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WP3. LARGE FIRES CASE STUDIES ANALYSIS

Deliverable 3.3. – Fuel management scenarios

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DELIVERABLE SUMMARY

The objective of the work presented here is to contribute towards the development of an innovative methodology for fuel management planning, aiming to reduce the potential for the occurrence of extreme fires. More specifically, the work presented in this deliverable is divided in three parts. The first part is a selective bibliographic review on fuel management and its costs, that focuses on the most relevant and practical contributions of the international scientific literature. Brought together this information provides ready-to-use information and ideas to fire managers.

The second part concentrates on evaluation of fuel treatment effectiveness. A large fire on August 4, 2017 on the island of Kythera, in Greece, is analyzed in depth through computer simulations performed on five different fuel maps. The first simulation uses the existing fuel map with the fuels before the 2017 fire as input. Then four different fuel treatment scenarios are tested. The results demonstrate the significant influence of fuel treatments on reducing fire growth, flame length and ultimately firefighting requirement.

The third part is dedicated on the optimization of fuel treatments. More specifically it focuses on developing rules that can support decisions on fuel treatment. Applied across large areas, this methodology helps to identify in which areas a fuel treatment is not feasible and which areas are preferable. A novel idea, incorporation of a Safe Separation Distance estimate in rule #4, provides a practical tool for fuel treatment while it is also a valuable tool for planning of firefighting.

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Introduction

Large and devastating wildfires are on the rise globally. In the last few years, in spite of continuous increases in the firefighting capacity of fire suppression organizations, with better training of personnel and more advanced and powerful firefighting equipment, many countries have faced catastrophic fire seasons with heavy material damages and often numerous fatalities. Climate change, landscape changes through increase of fuel continuity and load as a result of the abandonment of rural areas, and the development of extensive wildland-urban interface (WUI) areas, have been identified in various studies as the most important contributing factors. The potential for larger fires is growing, hence new policies are needed (Tedim et al. 2015)

As a rule, the powerful firefighting resources available today are able to control the vast majority of wildfires in their early stages. However, a small number of fires under extreme weather conditions escape initial attack, acquire characteristics that are beyond the firefighting capacity of any organization (Alcasena 2019) and run their course unobstructed (Xanthopoulos 2008), burning very large areas and causing heavy damages. These kinds of fires are often called mega-fires, and by definition, they only stop when the conditions that have favored their growth, change. A change in weather conditions, however, is unpredictable and cannot be influenced by man. Topography, also, cannot be altered. On the other hand, forest fuels can be affected, and if managed appropriately they can offer opportunities to the firefighting forces to take the upper hand.

The importance of fuel management (FM) in wildfire control has been identified for more than a century and has been practiced with varying intensity in most countries with fire prone forests. Even more so, the rising number of very large and devastating wildfires nowadays make the importance of effective and efficient FM even greater.

However, achieving an optimum result is not always straightforward and decisions need to factor-in many, often contrasting priorities, which range from technical issues to policy aspects and from social considerations to economic balances. The latter, refer not only to the cost of carrying out FM, but also to examination of economic benefits achieved through FM, and to the distribution of funding between the various fire management functions: prevention, presuppression readiness, suppression activities and post-fire rehabilitation. Although significant experience and scientific knowledge has been built-up in the last 2-3 decades, there are still many unanswered questions especially in the new reality of extreme fire events (Moreira et al. 2011).

The objective of the present work is **to contribute towards the development of an innovative methodology for FM planning aiming to reduce the potential for the occurrence of extreme fires**. More specifically, the work presented in this deliverable is divided in two parts. The first part is a selective bibliographic review on fuel management and its costs, that focuses on the most relevant and practical contributions of the international scientific literature. The second part concentrates on developing rules about location of fuel treatments and on testing and evaluation of FM scenarios at landscape scale, developed around a large fire that occurred on the island of Kythera. This exercise, in addition to the development of rules about FM that take into consideration the main findings of the literature review, result, in the last part of the deliverable, in conclusions and guidelines on how to maximize FM effectiveness and efficiency.

Part 1. Literature review on fuel management methods

FM planning requires making decisions on a host of issues. Questions to be answered include the **necessity** of FM, the **type** of FM to be applied, **where** FM should and should not be located, at which **intensity** and at what extent it should be applied, what are possible **restrictions**, how often it should be repeated, etc.. The **cost** and the elements affecting it also need to be clearly considered. The international scientific literature has tried to provide answers to most of these questions, sometimes through quantitative modeling and other times by employing "rules-of-thumb" in the decision-making process. In most cases, these rules apply only to particular ecosystems or fuel situations and the reasons and limitations need to be understood. A review of these sources of information is necessary as a foundation on which to build the approach laid out here.

There is a variety of methods for treating fuels which can either be used alone or in combination (Stephens et al 2012), depending on strategies, short and long-term fire management objectives, timing, vegetation types, fire regimes and location (Jain et al 2012, Moghaddas et al. 2010), and also on the different (fine and broad) spatial and temporal scales at which FM is applied. In order to present these methods in a systematic way, first the core rationale of FM is described briefly. Then the common FM and methods are presented and discussed, addressing the main issues that forest fire managers are faced with when making decisions.

Aims of fuel treatment

The main aim of FM is to affect fire behavior (Samara et al. 2018) in order to reduce the probability of fire ignition, to facilitate fire suppression and to reduce adverse fire effects. Fire behavior refers to a number of well-known parameters such as the rate of spread of a fire, its intensity and flame length, the heat release per unit area, the type of fire spread (surface or crown fire), the abundance of new fire starts through spotting etc.. Through FM it is attempted to stop the spread of the fire altogether or, through manipulation of vegetation characteristics, to prevent violent behavior that precludes direct attack by ground forces. In addition to affecting fire characteristics for easier and safer firefighting, FM also aims to reduce fire damages, to mitigate fire severity and to improve fire resilience over a particular landscape.

The spread of a fire can be stopped by barriers such as firebreaks, which entail complete fuel isolation, and to some extent by fuelbreaks. On the other hand, fire behavior across the landscape may be modified in many different ways. Surface fuel may be reduced in volume and load by physical removal or burning. In the case of tall forests or shrubs, part of the fuel (the crowns) may become unavailable by increasing the distance between surface fuels and the crown, by increasing the crown base height through pruning or selective shrub removal, or by enlarging the space between tree crowns. In addition to horizontal and vertical fuel continuity reduction, the properties of the surface fuel bed may be changed by increasing compactness through lopping, crashing and chipping. Furthermore, their moisture content may be increased by irrigation or by removal of dead material (Chandler at al. 1983). In the long term, forest management may promote favorable fuel conditions through clever silvicultural practices including species selection, choosing less flammable ones, spacing at the reforestation stage, stand thinning, etc.

The fuel treatment methods mentioned above are usually applied in predefined fuel strata which on some occasions are not easy to describe. This is because beyond the three broad categories of ground, surface and aerial (crown) fuels, further vegetation layers may be defined (Jain et al 2012) such as moss and lichens, low and nonwoody fuels, woody fuels shrubs and small trees (Sandberg et al. 2001, Riccardi et al. 2007).

Having explained the aims of FM, the next important consideration is how to apply it. The general methods used around the world (mechanical, prescribed burning, grazing, etc.) are summarized next, before delving into a general consideration of how to organize and apply them in the frame of FM.

Mechanical treatment

Mechanical treatment includes many different methods. Some of them are applied using heavy machinery, while others are based on manual labor using various hand tools. Examples of the former include the use of dozers for construction of firebreaks, while the latter include methods such as hand slash, hand prune, hand pile and burn, thinning, mastication, mowing and chipping and can produce forest products and energy fuels. Fuel treated areas include linear firebreaks, fuelbreaks (covered by herbaceous and shrub vegetation) and shaded fuelbreaks (covered by trees, herbaceous and shrub vegetation).

Firebreaks

A fire-break is a strip of land that has been cleared of all trees, shrubs, grass and other combustible material down to the mineral soil, providing a 'fuel free' area. According to Chandler et al. (1983), the idea of creating firebreaks to keep fire from spreading from wildlands into crops is as old as agriculture itself. In the 20th century it was extended to forests in an effort to compartmentalize the forest and reduce the risk of fires sweeping through entire stands (Figure 1). Firebreaks are often constructed with a machine such as a dozer, front end loader, grader, tractor or skid-steer loader (DFES 2021).

