 2000).

3.3. Entities and systems potentially at risk

3.3.1. Which are the receptors affected by the ffs and what are the possible problems caused?

3.3.1.1. Communities. A main problem caused by the ffs is that a number of people and fire- fighters are exposed to ffs complex mixture, which can have different physicochemical characteristics depending on the flame-front expansion (Statheropoulos and Karma, 2007). This mixed exposure can be the synergistic or additive result of the exposure to all the hazardous ffs components (Stefanidou-Loutsidou, 2005; Fowler, 2003). Although assessment of mixed exposure is a complicated issue, it should be taken into account during the risk estimation phase of the risk assessment procedure in order to evaluate the ffs impacts (USEPA, 1998). This is even more critical for the fire-fighters, who are exposed to high pollutants concentrations; a specific equation has been used in order to calculate mixed exposure of the fire-fighters during their work-shift for acroleine, formaldehyde and respirable particles ($PM_{3.5}$) (Reinhardt et al., 2000, pp.5–6).

3.3.1.2. Infrastructures. Infrastructures that can possibly be affected directly or indirectly by the smoke plume are among others, highways, airports, hospitals, schools or army-camps; this can happen either because they might be in the interface of the forest fire, or because the smoke plume may travel long distances and affect them. A major problem that critical infrastructures encounter due to a smoke episode is the visibility impairment. An illustrative example is that of 1994, when the smoke plumes of fires burning in Sumatra reduced the average daily minimum horizontal visibility over Singapore to less than 2 km; by the end of September 1994 the visibility in Singapore dropped to as low as 500 m, whereas at the same time the visibility in Malaysia dropped to 1 km in some parts of the country (WHO/UNEP/WMO, 1999, pp. 29).

3.3.1.3. Environment. High levels of smoke components concentrations and their physicochemical properties (e.g. Henry's Law constant) define their persistence in the environment (e.g. as green house gases). If persistence of smoke pollutants in the environment is combined with their ability to give photochemical reactions, this will lead under sun radiation to secondary products; the enormous wildfires in Alaska and the Canadian Yukon during the summer of 2004 generated huge plums of CO and other pollutants, affecting large areas of the Northern Hemisphere by ground-level ozone increase (Barry, 2005).

3.3.2. What is the susceptibility of the exposed groups?

The term susceptibility is attributed to the *sensitivity* of the receptors and is correlated to *the intensity of the exposure*. Regarding the exposed population, sensitive groups that are considered more vulnerable are the infants, the children, people with respiratory problems, the elderly, and the pregnant women (USEPA, 2001). According to Dawud (1999), the elderly and young children appeared to be more sensitive to the hazardous situation of the haze in Indonesia. Moreover, during California 1999 forest fires, 92 out of 289 residents that had pre-existing cardiopulmonary conditions were tested for ffs impacts (Mott et al., 2002). It was found that more than 60% of the subjects (178/289) reported increased respiratory symptoms during the smoke episode and that more than 20% (65/289) continued to report respiratory symptoms two weeks after the exposure. This information is also confirmed by another study, during California forest fires in 1987 (Duclos et al., 1990); according to hospital information in a 2 and 1/2-week period, increased respiratory morbidity was observed for people with pre-existing respiratory disease. Regarding the fire-fighters, a pre-existing medical condition often aggravates health impacts; generally, fire-fighters sensitivity has to do with the specific individual (Reh and Deitchman, 1992).

Intensity of the exposure is straightly correlated to the intensity of the stressor (concentration of ffs components), as previously described. Both sensitivity of the receptors and intensity of their exposure are critical factors that need to be considered for establishing exposure limits and also for addressing evacuation criteria.

