Forest Road Planning, Construction and Maintenance to Improve Forest Fire Fighting: a Review

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Abstract

Forest roads play a key-role in fire fighting activities. In fact, all ground-based activities are strictly related to the presence of forest roads as access to fire edge. In spite of this important role, forest roads are often planned and built without considering their use in fire fighting, and this also occurs in literature, where few studies are dedicated to the importance of forest roads in fire fighting. A well-developed and well-maintained forest road network is the answer to different needs in fire management. The objective of this review is to clarify basic principles for obtaining efficient road network also for fire fighting, collecting, defining and resuming the main roles, the most important aspects and the reported experiences to be taken into account in forest road network planning and maintenance in fire-prone areas. The most important themes treated are related to: i) the analysis of the functions of forest roads in fire prevention and suppression; ii) the importance of forest road planning and building also considering their importance for protecting forests against fires: iii) the construction and maintenance characteristics to be considered for building and maintaining an efficient forest road network against fires; iv) the importance of fire prevention and the related role of forest roads. Special attention has been dedicated to maintenance activities, because a not well-maintained forest road is a not efficient forest road, and it represents a useless economic and environmental cost.

Keywords: forest road network, fire fighting, fire prevention, forest management, accessibility

1. Introduction

Good forest roads are crucial to effective forest protection and management (Gumus et al. 2008), regardless of their main objectives. However, road building is often regarded with suspicion, because of its high potential environmental impact. The new priority given to environmental protection (Marchi et al. 2018) involves the re-thinking of road building in both its general lines and its technical details. Providing access to the forest can no longer be considered only one of the stages of wood production. Roads must be designed to satisfy multiple needs, and their construction should involve suitable practices to prevent environmental degradation (Spinelli and Marchi 1998), especially to protect particular ecological niches and biodiversity (Picchio et al. 2018).

The accessibility provided by a suitable road network is traditionally related to forest maintenance, wood harvesting, game control and recreational activities (Baldini and Pollini 1998, Chirici et al. 2003, Fabiano and Marchi 1991, Hippoliti 2001, Laschi et al. 2016, Pičman and Pentek 1998, Potočnik 1998, Potočnik et al. 2015, Pozzatti and Cerato 1984, Trzesniowski 1993). However, in the last decades, the relation between forest road network and forest fire prevention and suppression has been receiving more and more attention. Several authors highlighted the important effects of forest roads in fire-prone environment (Baldini and Pollini 1998, Bovio 2001, Calvani et al. 1999, Fabiano and Marchi 1991, Hinterstoisser 1990, Marinelli 1994, Pičman and Pentek 1998). The effects of inadequate forest road network, in terms of safety hazards and forest access, in the context of massive wildfire has been also underlined (Australia Parliament House of Representatives Select Committee into the Recent Australian Bushfires and Nairn 2003, Edgens 2000).

Forest fire, historically, represent one of the most important threat to forests and other wooded areas in many areas of the world. Moreover, under climate change scenarios, an increase in number of years with high fire risk, an increase in the length of the fire season and an increase of extreme events that could result in larger, more intense and more frequent fires are expected (Giannakopoulos et al. 2009, Moriondo et al. 2006). Climate change has already increased the occurrence of large fires that are responsible for most of the annual forest burned area, human casualties and severe damage to properties (Rodriguez-Silva 2011, Torre 2009) and in many countries, we are facing forest fires in conditions that were not known before (Viegas 2009). Finally, as experienced in several Mediterranean countries in the last years, forest fires may be a very dangerous threat for the communities living in the wildland urban interface.

This worsening of the problem is clearly an indication that it is important to improve knowledge and to continue finding new solutions to improve forest fire prevention and management, especially if one considers quite good predictability of forest fires as a phenomenon (yearly repetition, known fire season extent, short term fire danger prediction, etc.).

In order to reduce the occurrence of forest fires, their negative effects and to reduce the burned area, it is necessary to develop a full range of prevention activities that include (Raftoyannis et al. 2014):

⇒ fire fighting options: to improve the suppression organization (such as incident command system, infrastructures, means, training, safety, etc.) by increasing knowledge about the territory, fire behaviour and suppression system resources network

⇒ public options: to improve the awareness and responsibilities of citizens (public education, law enforcement, reduction of urban sprawling into forests, expansion of protected areas)

⇒ fuel management options: to reduce forest vulnerability to fire (reduction of surface fuels, use of grazing, increase of fire breaks, reduction of stand density, increased use of prescribed burning, etc.).