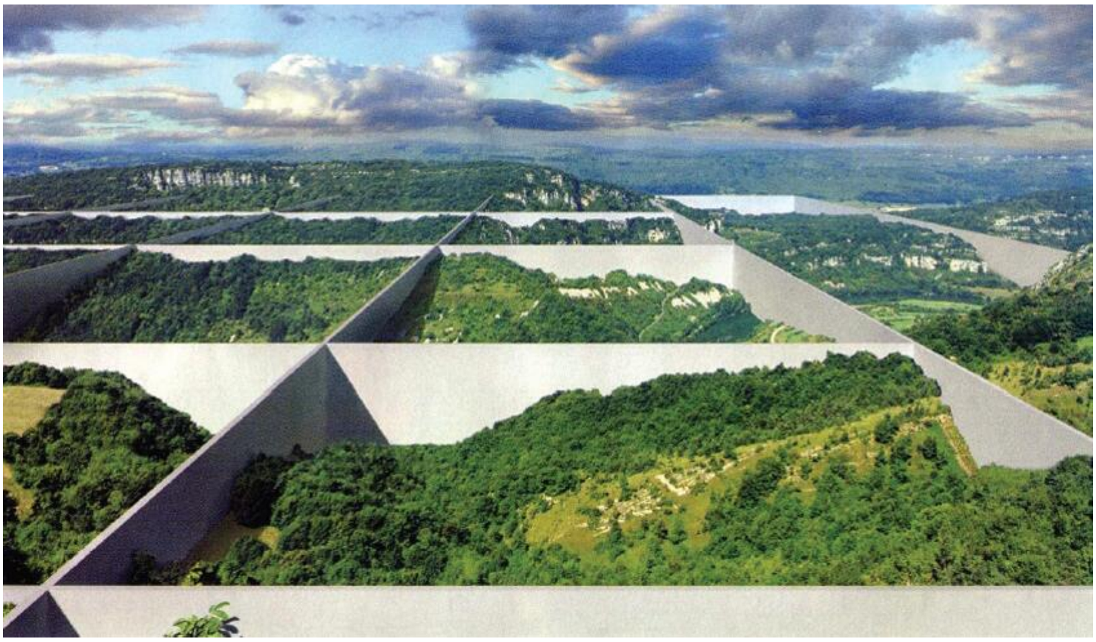

Figure 1. An illustration of the concept of "wildland partitioning" in France (Xanthopoulos et al. 2006).

Firebreaks were conceived as a strip where a fire could stop without human intervention. They have a significant advantage over other fuel treatment methods because the effort is concentrated on a relatively small, usually linear area. Using heavy machines for their construction reduces the cost while protecting a large area (Chandler et al. 1983). However they also have significant disadvantages. Environmentally, the soil in the cleared area, especially if on a steep slope, is prone to serious erosion (figure 2). Aesthetically it is far from pleasing. Financially, there is a cost for maintenance at least once every year. As a network of firebreaks increases, the annual cost increases, consuming a large part of the funds available fire prevention (figure 3). Finally, and most important, without human intervention only the less intense fires can be stopped (Figure 4). Even as early as 1934, a US Forest Service study found that a very intensive series of firebreaks in California was successful in stopping fires only 46 percent of the time (Chandler et al. 1983).

Figure 2. An example of soil erosion on a firebreak in Sithonia peninsula, Chalkidiki, Greece (Source: G. Xanthopoulos).

Figure 3. A newly constructed firebreak (left) and a firebreak in need of annual maintenance at the start of the fire season (right) in Greece (Source: G. Xanthopoulos).

In spite of the significant disadvantages, the use of firebreaks has not been abandoned. Their cost effectiveness, their easy-to-understand role and their straightforward method of construction are some of the reasons for the continuation of their use, although it is quite clear that they will not stop high intensity fires. Furthermore, quite often, paved and unpaved roads are incorporated in a firebreak network, since they have an obvious effect on fuel separation and they do not require annual maintenance, while also improving access. The width of the roads is usually inadequate, so, as a rule, vegetation is cleared at some distance along the two sides of the road. The easy access of firefighters along the roads and firebreaks increases their effectiveness significantly. For example, in Western Australia (DFES 2021), access for firefighting vehicles is listed as the first aim for firebreaks. Second aim is to provide a fuel free area from which prescribed burning can be undertaken. Finally, it is mentioned that "they may slow or stop the spread of a low-intensity fire however they should not be relied upon for this role". In short, in current FM, it is clearly realized that firefighting from a firebreak is necessary to increase the probability that a fire will stop there.

Figure 4. An example of a breached 40 m wide firebreak, in a 2002 fire in mature *Pinus pinaster* forest stand in the Barroso National woodland of the Vila Real district, Portugal (Source: Miguel Galante, Portuguese Forest Services – Forest Fire Prevention Division)

Fuelbreaks

Based on the realization that the completely fuel free strip of a firebreak usually is not enough to stop a fire while the annual cost and nuisance of firebreak maintenance is quite high, a new FM concept, that of the "fuelbreak", was introduced in the USA in the early 1950s (Green 1977, Chandler et al. 1983). According to the original definition, a fuelbreak is "a strategically located wide block or strip on which a cover of dense, heavy or flammable vegetation has been permanently changed to one of lower fuel volume or reduced flammability" (Green 1977). The purpose of a fuelbreak is not to stop a fire but to provide an area where firefighters can fight a fire, as they have to face a less intense fire and can easily create a narrow strip without fuel (a fireline) from which they can start a backfire. The presence of firefighters at the time the fire arrives is necessary so easy access to the fuelbreak is a must as has been demonstrated by Syphard at al (2011b). However, as the exact objectives may vary depending on the context (objectives, place, vegetation, resources, limitations, etc.), the term fuelbreak often means different things to different people (fire managers, the public, the media) (Mooney 2010). For example, Chandler et al. (1983) stated that "a fuelbreak differs from a firebreak in that the vegetation type on the break is permanently converted to a cover of low fuel volume and/or low flammability" and that "the preferred cover is almost always a perennial grass or some kind of prostate shrub", probably having mostly surface fuels in mind. A good example of a fuelbreak network with good firefighter access, systematic forest compartmentalization and availability of water, can be seen in Figure 5 from Turkey. On the other hand, in forest rich Canada, for the purposes of his study, Mooney (2010) defined a fuelbreak as a distinct area outside a community (or other value at risk) of any size and shape where anthropogenic modifications of forest fuels (i.e. fuel treatments) have been conducted to aid in the protection of that community from future wildfires". He further explained that "fuel treatments may include any combination of a reduction or removal of canopy fuels, surface fuels, and/or ladder fuels through any method".

Figure 5. A fuelbreak network in Turkey (left) and a detailed view showing good road access and a pond or tank with water for firefighting (Source: G. Xanthopoulos (left) & Google Earth (right)).

In France, fuelbreaks are categorized in three types according to their objective (Xanthopoulos et al. 2006):

- Type 1: The objective is to limit fire ignitions: fuel management aims to decrease ignition hazard and to increase success of early firefighting operations. It is mostly applied in or around Wildland Urban Interface areas.
- Type 2: The objective is to limit fire's effects on assets: fuel management focuses on making the circulation of firefighting crews and the public easier and safer (safer escape routes). It is mostly applied in or around Wildland Urban Interface areas. Fuel management for forest autoprotection (i.e. to avoid stand replacement fires) is included in this type of fuel break.
- Type 3: The objective is to limit the size of burned areas by breaking forest continuity. These are fuel breaks built at strategic locations to help firefighters control the head or the flanks of probable fires. They are generally built between 2 non-burning (usually agriculture) areas. In building type 3 fuel breaks two minimum objectives are:
    - To provide at least a safety zone for fire crews.
    - To enable efficient fire suppression actions.