3.4. Adverse effects of forest fire smoke

3.4.1. What are the effects of ffs on humans, infrastructures and ecosystems?

3.4.1.1. Communities. Health effects due to acute exposure (<24 h) (EPA, IRIS) can be nose and eye irritation, acute respiratory infection (ARI), or lung function problems (Reinhardt et al., 2000; Brauer, 1999; Malilay, 1999). Short-term exposure (<7 days) (EPA, IRIS) to smoke components, such as particles, acrolein, formaldehyde and CO, has been associated with lung function decrements and increases in airway responsiveness of the fire-fighters (Slaughter et al., 2004; Fowler, 2003; Liu et al., 1992). Possible long-term effects, due to sub-chronic or chronic exposure (months or years) (EPA, IRIS; Brauer, 1999) to ffs can be lung and chest diseases or cancer (USEPA, 2001, pp. 4–5; Pinto and Grant, 1999; Ward, 1999; WHO/UNEP/WMO, 1999, pp. 69–74). Association of hospitalizations with smoke exposure during 1997 in SE Asia has been reported by Mott et al. (2005). According to this study, the total number of hospitalizations among people of all ages was modestly elevated (by 8%) during the forest fire period from August until the end of October

1997, compared to the average number of hospitalizations that occurred during the same months in 1995, 1996 and 1998. According to Sastry (2000), during the peak period of smoke haze in Malaysia 1997, respiratory disease out-patients visits to Kuala Lumpur General Hospital increased from 250 to 800 per day; effects were found to be greatest for children, the elderly and people with pre-existing respiratory problems.

3.4.1.2. Infrastructures. Possible effects on infrastructures can be irregularities in operation of airports (e.g. reduced or cancelled flights), highways and hospitals, as well as army camps. Regional airports in Indonesia were closed during the worst of the haze period of 1997. In 1982–83, 1991, 1994 and 1997–98 the smog episodes in South East Asia resulted in closing of airports and marine traffic, such as in the Strait of Malacca and also along the coast and on rivers of Borneo (WHO/UNEP/WMO, 1999). In addition, human losses due to accidents in the highways, or possible airplane crashes can be symptoms of the reduced visibility. Several smoke-related marine and aircraft accidents occurred during late 1997 (WHO/UNEP/WMO, 1999). From 1979 to 1988, 28 fatalities and more than 60 serious injuries were attributed to smoke that covered roadways in the Southern United States (Mobley, 1990). According to a study (Muraleedharan et al., 2000), during the 1998 smoke episode in Brunei Darussalam there was a significant haze impact on areas where schools and hospitals were situated.

3.4.1.3. Environment. The long-term effects of forest fire emissions on atmospheric composition and global processes have been adequately studied (Houghton et al., 1992). Short-term effects of forest fires can include elevated aerosol and CO_2 levels, nitrogen deposition, acid precipitation and local climatic changes that may have direct negative or positive effects on plant functioning (Vitousek et al., 1997; Bazzaz, 1990; Fan et al., 1990). During the 1997 SE Asia forest fires, green house effect of gases that remained in the environment for many days was significant (Heil and Goldammer, 2001); enhanced concentrations of CO_2 and CH_4 were observed throughout the troposphere from eastern Java to the South China Sea.

FFS particles can pollute surface water directly by deposition, or can be part of the soil. In such case and after a rainfall, suspended soil particles, as well as dissolved inorganic nutrients and other materials can be transferred into adjacent streams and lakes, reducing water quality and disturbing aquatic ecosystems balance. In sandy soils, leaching may also move mineral through the soil layer into the ground water (USDA, 1989).

4. Using integrated ffs information: Example of endpoints and conceptual model

In this section, an indicative example on how to use the integrated information about ffs stressor will be presented. As part of the problem formulation phase, a number of possible endpoints and a conceptual model referred to a simple risk scenario are given. Enhancement of those endpoints and advanced conceptual models are needed, in order to be used as input for the analysis phase of a comprehensive risk assessment procedure.

4.1. Endpoints

Assessment endpoints are critical for addressing management concerns. In this example, the entity that is of significant concern is the fire-fighters. The management goal is to protect them from possible adverse health effects, due to the ffs stressor. Along with the criteria for selection of endpoints, presented in Section 2, a number of possible endpoints for the fire-fighters are shown below:

4.1.1. Fire-fighters with acute, short-, or long-term health effects due to ffs exposure

The percentage of fire-fighters with acute, short-, or long-term health effects after exposure to ffs can be a key indicator for assessing the ffs risk to the fire-fighters entity. A study carried out by the California Department of Health Services shown that 76% out of 94 fire-fighters examined during the Klamanth National forest fires of 1987 reported cough, wheezing, or shortness of breath (NIOSH, 2004). Seventy-six fire-fighters were studied for cross-shift and 53 for cross-season analysis, by using spirometric measurements and self-administered questionnaire data before and after the 1992 fire-fighting season (Betchley et al., 1997); it was found that they had significant declines in lung function. Another study on the Yellostown fires in 1988 has shown that 40% of the approximately 30 000 medical visits made by wildland fire-fighters were for respiratory problems and that approximately 600 fire-fighters required subsequent medical care (Reh and Deitchman, 1992). According to the same study, other kinds of sensitivities (e.g. allergies), of the individual fire-fighters played also a critical role in the severity of the symptoms.

4.1.2. Fire-fighters casualties due to ffs

The number of deaths among fire-fighters caused due to smoke inhalation can also be considered as an endpoint for ffs risk assessment. According to the literature, fire-fighters deaths have been reported due to asphyxia and acute carbon monoxide poisoning (NIOSH, 1999). In general, asphyxiation has been considered a main cause of death for many career and volunteer fire-fighters (US NWCG, 2004b; Fowler, 2003; USFA, 1995). Suffocation due to smoke inhalation has also been reported as a cause of death for a number of fire-fighters in Idaho and Tennessee forest fires (US NWCG, 2004b).

4.1.3. Fire-fighters without respiratory PPE

Personal Protective Equipment (PPE) is considered critical for controlling unwanted symptoms of the ffs exposure, especially for the fire-fighters of the front-line. NIOSH investigators suggest that wildland fire-fighters need to be provided with the suitable PPE that should be compliant to the National Fire Protection Association Standards of 1997, in order to avoid acute health impacts from smoke inhalation (NIOSH, 1999). Masks (half- or full- phase), or other respiratory equipment (e.g. respirators) can be used (Johnson, 1999).

Especially for the forest fire-fighters, PPE should be effective, easy to use and flexible; fast moving in the field is necessary to avoid flames, very high temperatures and smoke. Half-face masks and bandannas offer such flexibility. Masks with integrated filters of class N and 95% efficiency can be used for the forest fire-fighters protection from particles, according to the regulations 42 CFR Part 84 given by the NIOSH (Johnson, 1999). It should be noted that airtight sealing of those masks should be tested to provide sufficient protection (Reh and Deitchman, 1992). However, such filters do not offer respiratory protection for CO (Reinhardt and Ottmar, 2004; Johnson, 1999). In addition, bandannas were found to be inappropriate for CO (Reh and Deitchman, 1992) and fine particles (PM <10 μm) protection; scanning electron microscope pictures shown that the rectangular pore size of the fabric exceeded 100 μm (NIOSH, 2004). Self-contained breathing apparatus (SCBA respirators) and full-face respirators can provide a more adequate protection from gases and particles. However, they are not considered very practical in wildland fires; SCBA is heavy and also problems, such as heat load and fogging are very often (Reinhardt and Ottmar, 2004).

According to the above, half-face masks with the suitable filters can be used for respiratory protection from ffs particles, but also on-line monitoring of acute toxic gases concentration is necessary (e.g. the CO), as it will be described in the following.

4.1.4. Chemical composition and intensity of the smoke inhaled by the fire-fighter

According to the integrated information regarding the ffs, chemical composition of smoke is directly correlated to the respective adverse effects due to its specific physicochemical properties. Chemical composition of ffs depends on the flame-front path; when flame-front expands to a landfill, combustion products, such as PCDDs/PCDFs are evolved (Statheropoulos and Karma, 2007). These are known to be hazardous compounds and can cause long-term health effects, such as respiratory disorders, kidney and liver damage (Mester, 2006). In addition, intensity of the smoke near the flame-front is critical. High concentrations of pollutants in smoky conditions (see Table 1), combined with the extended work-shifts of the fire-fighters in emergency situations, might lead to acute unwanted symptoms; this can include irritation, shortness of breath, or dizziness due to the inhalation of CO, respirable irritants, (e.g. fine particles, diameter 2.5 μm<), and other smoke pollutants (Reinhardt et al., 2000). Intensity of the smoke pollutants depends on the distance from the flame-front and can be measured on-line by sensors, such as CO detectors or other field analytical instruments, such as portable GC-MS (Gas Chromatography-Mass spectrometry). Particles can be measured by portable particle analyzers or by ATOFMS (Aerosol Time of Flight Mass Spectrometer) that can also be used for the on-line field analysis of the fine particles composition (Freney et al., 2006).