Furthermore, fire fighting options are still considered the most important by the fire experts of Mediterranean countries (Raftoyannis et al. 2014). This means that one segment of the problem-solving process is the study of forest road network planning with the aim of achieving effective fire prevention and suppression (Stefanović et al. 2015). In order to accomplish this goal and to improve the efficiency and effectiveness of fire fighting organization, the analyses of forest road functions, planning, building and maintenance methods are needed.

The aim of this review is to summarize:

⇒ functions recognized to road network in relation to forest fire

⇒ new developments of forest road planning in fire-prone environment

⇒ best practices to optimize forest road functionality for fire fighting, in terms of both construction and maintenance

⇒ to highlight the main knowledge gaps and goals of future research.

2. Functions of forest roads in relation to forest fires

A well-planned and well-developed forest road network may fulfill several functions in relation to forest fire (Croisé and Crouzet 1975, Calvani et al. 1999, Eastaugh and Molina 2011, Marchi et al. 2010, Potočnik 1998, Stefanović et al. 2015). First of all, forest road network contributes in guaranteeing a continuous and high-quality surveillance, especially during high risk periods (Croisé and Crouzet 1975). All roads, but especially the scenic ones, can be used for the surveillance of the most vulnerable areas during high fire risk periods. These roads can be periodically trafficked by fire fighting vehicles, thus allowing reaching two objectives:

⇒ to implement a deterrent action against arsonists

⇒ to allow a very quick response in case of a fire detection (Calvani et al. 1999).

However, one of the most important functions of forest roads is the possibility for fire fighters to reach the fire edge as soon as possible. In fact, it is well known that a quick initial response, before the fire reaches the critical intensity, represents the key element for allowing an easy and fast fire extinction (Arienti et al. 2006, Dimitrakopoulos 2000, Psilovikos et al. 2011). Obviously, a well-organized forest fire fighting service is also required in order to guarantee a quick response in case of fire and to finalize a rapid fire put out.

A good accessibility for the emergency vehicles is important in order to operate under safe conditions.

In particular, forest roads are the best escape route in case of fire extinction failure ensuring higher safety levels to fire fighters. Forest roads may also guarantee a rapid and efficient access to emergency means in case of accidents and injuries to fire fighters. During forest fire, forest roads may also be very useful for a quick evacuation of citizens living in rural/forest areas or being in the forest for recreational purposes.

Under an operational perspective, forest road network plays a key role. In fact, usually direct attack to fire front with ground means starts from the forest roads that allow fire fighting vehicles to reach the points closest to the fire edge. Forest roads may also be very useful in indirect attack and for the following mop-up. In fact, forest roads aligned with the fire front may be used as starting lines for burning out operations.

In the easiest situations (ground fire, no wind, low-medium fire intensity) forest roads should be an efficient firebreak getting the fire slower down (Demir et al. 2009) and allowing an efficient and rapid extinguishment, with reduced effort and damages.

A well-developed forest road network is also very important for an efficient use and maintenance of fire fighting infrastructures (lookouts, helibases, communications repeaters, etc.). Thanks to the efficient development and maintenance conditions of forest roads, the fire fighting operations are optimized due to the easy and quick access to the water points.

In conclusion, all the aspects described above may be summarized in the following functions of forest roads:

⇒ allowing an efficient surveillance of the territory
⇒ allowing efficient and safe fire suppression activities
⇒ representing a safe fire line due to reduced fuel load
⇒ representing an emergency access for citizen evacuation or fire fighter accidents
⇒ allowing the infrastructure use and maintenance.