Fuelbreak creation and maintenance is usually (but not always) carried out through mechanical means. The treatments are intended to change the size and arrangement of forest biomass by either severing stems and creating smaller fragments (mastication) or by removing these stems from the site (Mitchell and Smidt 2019). Basic steps of mechanical treatments are "felling", "cutting and spreading", "skidding or yarding" and "processing" (i.e. grinding and mastication) and they are carried out by the use of hand tools, power tools or heavy equipment. There are many types of cuttings such as cleanings, weedings, improvement and liberation cuttings. In tall forests, a variety of thinning methods - which can be considered as intermediate silvicultural treatments – can be applied, namely low thinning (from below), crown thinning (from above), geometric thinning, free thinning, selection thinning and variable density thinning (Graham et al 1999, Peterson et al. 2005, Hunter et al. 2007, Graham et al 2009). Hand thinning is commonly called "lop and scatter" and is used to reduce the connectivity of vertical and horizontal fuels by felling trees. Depending on what is being treated, the resulting biomass may become valuable forest products, supporting commercial harvest, may be utilized for energy, may have to be disposed from the site at a cost, may be left on the site after being treated for decreasing fire hazard (lop and scatter, mastication), or may be prescribed burned through broadcast burning or through piling and burning.

Figure 6. An example of surface fuel treatment using a horizontal drum masticator masticator in the USA (Source: Jain et al. 2012).

Figure 7. An example of a rotary head boom-mounted masticator effectively shredding single trees in the USA (Source: Jain et al. 2012).

Regarding mastication, slope angle tends to decrease production especially when the machine works on slopes over 35% (Halbrook et al 2006). Except the insignificant emissions of equipment and vehicles exhausts, it does not produce smoke, it provides higher degree of control for managers, it reduces the complexity of prescribed burning and it may help keep large trees of fire-resistant species on area of interest. Although mastication fuel treatments in some shrubs (i.e. chaparral) can be seen as a sacrifice of natural resources, it can still be considered as an acceptable tradeoff to potentially mitigating fire hazard (Brennan and Keeley 2017). It is preferred in areas that cannot be burned since it is a viable and effective method despite its significant cost (figures 6 and 7). After its implementation, the nutrients remain on the ground, erosion potential is rather low and, if the drivers of the heavy equipment (masticators) avoid using repeatedly the same paths, the soil compaction may be prevented (Jain et al 2012) also. Chipping is generally more expensive than mastication even though the cost of the latter can be significantly high, depending among others on the size and sophistication of the chippers used (figures 8 and 9).

Figure 8. Forest thinning on Tenerife island and a high capacity chipper used for processing the residues of the treatment (Source: G. Xanthopoulos).

Manual clearing is a slow process that allows selectivity and quality work, its impact is low and can be used on rough terrain and stony soils (Figure 10). Mechanical clearing is rapid with an advantageous cost/benefit relation on relatively flat areas but may increase soil compaction and erosion (FAO 2001). When it is decided to leave the treated biomass on the site, for reasons such as maintaining nutrients, erosion protection, low value of residues, no market for the byproducts, etc., a ground slope of 35% is considered as the limit for mechanically treating fuels using a heavy machine such as a masticator. Hand thinning is the preferred option at ground slopes higher than 35%. When the decision is made to remove the treated biomass (e.g. because they include quality sawlogs, existence of market for pulpwood and/or energy, etc.), various mechanical methods can be used for collection and transportation (ground based, cable, helicopter) (Jain et al. 2012).

	
Figure 9. An example of chipping forest treatment (pruning, understory shrub removal) residues in a *Pinus halepensis* forest in Greece, after carrying them to the forest road, using a low capacity chipper (Source: G. Xanthopoulos).	Figure 10. Manual clearing of understory shrubs and pruning, using chainsaws, in a *Pinus halepensis* forest on Mount Parnis, Greece (Source: G. Xanthopoulos).

In general a decision tree for identifying the most appropriate fuel treatment is quite complex, as illustrated by Jain et al. (2012) in the USA (figure 11). However, in Europe, especially in the Mediterranean countries, there generally are fewer options (e.g. helicopter use and cable systems are uncommon), and the decisions are simpler.

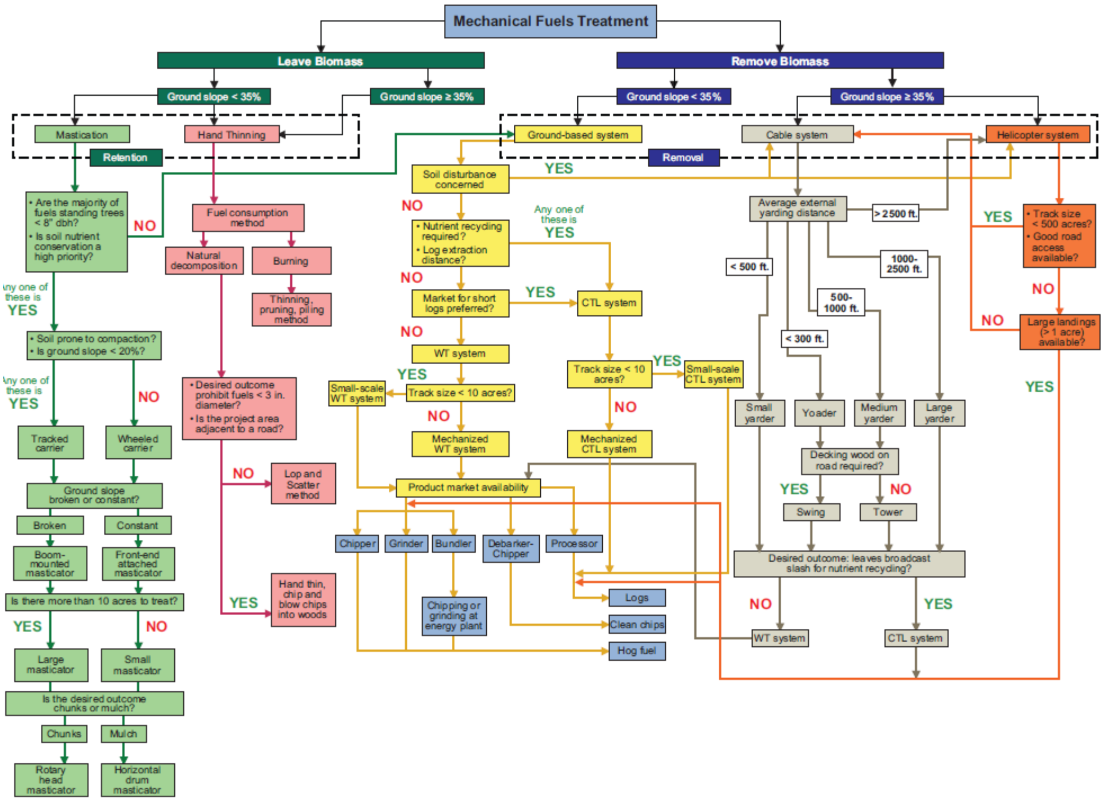

Figure 11. A flowchart illustrating the complexity of the decision tree for identifying the appropriate mechanical treatment (Jain et al. 2012).

Prescribed burning

Prescribed burning (figure 12) is a technique that involves controlled application of fire to vegetation under specific environmental conditions to attain planned resource management objectives (FAO 1986). The terms used to describe the use of fire to manage the fuels are “prescribed burning”, “prescribed fire”, “controlled burn” “planned burn” or “broadcast burn”.

Uncertainty, complexity, potential unique situations due to local conditions, and risk, accompany the use of fire for treating fuels (NWCG 2017). Prescribed burning is used to improve habitats (Young and Baily 1975, Bock and Bock 1984; Harrington 1985; Sieg and Wright 1996;), protect biodiversity, control disease (Alexander and Hawksworth 1976; Conklin and Armstrong 2001) and insects, enhance aesthetics, reduce fire hazard and mitigate the risk of catastrophic wildfires, improve forage, and maintain the function of forest ecosystems (Papanastasis 1976, Jain et al 2012). Prescribed and controlled burns may reduce the size, severity (Fernandes 2015), and resultant ecological effects of wildfires (Choromasnska and DeLuca 2001; Kallander 1969; Pollet and Omi 2002; Omi et al. 2005; Wagle and Eakle 1979). Ignitions may be either human- or naturally caused, the latter referring to fires allowed to burn as long as they occur under pre-specified conditions that will help fulfill management objectives such as those described above.

Prescribed burning is often underutilized, particularly in forests, due to multiple barriers that limit its implementation (Miller et al. 2020). Potential impacts of smoke and/or proximity to populated areas and values as well as lack of experienced practitioners, have to be taken into consideration before planning a prescribed burning. Controlling where the smoke will go is an important part of every prescribed burn. Thus, detailed meteorological prediction including the atmospheric profile at the time of the burn, as well as local topography and location of inhabited areas relative to the area of the burn must be carefully taken into consideration.