4.2. Risk hypothesis — scenario

In the following, the basic elements of a risk scenario regarding fire-fighters and smoke impacts are presented. The conceptual model referred to the specific scenario is also presented and actions for coping with the ffs impacts are suggested.

4.2.1. Description of the situation

According to the scenario, the fire is initiated at a forest nearby a landfill. Due to the specific meteorological conditions (wind velocity and direction), the fire expands and co-burns the disposed wastes. A smoke column is produced, moving up at a height of about 500 m. The smoke is travelling towards the area that the fire-fighters are posited, due to a moderate wind. A sudden change of the wind from moderate to strong curves violently the smoke to the area.

Generally, conditions near the flame-front are considered very hostile and heavy, since high temperatures are observed due to heat radiation, and also turbulent evolution of smoke emissions, such as gases, embers, soot and tars takes place. Moreover, during the forest fire, rapid changes of emissions concentration gradients in space and time usually take place, so that flexibility and quick movements in the field are required.

4.2.2. Procedures involved

Ground level fire suppression is taking place; a group of fire-fighters is involved. The personnel are equipped with half-phase masks. Some members of the group, during their extended workshift (over 8-h), went for camping away from the smoke front but they did not completely recover from the CO inhalation.

4.2.3. FFS impacts

Due to the sudden curving of the smoke to the area, the group of the fire-fighters is trapped into the smoke column. Acute symptoms may include eye and nose