A well-developed spatial arrangement of a forest road network reduces the incidence of fires and prevents the spread of fires on larger areas (Lugo and Gucinski 2000, Stefanović et al. 2015). In fact, a dense road network, together with an efficient surveillance service, enables fast detection and initial attack and creates firebreaks for spreading surface fires, thus reducing the size of most of potentially larger forest fires (Larjavaara 2005). On the other hand, forest roads are potential routes for recreational use of forest, thus increasing the probability of ignition of forest fires because of the more intense human activity (Chuvieco and Congalton 1989). In many human-dominated landscapes, in which anthropogenic fires are more frequent than natural ones, both accessibility and human infrastructure density are likely to be strong predictors of ignition risk (Massada et al. 2013). More in detail, human-caused fire occurrences are statistically spatially clustered in relation to some anthropogenic factors, such as ownership, accessibility, and population density. Human accessibility is a function of proximity to roads that makes the places close to roads generally associated with higher fire risks (Yang et al. 2007). Moreover, Arienti et al. (2009) found a positive association between lightning fire frequency and road density, including forest roads. The authors explained this occurrence by the increased availability of flammable fine fuels near roads.

In relation to forest fires, roads represent the lines from which the direct attack to the fire front starts. Fire fighters equipped with hoses or tools usually reach the fire edges starting from the closest road or use the roads as fire lines when trying to put the fire out.

3. Forest road spacing and density in fire-prone environment

Road density (RD) is the number of linear meters of road per hectare (m ha^{-1}). In forestry planning, RD is frequently used as the main parameter for describing road network and for assessing the forest accessibility in a given area (Eastaugh and Molina 2011, Gumus et al. 2008, Potočnik et al. 2015, Ryan et al. 2004). In the last decades, several authors suggested optimal values of road/trail density and/or road/trail spacing in relation to forest fire fighting needs (Table 1 and 2). They developed methods for determining the optimal forest RD or for suggesting road/trail spacing values on the basis of different approaches.

Table 1 Suggested optimal values of Road/Trail density in relation to forest fire fighting needs

Reference	Road Density, m ha^{-1}		
	High fire risk Difficult conditions	Medium fire risk	Low fire risk Easy conditions
Croisé and Crouzet, 1975	13–17	–	9–11
De Montgolfier, 1989	25	12.5	6.25
Fabiano and Marchi, 1991	17		
Potočnik et al., 2008	25		
Psilovikos et al., 2011	22	–	12.5

Table 2 Suggested optimal values of Road/Trail spacing in relation to forest fire fighting needs

Reference	Road type	Road/Trail spacing, m		
		Difficult conditions	Medium conditions	Easy conditions
Croisé and Crouzet 1975	Trail	400	–	800
	Ascending road	3000–4000		
	Horizontal road	2500–3000		
De Montgolfier 1989	All	4000	800	1600
Fabiano and Marchi 1991	All	600		
Potočnik et al. 2008	All	400		
Psilovikos et al. 2011	All	450	–	800

Croisé and Crouzet (1975) started the analysis on forest roads in fire-prone environment taking into consideration the duration of the transport of personnel and equipment from rescue centers to fire front. This response time includes transportation on public roads, forest roads and trails and finally the displacement on foot to the fire edge. The distance between two horizontal trails (or 1 trail and 1 road) was considered as the distance that a fire fighter should cover on foot for reaching the fire edge. Assuming the use of water for a direct attack on the fire, this time and distance depend on the length of the hose to be unrolled (they are theoretically limited by this length), but, in practice, this time and distance are influenced even more due to the difficulties of moving on forest ground and the possible high fire rate of spread. Moreover, the same authors, considering that forest trails were not always trafficable or arranged summarily, suggested maximum distances between the roads around them. Two different types of roads were considered: ascending and horizontal roads (Table 2).

(De Montgolfier 1989) determined the road network density for fire fighting taking into consideration a simplified fire spread model. On the basis of the distance between two forest roads, he determined the theoretical length of the fire front when it arrives at one of the road starting from a given point. He considered that the maximum distance between the roads should correspond to the maximum length of fire front that may be extinguished close to the roadside by ground crews.

Fabiano and Marchi (1991) suggested the RD on the basis of the maximum distance between the potential fire edges and the nearest road. The authors estimated this distance considering the maximum time needed by fire fighters for reaching the fire front from the closest road, with all the necessary equipment, and the maximum length of hose line usually set up in Italy. It is not easy to determine this distance because it is affected by many factors such as: terrain slope; presence of barriers or fences along the access paths; fire intensity and rate of spread.