In unmanaged and untreated areas where prescribed burning seems to be a complicated task, mechanical treatment needs to forerun the use of fire. Combination of thinning and prescribed burning may be needed to achieve fuel management objectives such as reduction of crown density and surface fuels (Agee and Skinner 2005). For example, within the first year of a thinning operation, a fraction of the slash loading may be reduced by prescribed fire if it is carefully applied when the duff and the 100-hour fuels are wet enough to ensure that it is safely accomplished. However, mechanical treatment may not be feasible in non-accessible areas or where access is limited or when other restrictions are imposed. Hence, prescribed burning is still an appropriate method for reducing surface fuels on a rough landscape and increasing crown base height (Jain et al 2012), although it may not be suitable for very steep slopes (Hunter et al 2007). When its cost is low, it is desirable to use fire because it is an economically viable option but the more complex the burn is to be, the higher its cost becomes.

Developing a burn plan includes separate but necessary and interconnected actions, therefore a complexity analysis needs to be conducted. Experience and knowledge, science and fire behaviour models, need to be used in combination by skillful practitioners in order to develop prescriptions for applying fire. Pre-burn considerations such as line building, snag removal, preparation of features that need protection along with preparation of critical holding points are of major importance. Fuel sampling and weather measurements prior, during and after the burn is crucial, while approving and distributing the plan among cooperators is necessary. Organization, equipment, and communication for maintaining safety, especially in case of fire escape, is mandatory. In U.S.A., the Prescribed Fire Complexity Rating System Guide (2017) has been developed and maintained by the Fuels Management Committee, an entity of the National Wildfire Coordinating Group (NWCG).

During prescribed burns, shaded fuel breaks may be used as anchor points (Agee et al 2000). In general, two are the most used patterns:

1. A backing fire spreads against the wind or down a moderate slope (Brown and Davis 1973; Chandler et al. 1983; Kilgore and Curtis 1987; Pyne et al. 1996); it is a slowly moving fire of minimal intensity that usually results in more complete surface fuels' combustion.
2. A strip fire is set so that the flaming front spreads in the direction of the wind or slope (Brown and Davis 1973; Chandler et al. 1983) and is faster and more intense because it is a head fire (figures 12 and 13). Its intensity will vary with fuel moisture and load (Kucuk et al 2008) and can be controlled by the spacing interval between strips which depends on the fuel size, topography and desired fire behaviour, the latter being controlled by the use of different ignition techniques.

	
Figure 12. Prescribed burning in masticated fuels using strip fire ignition in the USA (Source: https://www.fs.fed.us/psw/topics/fire_science/ masticated_fuels/a_groundeffects.shtml).	Figure 13. Strip head fires in grass fuels in the USA (Source: Cal Fire 2018).

Low intensity prescribed fire can be used to reduce litter, duff, and woody debris (Cooper 1961, Davis et al 1968, Biswell et al 1973, Sackett 1980, Harrington 1981, Covington and Sackett 1984, Bastian 2001) to consume small tree seedlings to slow development of ladder fuels (Harrington 1981, Harrington 1985, Arno and Harrington 1997, Arno and Fiedler 2005), to burn small trees, to scorch the lower limbs of trees and saplings, to increase crown base height and reduce the potential for torching of trees (Gaines et al. 1958, Agee and Skinner 2005, Johnson et al. 2011) and kill few mature ones. In ponderosa pine forests, low intensity surface fires act as a natural thinning agent and create uneven-aged stand structures (Hunter et al. 2007). In those ecosystems, the use of prescribed fire – even without previous thinning or mastication – may improve resilience to wildfires (Zhang et al. 2019) while, season, and interval of prescribed burning do not cause large changes in understory species composition (Zald et al 2020) which is evident for phryganic rangelands also (Papanastasis 1980).

Prescribed burns conducted when fuel moisture contents and/or relative humidity are high and wind velocity is low, result in low intensity fires. Even in the summer, in some cases red slash has been burned, two to four days after rain episodes (Orozco and Carillo 1992, 1993).

High intensity prescribed fire treatment that exhibits some torching, may be appropriate in some cases because it reduces tree density and creates forest openings (DellaSalla and Frost 2001, Fule et al. 2002, Aplet and Wilmer 2003). The potential for severe wildfires is more likely to be reduced by large prescribed fires (>800 acres or 324 ha) (Finney et al 2005) than by small (< 100 acres). High intensity prescribed fire may be used to a limited extent (< 5 acres in size) to create landscape heterogeneity in a small scale, however, the extensive use of this technique is not recommended.

Prescribed burning may benefit carbon balance of the land use but more accurate data are needed regarding fuel load, consumption and emissions so as to eventually assess the leverage of prescribed burning (Vilen and Fernandes 2011). The periodic use of prescribed burning results in creating openings in dense shrublands and managing pastures but requires training, favorable conditions for application, preparation of the site and surveillance by specialists (FAO 2001). Determining how often to apply prescribed burning should not only focus on the objective, such as fuel load reduction, but should also consider the natural fire frequency (fire return return) of a site. The appropriate implementation frequency may vary significantly among various locations and elevations and may be 3 to 10 years, (Allen et al. 1968; Biswell et al. 1973; Harrington and Sackett 1990; Sackett et al. 1996) or 15 to 25 years (Bachelet et al. 2000) so as to achieve diversity at stand scale (Severson and Rinne 1990), create heterogeneity which are important for maintaining biodiversity (Reice 1994), and achieve resilience and sustainability at the landscape scale. The intervals may be longer where natural fire is historically less frequent or may be shorter in regions where surface fuels accumulate at rapid rates. The balance between biomass production and decay plays a key role in determining the need for prescribed burning and the appropriate frequency. In areas where decay is not sufficiently rapid and cannot cope with the annual accumulation of forest debris, fire will eventually do the job (Chandler et al. 1983). It may be a wildfire or alternatively a prescribed burn.

In Australia, in the states with Mediterranean climate, where fuel breakdown is slow, prescribed burning for fuel reduction is used extensively. The Victorian Bushfires Royal Commission, that was appointed after the devastating 2009 “Black Saturday” fires in Victoria (Teague et al. 2009), recognized that “Prescribed burning is one of the main tools for fire management on public land. It cannot prevent bushfire, but it decreases fuel loads and so reduces the spread and intensity of bushfires. By reducing the spread and intensity of bushfires, it also helps protect flora and fauna”. The Commission stated that the 130,000 ha that the Department of Sustainability and Environment (DSE) burned until then, which amounted to 1.7% of the 7.7 million ha of public land in Victoria is managed by the DSE, was well below the amount experts and previous inquiries had suggested as necessary to reduce bushfire and environmental risks in the long term. The Commission’s recommendation was that the State should make a commitment to fund a long-term program of prescribed burning, with an annual rolling target of a minimum of 5 per cent of public land each year, and that the State should be held accountable for meeting this target (Teague et al. 2009). Although knowledge and technological advances in Australia have increased the effectiveness, efficiency and safety of prescribed burning, catching-up with the ambitious targets that have been set is always a challenge. Prescribed burning is and remains an important land and fire management tool for meeting land management objectives, including wildfire mitigation (Morgan et al. 2020).

In Europe, especially in the Mediterranean countries, fire has been used for managing the land for millennia. Agricultural practices, fuel removal for use as energy and use of fire on the landscape maintained fire hazard at relatively low level. However, in the second part of the 20th century, the traditional fire use as a tool for land management has been discouraged and almost criminalized by an urban-centric perspective and anti-fire bias (Tedim et al. 2016). Fuel built-up on the landscape and the effects of climate change are commonly cited as two of the main causes of the increasing trend of large devastating fires in Europe. Many EU funded research projects addressed the issue of prescribed burning to some extent, while it was the focus of the Fire Torch project in the early 2000s (Botelho et al. 2002) and of the Fire Paradox project that was completed in 2010 (Silva et al 2010). Thus, the number of scientific papers increased very steeply with time. However, progress in adopting it across Europe remains relatively limited. Although it is practiced quite often, mainly in the context of fuel reduction, in Portugal, Spain and south France (figure 14), in many parts of Europe there is practically no prescribed burning (Rego et al. 2010) (figure 15). A robust, evidence-based, and adaptive approach to prescribed burning is needed that has to take into consideration the biology and ecology of species and habitats (Fernandes et al 2013).