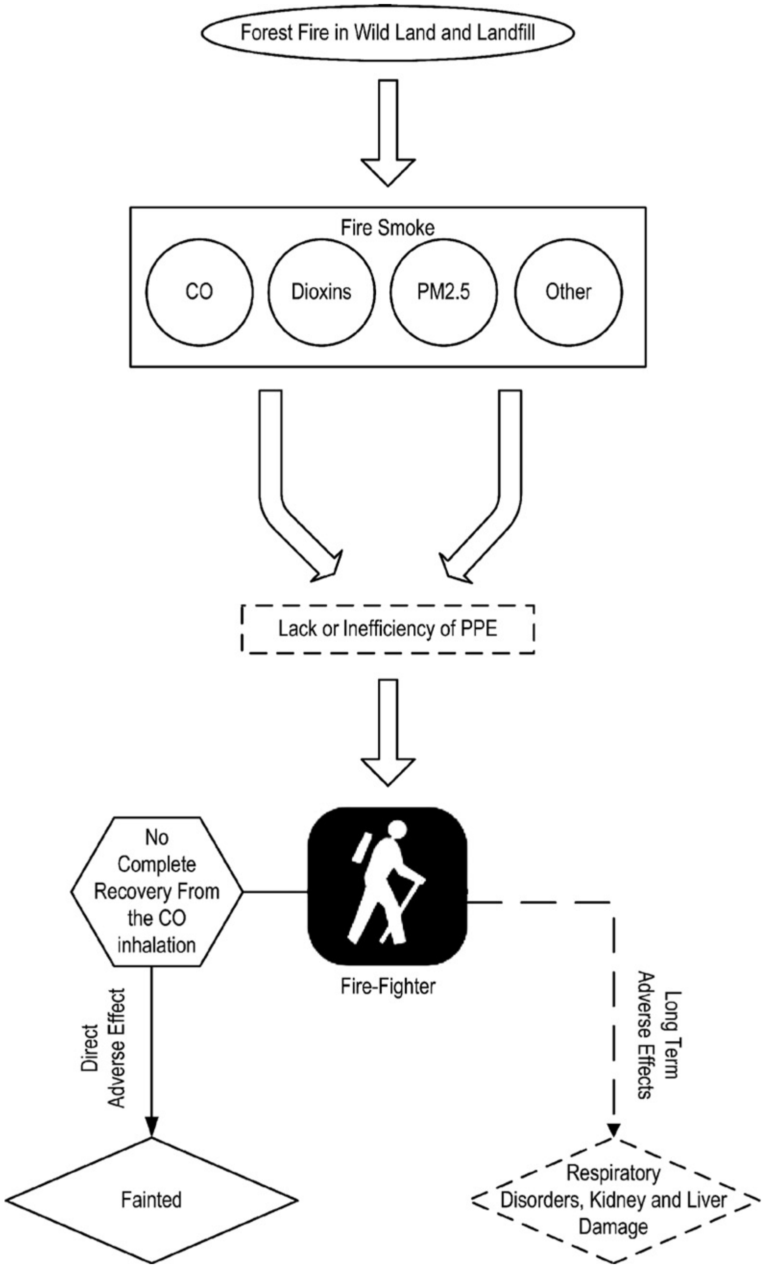

Fig. 1. Conceptual model of an ffs risk scenario.

irritation, lung function decline and fainting, due to exposure to CO, fine particles ($PM_{2.5}$), dioxins, and other smoke components. The situation is considered a mixed exposure case.

4.3. Conceptual model

Fig. 1 presents the conceptual model that describes the ffs risk scenario. Based on the integrated information, derived from the critical questions raised regarding ffs, a number of general actions for countering ffs impacts can be proposed related to the specific risk scenario. Such actions may include: 1) on-line measurement of critical compounds concentration (e.g. CO), in order to fast escape from the scene 2) occasional replacement of the half-face mask by a respirator (oxygen supply) in dense smoke conditions (high CO concentrations), if quick moving is not judged necessary 3) establishing exposure limits for smoky conditions and 4) extensive recovery time for the affected personnel.

5. Discussion and conclusions

Table 3
Number of documents regarding ffs impacts on three receptors categories

Categories of receptors	Number of relevant documents	Comment on data obtained regarding ffs impacts
1. Communities		
Fire-fighters	22	Data regarding mixed exposure of fire-fighters, depending on the flame-front path, are missing.
Population	19	Limited data regarding evacuation criteria of population in ffs episodes.
2. Infrastructures	2	Lack of case studies and data regarding ffs impacts on hospitals, schools, army-camps. Limited data regarding highways and airports.
3. Environment	23	Enhancement of ffs environmental impacts with recent studies might be needed, e.g. due to smoke deposition on forest leaves.

In Table 3, the number of documents found in literature regarding the three categories of receptors studied in this work (communities, infrastructures and the environment), is presented. For each category, a comment regarding the adequacy of the data obtained is also provided, in order to facilitate future approaches.

It appears that the study of the fire-fighters mixed exposure to ffs, especially when the flame-front expands and co-burns other materials and fuels, is an issue that needs further investigation. Epidemiological studies are also needed for that. In addition, limited data regarding evacuation criteria and emergency plans in smoke episodes exist for controlling ffs impacts, especially for the sensitive groups. Regarding the infrastructures, no data or case studies exist in relation to ffs impacts on critical infrastructures, such as hospitals, schools or army-camps. Nevertheless, there is some limited data regarding reduced visibility effects on highways and airports, as well as a number of related accidents caused. Further research is needed towards those directions. Finally, regarding the environment, it seems that many issues have been studied so far. Though, enhancement of ffs environmental impacts may include studies on smoke deposition (e.g. soot, tars) on forest leaves, or possible smoke effects on aquatic ecosystems.

It seems that application of USEPA guidelines on ffs for initial risk assessment was quite productive. It facilitated the indication of critical factors, which define ffs as a stressor, and that should be taken into account for evaluating ffs impacts on possible receptors. The focus was on the problem formulation phase of the risk assessment procedure; integration of the available data found in literature was carried out in the format of critical questions and answers. This work can be used as input for enhancing the existing guidelines referred to ffs risk assessment, under the framework of a specific risk assessment procedure.

A number of assessment endpoints and a conceptual model were also presented as an indicative example referred to a simple risk scenario. The scenario can be used as a platform for the development of more complicated and advanced risk scenarios; this will also include addressing enhanced assessment endpoints and conceptual models, in order to support further ffs risk assessment (analysis and risk characterization phases). Moreover, this work may provide the basis for an ffs emergency respond decision support tool, which will be mostly operational in character and can be used by the relevant services.

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