Potočnik et al. (2008), in accordance with the opinion of experts (Slovenian Fire Fighting and Rescue Service, Forest Service and Forest Technology Department) suggested an optimal area, for a slightly sloping area, where fire suppression can be managed with forest fire engine.

Psilovikos et al. (2011), in a study carried out in the suburban forest of Thessaloniki, analyzing the operational capacity of firefighters, distinguished a »practical protection zone« and a »theoretical protection zone« based on the fire brigades personnel experience. Taking into account the maximum hose length of 500 m from the fire trucks, the authors define:

⇒ »practical protection zone« as a fire suppression bandwidth (a buffer zone) with a capacity radius of 150 m uphill and 300 m downhill even on a steep terrain

⇒ »theoretical protection zone« as a fire suppression capacity of 300 m uphill and 500 m downhill, on a flat terrain.

Most of the above density values were based only on the distance between the potential fire and the closest forest road. These are simple and useful methods but they do not take into consideration different aspects that may affect fire fighting efficiency and effectiveness such as: initial attack efficiency, water supply difficulties, and contribution of aerial means.

The forest RD is actually a very useful parameter for determining optimum road length from an economic point of view, i.e. the total length of forest road that minimizes the combined cost of construction, maintenance and timber extraction (Ryan et al. 2004). However, this approach is only marginally relevant to the issue of assessing and planning road networks for their ability to provide efficient access to random points (such as fire ignition sites) rather than defined harvest areas (Eastaugh and Molina 2011).

RD is frequently considered a rather blunt instrument that gives no indication of spatial arrangements of the roads and is thus often a poor predictor of road network efficiency (Eastaugh and Molina 2011). Roads evenly distributed may have the same RD of roads concentrated in one part of the forest but the first case may give a good access to forest and the latter give a poor access overall. In conclusion, the use of roads density in forest road planning should be carefully considered and, hopefully, included in a deeper analysis.

Nevertheless, the evaluation of the forest road network density in fire fighting activities should be connected to the other functions of forest roads. (Calvani et al. 1999, De Montgolfier 1989). In this context, it is important to highlight that the density values applied in forest operation of wood extraction are similar or higher if the sum of the length of forest roads and skid trails is considered (Calvani et al. 1999). In fact, the density values for forest roads may range from 20 to 30 m ha^{-1} (Hayati et al. 2012, Jourgholami et al. 2013) or higher if the trails are included (Hippoliti 2001).

Eastaugh and Molina (2011), in order to overrun the problems related to the use of forest RD highlighted above, suggested the development of three more metrics to be used in GIS environment: road network coverage, road network efficiency and road network convenience.

The road network coverage (RCVR) takes into account both the length and condition of the road and the hiking distances to off-road locations. Forest roads were reclassified by the authors into five speed classes of fire fighting vehicles (100, 80, 50, 40, 30 and 15 km/h), based on personal knowledge of their study areas. The off-road (hiking) speed was estimated to 1 km h^{-1}. RCVR is a ratio between the travel times from the fire fighter base to all points within the forest if there is no road network and those times would include the presence of forest roads. The higher the index, the higher is the road network coverage. However, it is possible to have the same RCVR with different RD, i.e. achieve the same coverage with different road lengths.

For this reason, the authors introduced the metrics Road network efficiency (REFF) as a ratio between RCVR and RD. REFF is able to measure how well the given road network coverage is achieved. However, both RCVR and REFF relate with travel time from a given point and do not consider the travel time from one point to another point in the forest, thus not considering the redeployment of fire fighting vehicles during the same event, practice very common and frequent in fire suppression.

For considering this issue, the authors introduced the Road network convenience (RCON), which is a ratio between the surface of the forest under investigation and a function that includes the mean travel time from all nodes to all other nodes of the road network (for more details see Eastaugh and Molina 2011).

All these metrics may be very useful for comparing different management scenarios in forest road planning, including road upgrading, decommissioning or new constructions. However, the authors highlighted the potential limitations of these metrics and namely the lack of analysis of:

⇒ safe use of roads by large vehicles

⇒ position of the road in relation to the potential fire behavior

⇒ the use of roads as fuelbreak or backing fire initiation line.