Figure 14. Fuelbreak maintenance through prescribed burning in June, in Corsica, France (Source: G. Xanthopoulos).

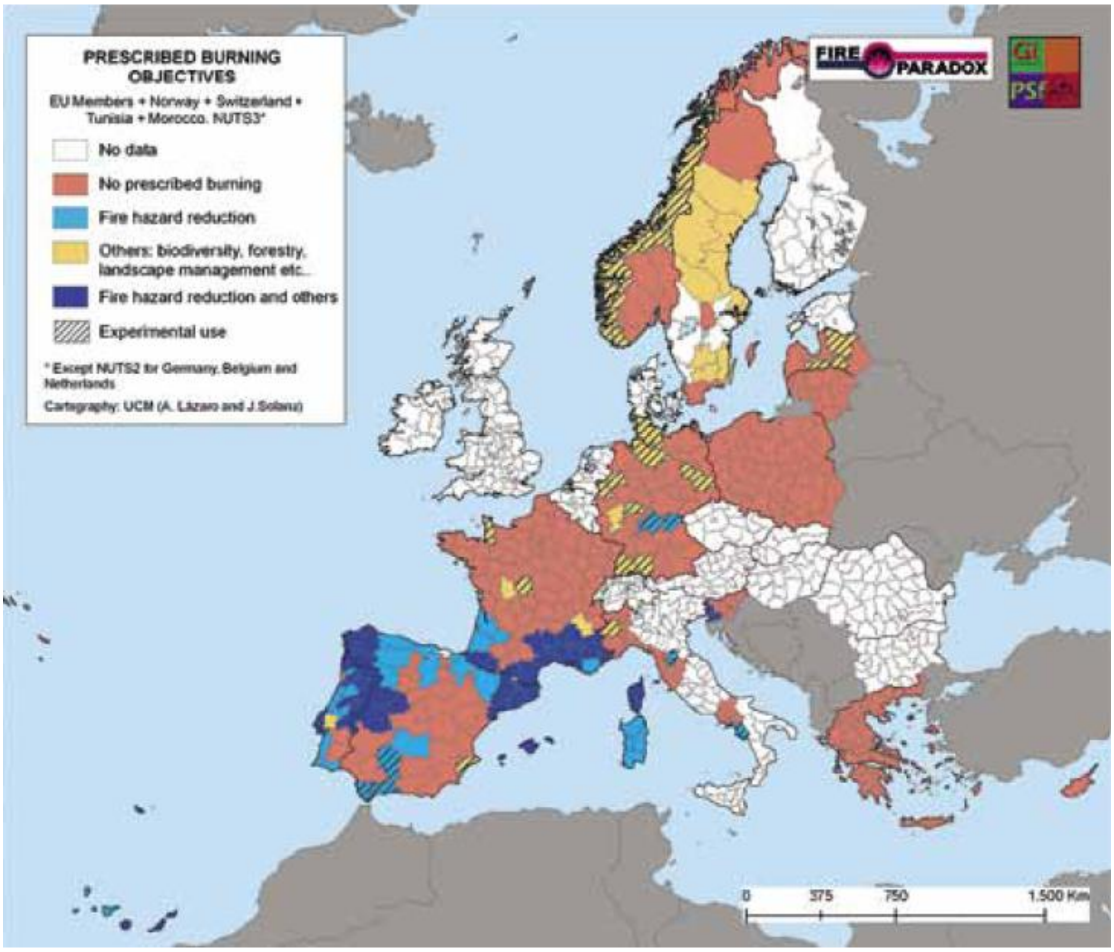

Figure 15. Use and objectives of prescribed burning in Europe (Source: Rego et al. 2010).

Grazing

Animal grazing is a practice used around the world for the production of food and other products. In parallel, it also acts as a method of biological control of fire hazard as it leads to fuel reduction. According to Hao and He (2019), who reviewed 86 published articles on the subject, grazing significantly decreased the total biomass, above-ground biomass, below-ground biomass, and soil organic matter, but increased theroot-to-shoot ratio and the bulk density. From fire behavior theory, it can easily be deduced that these changes affect negatively the spread of fire in grazed vegetation.

Grazing can be broadcast over an agroforestry landscape but can also concentrate in a specific area. Sheep, goats, horses and cattle may help shape carefully selected areas and control particular vegetation species. Wild grazing animals can also have an effect on fuels if present in adequate numbers (figure 16). Livestock can be used to manipulate understory herbaceous and woody (shrubs and trees) vegetation. Low to moderate grazing intensity may promote grass growth in thus increasing fire frequency (Borman 2005; Madany and West 1983; Rummell 1951), and subsequently may increase rates of spread. However, high grazing intensity usually reduces fine fuel loadings very sharply, thus decreasing fire frequency and rate of spread (Bachelet et al. 2000).

Figure 16. Wild goats grazing on the island of Kythera, Greece, with a notable effect on shrub height (Source: Miltiadis Gletsos).

Overall, the effects of grazing may be significantly different and erratic in different ecosystems and conditions (Foster et al. 2020). Multi-species grazing can be effective because of the different dietary preferences which are also affected by the sex, age and body condition of the animal. Sheep consume the flower heads, removing the seed production, cattle and horses consume grass, and goats with worn teeth don’t prefer grasses but tender-leaved shrubs versus those with unworn teeth (Burritt and Frost 2006). Moreover, sheep graze steeper terrain than cattle while goats can browse on almost any ground slope. It takes knowledge and experience to pair species of livestock and combine grazing duration, intensity and seasonality issues so as to achieve predefined management goals; it may take at least three years to perceive noticeable results.

Heavy animals can be used for an initial clearance and used also in forage zones of fuel breaks and/or understory of oak species (e.g. holm oak (Quercus ilex) or white oak (Quercus alba)) (FAO 2001). Cattle and goats can exploit shrubs and trees to a height of 1.8-2.0 meters while sheep utilize the grazing area up to about 1.0 m. Of course there are differences among livestock species in other parameters, such as browsers vs. grazers, selective vs. more generalist, and other physiological attributes (Hofmann, 1989).

Goats can help to mitigate wildfires by consuming fuels with their specific grazing/browsing habits and thus reducing horizontal and vertical continuity of fuels. The goat is the most suitable species for this purpose because of its browsing ability. Goats exhibit very peculiar feeding habits: their nimble lips and very prehensile tongue permits them to graze on a variety of shrubs, very short grass or even poisonous wild shrubs, being resistant to many plant toxins and non-nutritive factors, and even browse on foliage not normally eaten by other domestic livestock (Hart 2001, Georgoudis et al. 2005).

Goats are the most cost-effective, non-toxic, non-polluting fuel management solution available, especially in Mediterranean shrub ecosystems (Lovreglio et al. 2013). As they are not pure browsers (Papanastasis 1985), they consume all live fine fuels (shrub leaves and twigs, grasses and forbs) before they become fine dead material on the ground promoting fire spread (Lovreglio et al. 2013). Their grazing contributes to fuel management longevity by keeping shrubs at a very low height (figures 17 and 18) especially after mechanical treatment or prescribed fire.

	
Figure 17. Heavy goat grazing has kept shrub height relatively low in this Mediterranean evergreen shrubland in Greece (Source: G. Xanthopoulos).	Figure 18. Very intense goat grazing in the area of Anopolis, Chania, Crete, Greece, has kept the Quercus coccifera understory of a *Pinus brutia* forest at less than 50 cm height (Source: G. Xanthopoulos).

The ecological effects of grazing and over-grazing in the Mediterranean have been debated for a long time. According to Perevolotsky and Seligman (1998), the traditional heavy grazing in the Mediterranean region is not only an efficient form of land use, but one that is ecologically sound. On the other hand, serious overgrazing for many years, apart from reducing fire spread potential, has often produced negative results, changing the landscape dramatically and initiating desertification trends (Figure 19). Furthermore, it may create a vicious circle of overgrazing and fire in an effort by the shepherds to rejuvenate the vegetation and increase forage production through fire (Figure 20). While vegetation formations that recover rapidly from occasional fire are also unlikely to be destroyed or seriously degraded solely by grazing, the accelerated recurrence of fire can create serious problems. According to Le Houerou (1993), "the extremely degraded condition of the Mediterranean vegetation results from the combined effects of overstocking and repeated burning. As these shepherd fires are illegal in countries such as Greece, the result is that these fires are treated as, and often become wildfires (Xanthopoulos et al. 2006) adding to the yearly cost of firefighting.