4. New approaches to forest road planning in fire-prone environment

In recent years the use of GIS, drones and/or lidar have stimulated the development of dedicated Decision Support Systems (DSS), which have helped and will help forest managers in improving the efficiency of road network during fire fighting. The main aspects studied are referred to the accessibility analysis for fire fighting vehicles, and some experiences have been used in developing navigation systems optimized for fire fighting activities (Akay et al. 2012, Wang et al. 2014). In their recent paper, Stefanović et al. (2015) applied, in a case-study carried out in a fire-prone environment (i.e. a Serbian National Park), a multi-criteria analysis in forest road network planning. The authors evaluated four options suggested for improving forest road network taking into consideration the fire frequency, the behavior of a recent big fire, and seven different criteria, through the entropy weight coefficients (EWC) method. The seven selected criteria were chosen in order to consider costs, forest accessibility and efficiency in fire fighting activities, for the identification of the best cost effectiveness solution for an efficient defense against forest fires.

Majlingová (2012) made an estimation of forest accessibility in the territory of Slovensky Raj National

Park (Slovenia) taking into account the needs of fire fighting activities and the characteristics of the most common fire fighting vehicles used (CAS 32 – TATRA T815 and »UNIMOG« on Mercedes chassis). The analysis was developed by GIS software considering terrain characteristics. Results gave back three classes of accessibility (»total opened up«, »partially opened up« and »unopened« areas) for each of the two vehicles analyzed, being an important DSS for road network improvement.

Another evaluation on accessibility in fire-prone forest areas was made in a large area of Turkey by Akay et al. (2017), considering terrain characteristics, forest fires history and the needs of vehicles and tools used by fire fighters.

Another example of multi-criteria approach is the one developed and applied in a test area in Italy for planning the forest fire prevention infrastructures, including forest roads. In this study an Operational Difficulty Index in Fire fighting (ODIF) was implemented for:

- ⇒ assessing the efficiency of the existing infrastructure (forest road, water point, hydrant, fire fighting bases, aerial mean basis)
- ⇒ planning the improvement of forest fire prevention infrastructures in terms of location and characteristics of new infrastructure or removal of unnecessary ones
- ⇒ organizing prevention and management of fire fighting activities for improving efficiency in high risk seasons and areas (Bonora et al. 2013, Bonora et al. 2007, Marchi et al. 2010, Marchi et al. 2007, Marchi et al. 2006).

The ODIF analyses several factors affecting the efficiency and effectiveness of extinction activities carried out by both ground and aerial resources (e.g. road network, water points distribution, location of fire fighter bases). It included parameters measuring:

- ⇒ the efficiency of the initial attack by air and by ground, the latter strongly affected by road network density and characteristics
- ⇒ the fire fighting efficiency by air and by ground, such as the time needed to a fire fighting ground vehicle for reaching the closest useful waterpoint from the point on a forest road/track closest to the potential burning area.

The final result was a GIS-based map in raster format showing the estimated spatial distribution of different levels of efficiency and effectiveness in fire fighting operation (i.e. the ODIF value for each pixel).

5. Navigation systems

Some important developments for supporting crews during fire fighting activities have been made in the field of navigation. During the emergency, it would be very useful to have a navigator supporting operator to find the best route to reach the fire edge. Normal navigators cannot be useful, even if able to navigate in forest road network. In fact, there are constraints and obstacles due to the evolution of fire that are not a problem in a normal situation, but that could become a problem in case of fire. For these reasons, Wang et al. (2014) developed a model for navigation able to consider and evaluate changes in fire behavior considering different factors, in order to define the best route in fire fighting operations. In particular, their objective was to design a system architecture for routing, avoiding fire-affected areas, through a simulation using terrain data, fire simulation model and real time data directly collected by operating crews. In fact, these crews are equipped with specific sensors – collecting information such as wind speed, direction, etc. – during their normal extinguishing activities carried out in the field during forest fires. Several aspects have been considered in order to develop an algorithm able to define the best route for fire fighting taking into account both operating and safety needs.

6. Forest road construction in fire-prone environment

Many construction features are not related to the road function but are general and valid for all different uses of a road network. All this features are very well described in several handbooks and guidelines (e.g. Alexander 2000, Kramer 2001, Ryan et al. 2004). However, some construction features may strongly affect the use of forest roads and tracks for forest fire fighting purposes. The same considerations are true for road network maintenance. In fact, many aspects of maintenance are general and useful for road conservation and for an efficient use of the road network, while others may have particular importance in fire-prone environment.

The »traditional« forest roads characteristics/design/construction aspects not always meet the requirement of forest fire fighting. The most important forest road characteristics that should be reconsidered in fire-prone environment are related to: one way roads and passing places; dead-end roads; U-turn areas. In forest road construction, it is usually assumed that forest road traffic is one way. It is quite rare that two vehicles need to pass on the same point of a road and at the same time in opposite directions (Hippoliti 1997). For these reasons, the width is usually reduced in comparison to public roads, in order to reduce the cost of construction and to minimize the environmental impacts (Spinelli and Marchi 1998), especially in mountainous condition. Nevertheless, during a fire event, several fire trucks should pass on the same road in opposite direction or have to stop along a forest road for reaching the fire edge with hoses and tools for putting out the fire (Calvani et al. 1999). If a fire truck stops along the road, the other fire fighting vehicles should have the possibility to continue to go on the road for reaching the fire edge or the closest water point for refilling the tank. This means that narrow road may strongly reduce the capacity of individual roads to be safely used by the fire fighting vehicles, with particular reference to whether or not two vehicles may safely pass in opposite directions, thus affecting the efficiency and effectiveness of fire fighting (Martinez-Lopez 2002). These aspects highlight the needs of wider forest roads in fire-prone environment. However, in determining the width of forest roads for fire fighting needs, the width of the carriageway should not be considered but rather the width of the formation (Calvani et al. 1999). If it is necessary to use the berms, in dry condition (during the fire season the soil is usually dry) they should have a bearing capacity adequate to the mass of the passing vehicles. However, in relation to this issue, it is important to provide well designed and frequent passing places in fire prone environment. De Montgolfier (1989) and Doukas (2004) suggested that the maximum distance between passing places in fire prone environment was to be 100–200 m and 250 m, respectively.

It is quite common for forest road layouts to be designed for reaching different parts of forest without considering the network »shape«. For this reason, the main target (forest accessibility) is usually achieved by the provision of a main access road, sometimes in the form of a loop, and several other dead-end roads (i.e. culs-de-sac) starting from it. Nevertheless, for fire fighting purposes, this network »shape« does not guarantee the necessary operational and safety standards. In forest fire fighting, for the safety of vehicles and fire fighters, roads in the form of loop are of paramount importance, guaranteeing a better chance of escape in case of emergency (Calvani et al. 1999). Moreover, a loop road may allow a quicker and easier re-displacement of fire fighting vehicles along the fire edge, thus improving the efficiency and effectiveness of the extinction activity. For this reason, in designing the forest road network in fire-prone environment, it is necessary to avoid as much as possible long dead-end roads and at the same time increase the number of loop roads (Calvani et al. 1999).

Forest roads not of loop form (i.e. cul-de-sac) are usually provided with one turning area at its end. However, for safety and operational reasons, in fire prone environment the turning areas should be more frequent, at least along the dead-end roads. Doukas (2004) suggested a maximum spacing between turning areas of 500 m, while De Montgolfier (1989) suggested a spacing of 500 to 2000 m, depending on the type of road. In France, at present a spacing of a maximum of 1 km is suggested on the main forest roads (Conservatoire de la Forêt Méditerranéenne 2014). Another important aspect to be considered is the type of turning areas. Turning circles should be preferred because they can be negotiated by vehicles in forward gear, allowing a safe and quick U-turn.

Turning areas, especially the turning circle, may also be used by fire fighters as safety zones in situation of extreme emergency. For this reason, it should be important to carefully select their location and apply fuel management practices to the surrounding vegetation (Agee and Skinner 2005). The location should be decided taking into consideration the main topographical, meteorological and vegetation aspects affecting fire behavior (De Montgolfier 1989), e.g.: vegetation type, slope inclination, prevailing wind direction, changes in vegetation, etc.