Figure 19. Very intense goat grazing in the area of Anopolis, Chania, Crete, Greece, has reduced fire hazard but has also changed the landscape (as evident from the mature *Quercus coccifera* forest at the far slope) and brought signs of desertification.

In recent years, most countries along the north coast of the Mediterranean sea have experienced a decrease of rural populations (Xanthopoulos and Nikolov 2019) and with it a drop in extensive grazing by free-roaming grazers. Reduction of ruminant grazing on traditional rangelands in some countries around the Mediterranean Basin has aggravated the fire hazard to such an extent that the burned area has tripled in size from the 1960s to the 1980s (Le Houerou 1993) (Perevolotsky and Seligman 1998). Today, paradoxically, heavy grazing pressure, far from being a threat, is becoming a desirable but elusive management tool. Undergrazing is becoming a bigger problem than overgrazing. Indeed, heavy grazing of woody vegetation in the Mediterranean is one of the most efficient management techniques for fire prevention and maintenance of habitat diversity (Perevolotsky and Seligman 1998). It is quite clear that the conflict must be resolved through better management decisions (Papanastasis 1986) including prescribed burning, in order to maximize the benefits that grazing can offer to fire hazard reduction in addition to improving production.

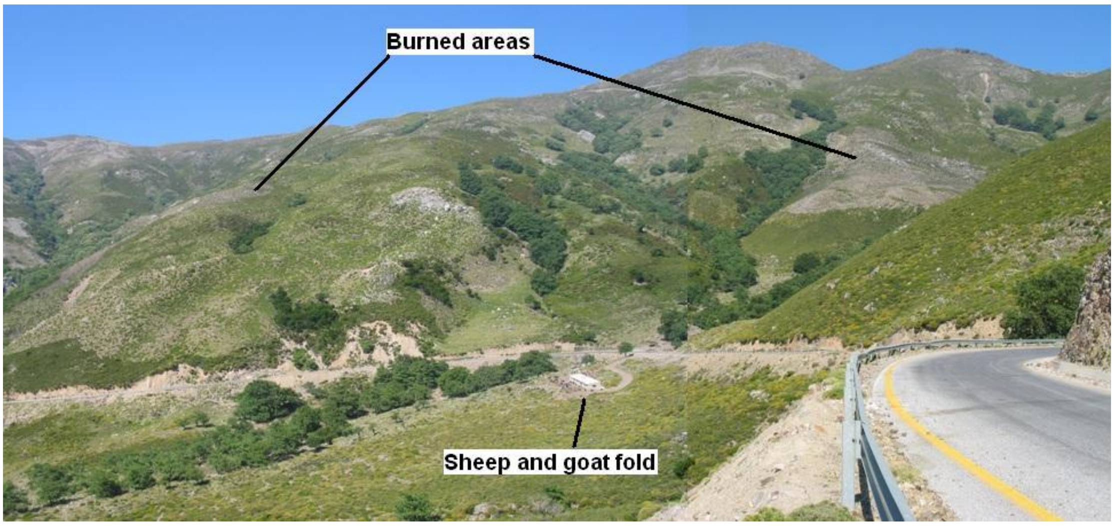

Figure 20. An example of burn scars near a sheep and goat fold in the area of Chania, Crete, Greece (Xanthopoulos et al. 2006).

Chemical techniques

Chemical fuel management is preferred when the cost of mechanical treatment is very high or where the latter cannot be applied (e.g. steep slopes). It can be achieved by spraying either growth inhibitors or herbicides (FAO 2001). In highly dense and tall shrubs of dry conifer forests, it may be the best option if prescribed burning or mechanical treatment are difficult to implement.

Herbicides can be very effective on surface fuels; factors such as the current condition, type and size of the vegetation, terrain (steepness and accessibility), soil type, the cost and their application effects, need to be considered before choosing chemical treatment over other methods. Foliar applications are generally more effective than soil treatments (Van Epps 1974) but the effectiveness of herbicides varies significantly (Harper et al. 1985).

Chemical treatments do not remove fuels, but can target invasive species to encourage the growth of natural fire-adapted vegetation (https://ucanr.edu/sites/fire/Prepare/Treatment/). Dead and decicated fuels often make necessary a follow-up of prescribed burning.

One of the most common and profound uses of herbicides is to control shrub regrowth after cleaning the understory of fuelbreaks, aiming to reduce maintenance needs. A variety of herbicides may be used depending on the specific objectives. The most commonly used is 2,4-Dichlorophenoxyacetic acid, commonly referred to by its ISO common name 2,4-D. A mixture of 2,4 D and 2,4,5-T is often used for some hard-to-kill shrub species. These and other similar herbicides at low application rates kill shrubs without affecting grasses which remain on the site for soil protection. If they are applied for 3 consecutive years most shrubs can be controlled effectively and efficiently as the cost is lower than in all other treatments (Green 1977). However, as there exist many doubts, nowadays about the broadcast use of herbicides, it is required that managers must always be current on legislation regulating herbicide use, when determining to apply this method and in selecting a safe product.

Application considerations

Firebreak and Fuelbreak locations and standards

Determination of where to build a firebreak of a fuelbreak is not a simple task as it has to observe a number of criteria in order to combine and maximize, to the extent possible, both effectiveness and efficiency. These criteria mainly include topography, prevailing wind direction, changes in vegetation (fuel loading and structure but also need for maintenance), fuel discontinuities and access (Laschi et al. 2019). However, in addition to the technical criteria, there are also many restrictions and limitations that must be considered (Jain et al. 2012). Such limitations vary from ecological implications (such as considerations for threatened, endangered or sensitive species) to visual aesthetics, and from allowed uses in a particular landscape to land ownership considerations.

The proper location of a firebreak is a critical element that determines firebreak performance. Since the goal of firebreaks is to stop the spread of a fire, they should be established in areas where fire intensity is naturally lower. When firebreaks are created with the aim of facilitating application of prescribed fires, it should be tried to select locations where it would be convenient for stopping subsequent fires. Thus, when determining the best place for a firebreak, areas with gentle slopes or flat topography are usually preferred since steep slopes favor the quick spread of fires. Also, such areas usually allow easier, faster and safer travel of vehicles, crews and equipment, which is also an important consideration. Actually, paved roads or even well-maintained dirt roads can often be used as part of a firebreak network. On the other hand, there are several features that should be avoided when establishing firebreak locations. For example, the guidelines of the State Bushfire Coordination Committee of the Government of South Australia mandate that “Firebreaks and access tracks should be located where they will have the least impact on the environment, unless there are no acceptable alternatives. Environmental considerations include - significant flora and fauna, reduced scenic values, cultural sites, wilderness value and erosion (related to soil type/steepness and rainfall)" (GAFMWG 2005).

Specific operational guidelines on firebreak and fuelbreak location are mostly found in practical handbooks. The number of scientific publications on the subject is quite small, probably as a result of the varying situations and the specificities of the context for establishing them. Thus the Texas Forest Service recommends to locate firebreaks on ridge tops, on the contour, and through the forest at intervals of 200 to 600 m depending on the risk level. It also recommends to tie firebreaks into existing barriers such as roads, cultivated fields and pastures. On the other hand, given the potential of increased erosion on a firebreak, it cautions to avoid tying lines directly into a lake, stream, pond or swamp, which may result in siltation of the water body, thereby degrading the water quality.

Location of a firebreak at a ridge top has certain advantages. At a ridge top, fire behavior changes. Commonly vegetation is less dense resulting in lower intensity, but this is not always the case. Firefighters can start backfires from there and control them with relative ease. If there is a fire run to the top, firefighters may retreat on the back side of the ridge, enough to avoid the long flames. On the other hand, according to the guidelines of the Department of Fire & Fire and Emergency Services of the Government of Western Australia (DFES 2021), "on sloping or undulating terrain, fire-breaks should be placed low in the landscape. This will result in a fire reaching the break while travelling downslope, making it slower, less intense and therefore less likely to cross the break. This is also a safer location for firefighters to approach a fire". Agee et al. (2000) agreed with both options, saying, based on literature, that most fuelbreaks are located where indirect attack tactics would be employed, such as along ridges, or roads along valley bottoms, and upper south and west slopes. Ascoli et al. (2018) further confirm both alternatives.

As firetrucks must be able to travel on a firebreak, water erosion such as that caused by water flowing along the break, is an important consideration, especially when a road also serves as a firebreak. Thus, on mountain slopes firebreaks should be constructed so that they follow the contours. If a firebreak must be created down a slope, it is necessary to take measures to reduce water erosion. The steeper the slopes, the more water management is required. One key measure is to create water turn-outs that will allow water to escape from the surface of the firebreak. For example, on roads with erodible surface and a slope of 1% one water turn-out is recommended every 100 m. When the road slope is 4% the distance between water turn-outs decreases to 25 m, and becomes 12.5 m when the slope is 8% (Smith 2009).

In the literature, there are numerous rules and suggestions for the required minimum width of a firebreak or a fuelbreak, that generally reflect the aims for their construction and the conditions in which they have to perform. The following constitute a representative list.

Regarding firebreaks, their required width logically depends upon the predicted length of the flames. This makes it practically impossible to give specific firebreak widths. A "rule of thumb" is the break should be 1.5 times the flame length (https://oaksavannas.org/fire-preparation.html). In spite of that, various authors have offered more concrete recommendations, obviously having specific conditions in mind such as the type of vegetation. Thus, the absolute minimum width suggested by Green (1977) in California, is 3.3 m. He also mentioned that firebreaks can be wider than 6-9 m, or even more. The Natural Resources Conservation Service (NRCS) of the USA specifies 3.5-5 m fire breaks for grass fuels. This, however, is considered as inadequate in other fuels such as oak savannas (https://oaksavannas.org/fire-preparation.html). In South Australia, according to the official guidelines, the width of a grassland firebreak should be between 4 and 10 m, including a track used for fire access. It should be noted however, that according to Wilson (1988) a firebreak of 5 m would only stop fires of less than 7 MW/m at best, corresponding to flame lengths of 4.5 m approximately (based on the relationship of Byram (1959) or Clark (1983), as reported by Alexander and Cruz (2021)). In case trees are present within 20 m from the firebreak the probability of the fire crossing increases steeply, mainly due to firebrands such as burning bark or leaves causing spotting, and only wider firebreaks (10-15 m) have a chance to stop the fire front. As Fogarty and Alexander (1999) note: "In the absence of trees or shrubs, the minimum widths agree reasonably well with Byram's (1959) rule of thumb where he suggested that a firebreak or fireguard should, in the absence of spotting, be one and a half times wider than the expected flame length in order to stop a fire's advance".

In an effort to reduce negative environmental effects, the vegetation within a grassland firebreak should be maintained to a maximum height of 10 cm during the Fire Danger Season. Additionally, where practicable and environmentally acceptable, a firebreak should incorporate a fuel-free strip of a minimum width of 1.8 metres, and this may form part of the access track (GAFMWG 2005).

In native vegetation in South Australia a limit of 5 m is imposed on firebreaks, mainly for environmental reasons. If a wider firebreak is proposed, it is required to submit an application to the Native Vegetation Council in order to ensure that ensure that any greater clearance will be subject to environmental assessment. On the other hand, in large (>400 ha) commercial plantations the required width of a firebreak along the perimeter is 20 m, while narrower strips are acceptable for smaller plantations. Large plantations should generally be divided into units, not exceeding 400 hectares, by firebreaks (GAFMWG 2005).

Plana et al. (2005), citing Leone (2002), listed the following recommendations for firebreak width, in relation to the conditions:

- Two to four times the height of adjacent trees.
- Six to seven times the height of trees: wind regime passes from laminar to turbulent, letting flying embers and firebrands fall in the strip.
- Average wind speed multiplied by time of flight of burning embers (about 15 seconds)
- Width greater than potential horizontal length of flames to be expected at the head of the fire.

Additionally, Plana et al. (2005) summarized the guidelines of Velez (2000) in table 1.

Table 1. Minimum needed firebreak width with high risk conditions (Source: Plana et al. 2005).

Vegetation	**Flat land**	**Land with 70% slope**
Tree stand and low, dense brush	12m	20m
Tree stand and dense brush	25m	35m
Terrain	**Width**	
Crests with slopes higher than 50%	60 m	
Crests with high slope in one side (50%) and low slope in other (20%)	80 m	
Crest with slow slopes (20%)	60–100 m	
Flat land	100 m	
Thin watercourse	150 m	

Regarding **fuelbreak** standards of construction, there are no absolute standards for width or fuel manipulation (Agee et al. 2000). Fuelbreak width and length must be sufficient to reduce fire spread and intensity. Width on level ground will vary based on fuel types; i.e., short widths are generally required in grasses (approx. 46 m) and longer widths are required on forested sites. Variation in width is largely determined by vegetation type, slope, access, and other site specific needs and objectives. Fuel break length will generally be designed to match the length of the ignition source to the extent feasible, such as along a road or highway. Green and Schimke (1971), based on radiant heating from chaparral fires recommended a minimum width of 61 m, but a few years later Green (1977) suggested a 91 m width for primary fuelbreaks. However, as early as the 1960s fuelbreaks as wide as 300 m had started being considered, while 400 m fuelbreaks were approved by the U.S. Federal Government by 2000 (Agee et al. 2000). Kennedy et al. (2019) found through modeling that a significant reduction in fire severity was detected more than 400 m into the treated area, greater than the standard width of the prescribed fuelbreak.

Fuelbreaks are often developed close to communities to protect them from destructive fires. Dennis (2003), suggested that the minimum recommended fuelbreak width is approximately 91 m for level ground, and noted that since fire activity intensifies as slope increases, the overall fuelbreak width must also increase. He provided a table in which suggested fuelbreak width increases with slope. A few years later, Bennett et al. (2010) provided a similar table, adapted from Dennis (2003), in which the minimum recommended widths are substantially smaller. Then, Laschi et al. (2019) modified the values presented by Bennett et al. (2010) a little more (table 2). The differences in this table are a demonstration of the fact that it is hard to develop hard-and-fast rules, and a lot depends on the specific conditions and the desired safety margin. For example, regarding fuel clearance around homes in the wildland-urban interface in Southern France, where homes are generally more fire resistant than those in the USA (Xanthopoulos et al. 2012), a fuel clearance zone of 50 m around each house is required (Rigolot 2003).

Table 2. Different recommendations for fuelbreak width for protecting properties.

Percent Slope (%)	Total width of modified fuels (m) (Dennis 2003)	Total Fuelbreak Width (m) (Bennett et al. 2010)	Total Fuelbreak Width (m) (Laschi et al. 2019)
0	91.4	61.0	60
10	92.4	62.5	62
20	94.5	64.0	64
30	96.0	65.5	67
40	97.5	67.1	68
50	99.1	68.6	70
60	103.6	70.1	72

Fuel treatment costs

Especially after devastating wildfires, inadequacy of fuel treatments becomes a central point of criticism towards the fire management agencies or even the governments. However, as a rule, such criticism does not take into consideration the substantial cost fuel treatments can have per treated area. Thus good knowledge about this cost by type of treatment, is necessary in order to develop a rational dialogue, and most important to make optimum fuel management decisions. Comparison of budget spending alternatives can also help in such decisions. For example, in a 1999 study of nine fuelbreaks in France, which took into consideration the cost of construction (amortizement), maintenance, outcomes from grazing (production) and external costs, over a 5 to 15 year period, it was found that the annual cost of a 30 to 40 ha fuelbreak is equal to one hour of aircraft flying time delivering three retardant drops (Xanthopoulos et al. 2006).

In the effort to identify fuel management studies reporting on cost, some general points must be made first:

- Rideout and Omi (1995), using nationwide data from the National Park Service in the USA, demonstrated a principle that should be expected to apply under all conditions: the unit cost for fuel treatment declines with increasing scale. Furthermore, they found that the importance of scale depends fundamentally on the scale level. More specifically, they found that unit cost was very sensitive to changes in scale when scale was small.