7. Road maintenance in fire-prone environment

Road maintenance is concerned with keeping roads in a usable condition. It should be carried out on an ongoing basis and particular attention should be given to the maintenance of road surface, drains and culverts. It should not be confused with road repair, which is concerned with the reinstatement of road facilities to a former condition after particular events. Repair is usually associated with road failure due to landslide or mudflow, rock fall, etc.

In addition to traditional maintenance practices, in fire-prone environment, vegetation management beside the roads is a specific and relevant aspect of road management. In fact, fuel (vegetation) load and distribution beside the road may strongly affect the efficiency and safety of fire fighters during forest fire extinction. Fuel management beside road may also strongly affect fire danger. In fact, it is well known that the use of forest roads for timber harvest and recreational activities (such as hiking or mountain biking) leads to a higher ignition probability (Arndt et al. 2013). In Europe, the majority of fires (more than 98%) take origin from human activities (incidents or criminal actions) and statistically the highest number of ignition points are close to urban areas or along the roads (Bonora et

Fig. 1 Fuel treatment beside forest road: a) firebreak-like (L. Tonarelli); b) shaded fuelbreak (A. Laschi)

al. 2007). In this context, forest road density is one of the socio-economic and infrastructural factors explaining forest fire danger (Arndt et al. 2013).

Fuel management is a pillar of fire smart management of forest landscapes (Corona et al. 2015), which demands to reduce the energy output rate of fires (Martin et al. 1979) to a point where conventional fire fighting methods can be effective (Weatherspoon and Skinner 1996, Alexander 2000). Fuels treatments are defined as the »act or practice of controlling flammability and reducing resistance to control of wildland fuels through mechanical, chemical, biological, or manual means, or by fire, in support of land management objectives« (Xanthopoulos et al. 2006). They are designed to reduce quantity, quality and continuity of forest fuels (Cochrane et al. 2012), thus modifying forest fire size and severity, and facilitate suppression by providing safe access and egress for fire fighters, as well as possible counter-firing opportunities (Martinson and Omi 2003).

In the European countries, forest road networks are quite dense in comparison with other countries, such as USA and Canada, even if forest roads are generally narrower in Europe, especially in Mediterranean area (Hippoliti 1976). Clearing vegetation on the sides of forest and rural roads, either manually or mechanically, may result in fuelbreak-like belts of reduced fire hazard. These belts may have two objectives:

⇒ to make more efficient and safer suppression action of fire fighters

⇒ to slow down the intensity and spread of a fire that starts by the road, thus delaying crown fire initiation and increasing the probability of successful initial attack (Xanthopoulos et al. 2006).

In this context, the suppression efficiency and safety is guaranteed by a spatial distribution of fuelbreaks that consider fuel loads and terrain conditions (Eastaugh and Molina 2012).

The treatments that may be applied beside forest road are based on the general principle of fuel management well described in Agee and Skinner (2005). Fuel treatment beside forest road may be in the form of traditional firebreak or shaded fuelbreak (Fig. 1 and 2) (Bennett et al. 2010). In the shaded fuelbreak, the

Table 3 Pros and cons firebreak and shaded fuelbreak (from Bennett et al. 2010, modified)

	Firebreak	Shaded fuelbreak
Pros	⇒ Deprives the fire of fuel and reduces radiant and convective heat transfer	⇒ Aesthetically pleasing ⇒ Less costly to construct on per area basis ⇒ Sale of merchantable trees can offset costs ⇒ Tree health and vigor are improved
Cons	⇒ Expensive to construct and maintain on a per area basis ⇒ Significant potential for erosion when built on medium to steep slopes ⇒ Invasive weeds may establish unless non-combustible mulch or herbicide is used ⇒ Aesthetically, they look unnatural	⇒ Fires can burn through the treated belt, although at reduced intensity and rate of spread ⇒ Effective shaded fuelbreaks need to be much wider than firebreaks

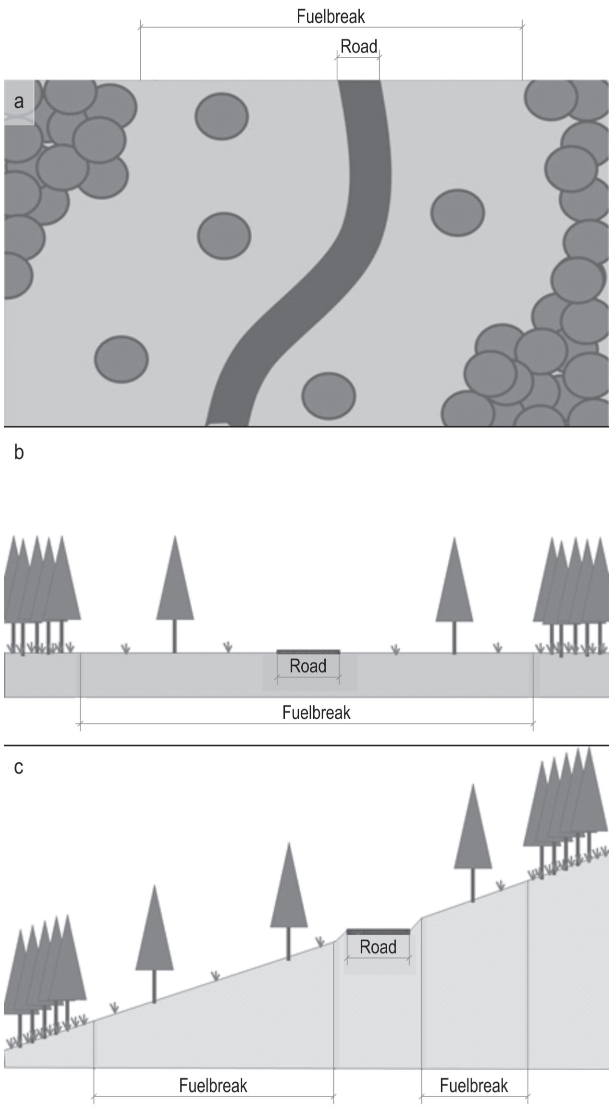

Fig. 2 Shaded fuelbreak beside forest road, a) view from above; b) on flat terrain; c) on slope terrain

fuel management practices described above are applied, while in traditional firebreak, all vegetation and organic matter is removed down to mineral soil. Both solutions may be effective for fire prevention but they also present some constrains (Table 3); therefore, the type and location of the treatment to be applied should be determined on the basis of the local conditions.

Xanthopoulos et al. (2006a) suggested a width of at least 40 m for firebreaks and a width of 30 m on each side of forest road for fuelbreaks. Bennett et al. (2010), because fire spread and intensity increase as slope increases, suggested enlarging the fuelbreak width in relation to slope steepness (Table 4).

Table 4 Minimum fuelbreak distance uphill and below road depending on percent slope (from Bennett et al. 2010, modified)

Slope, %	Uphill distance, m	Downhill distance, m	Total width, m
0	30	30	60
10	27	35	62
20	24	40	64
30	21	45	67
40	18	50	68
50	15	55	70
60	12	60	72

8. Conclusion

Forest roads are common and simple infrastructures, which are fundamental for all the activities carried out in forest. Planning, construction and maintenance are key-phases for obtaining an efficient road network. Regarding forest fires and fire fighting activities, forest roads have to respond to different needs in comparison with the other operations carried out in forest (e.g. logging, recreational activities, etc.), especially due to the operational needs in emergency. In fact, several elements, such as passing place and U-turn areas, are very important and required more often in fire fighting than, for example, in logging. For these reasons, it is fundamental to follow specific rules in forest road network management in fire-prone environments. Moreover, DSSs are tools with a high potential to facilitate the achievement of this objective. In literature, there is a good number of studies and reports of experiences taking into account forest roads concerning forest fires, but more efforts in finding solutions are recommended in order to optimize investments, reducing economic and environmental costs and improving forest road networks for fire fighting. In order to improve the knowledge on this topic, specific research on the vehicle speed in relation to its class and road characteristics should be carried out. This study should highlight the main road characteristics representing bottlenecks for the road trafficability by emergency vehicles. Moreover, more data on the average speed of the vehicles in relation to their class and road type will allow improving DSS and navigation systems, thus increasing efficiency and effectiveness of fire suppression activities.

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