- The treatment cost values (e.g. €/ha) reported in literature in various currencies and at various times, ranging over many decades, cannot be used readily for planning and budgeting purposes. Changes in salaries with time, spatial variation of salaries even within the same country (e.g. the USA), as well as changing currency exchange rates, at a minimum, complicate the effort to make comparisons. Studies that have reported the cost in terms of required labor are much easier to use.
- The data reported in the various studies are not universally useful as they apply to specific fuel conditions, use of certain equipment etc. Any reporting of costs also needs to specify the conditions to which it applies.

Regarding the choice of development of firebreaks vs fuelbreaks, the initial costs of fuelbreaks are much higher per kilometer compared to firebreaks. This is because fuelbreaks are much wider so a larger area is treated per km of fuelbreak. Also, more work is needed for achieving permanent vegetation type conversion compared to using a heavy machine such as a dozer for creating a firebreak. Additionally, fuelbreaks are not completely maintenance free. In order to continue being effective, within 5 to 10 years after treatment, fuelbreaks need some maintenance by prescribed fire, mechanical treatment or grazing (Chandler et al. 1983).

Table 3. Cost of fuel-reduction methods when used as stand-alone treatments (from Bennett 2010).

Method	**Cost per ha ($/ha)**
Thinning	247-1977
Pruning	124-618
Prescribed under-burning	124-1112
Cut and scatter	124-1112
Cut, pile, and burn	680-3706
Chip and scatter	1235-3706
Mowing	99-371
Slash-busting/mastication	618-1730
Utilization	Offset costs or produce a small profit

Table 4. Examples of fuel treatment implementation costs in various US National Forests (NF) and other forests, not including the cost of planning (from Hunter al. 2007).

Treatment	**Cost ($) per ha**	**Year**
Prescribed fire (Black Hills NF)	741	2006
Mastication(Black Hills NF)	865	2006
Prescribed fire (Colorado State Forest)	185-371	2006
Thinning (no utilization) + prescribed fire (Colorado State Forest)	1483-2965	2006
Broadcast burn (Colorado Front Range)	282	2004
Pile burn (Colorado Front Range)	326	2004
Mastication (Colorado Front Range)	843	2004
Thinning (utilization) (Colorado Front Range)	899	2004
Thinning (no utilization) (Colorado Front Range)	1616	2004
Broadcast burn (San Isabel NF)	247	2003
Mastication (San Isabel NF)	618	2003
Broadcast burn (Santa Fe NF)	1112-1235	2006
Naturally ignited fire use (Gila NF)	62	2004
Broadcast burn (Gila NF)	62-247	2004
Thinning (Gila NF)	494-1235	2004

The cost of various fuel treatments per ha is highly variable, even for the same treatment under different conditions. Especially, costs for thinning operations can be highly variable and the same is true for combined treatments. Chipping is generally more expensive than mastication or pile burning. Table 3 provides a good summary of the range of cost of various fuel treatments, mainly applicable to tall conifer forests in the northwest of the USA, allowing relative comparisons (Bennett 2010). It should be noted that the existence of markets (e.g. for timber or for energy) influence the choice of treatment as sales of fuel treatment products can help offset some or all of the cost. At about the same time the costs reported by Hunter et al. in Colorado, South Dakota and New Mexico National Forest in the USA are quite different for some treatments (table 4).

For comparison, In northeast and central Alberta, the cost per hectare, treatments as reported by Mooney (2010), varies between CAN\$5,000 and CAN\$7,500 for mechanical and between CAN\$7,500 and CAN\$10,000 for manual treatments.

In Mediterranean Europe it is very common to do shrub cutting and removal through manual work using handtools. Estimates of cost for this task, based on required work per ha, can be very useful and valid for many decades. This cost was the focus of two EU funded research projects in the 1990s (PROMETHEUS (EV5V-CT94-0482)) and "PROMETHEUS - System Validation" (ENV4 – CT98 – 0716)). Based on an experimental fuel treatment in a *Pinus halepensis* forest with shrub understory in Attica, Greece, a regression equation was developed for prediction of the required work for cutting of shrubs, pruning of the lower branches of trees and removal of the slash to the nearest road (Xanthopoulos 2002):

WORK = 36.56485 + 0,359878 BIOMASS + 0,000523 (BIOMASS SLOPE DISTANCE)

where

WORK: Required manual labor (8-hour work-days/ha) for shrub cutting, tree pruning and removal of biomass, including rest.

BIOMASS: Shrub biomass expressed in t/ha

SLOPE : Site slope (%)

DISTANCE : Average distance at which biomass is moved (m)

An allometric equation for obtaining BIOMASS estimates based on measurement of shrub height and cover is also presented in the same publication and a similar one is available in Xanthopoulos and Manasi (2002). The equation for the prediction of WORK should be used in the range of values of the variables used for the development of the equations (table 5). Equation (2) should only be used for first-time fuel treatment in *Pinus halepensis* forests with shrub understory, where tree pruning will comprise a significant part of the work. It is not appropriate for maintenance treatment to remove shrub regrowth (Xanthopoulos 2002). A different equation, based on further analysis of the same dataset to exclude the work for pruning, was estimated (Xanthopoulos 2002):

SHRUB_WORK= 11.86 + 0.00736 (COVER DISTANCE)

where

SHRUB_WORK: Required manual labor (8-hour work-days/ha) for shrub cutting and removal of the resulting biomass, including tool maintenance and worker rest.

COVER: Shrub cover expressed as a percent (0-100%)

DISTANCE : Average distance over which biomass is moved (m)

The equation above is compared graphically (figure 21) to the official required work estimates for "Manual cutting of forest understory and moving it along firebreaks and roads, in a zone 20 m wide, for fire protection purposes" issued by the Greek Forest Service in 1981 (Xanthopoulos 2001).

Table 5. Range of values of the variables used for the development of the equations.

Parameter	Minimum value	Maximum value
Shrub COVER (%)	38	85
Shrub HEIGHT (m)	16	76
DISTANCE (m)	29	61
SLOPE (%)	12	58
Estimated BIOMASS (t/ha)	3	21
WORK (total) (man_days/ha)	26	72
SHRUB_WORK	13	45

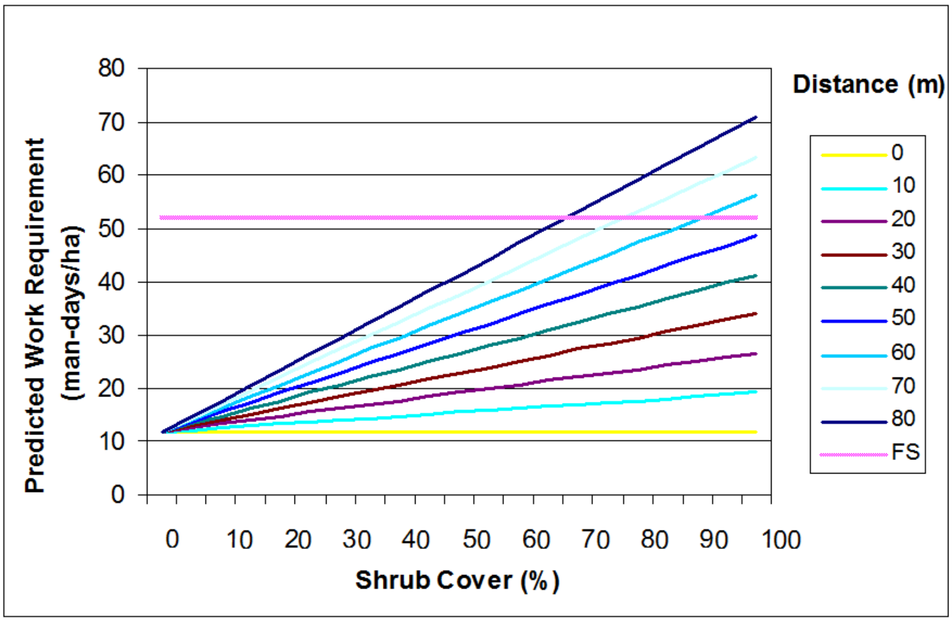

Figure 21. Behavior of the equation for the prediction of work needed for shrub cutting and removal, for shrub COVER values from 0 to 100% and moving DISTANCE values from 0 to 80 m, and comparison with the average value of 52 man-days/ha specified by the Greek Forest Service (FS).

Regarding the cost of **prescribed burning**, it can also be highly variable. Factors such as size of burn, type of equipment used, accessibility, and type of firing pattern used, all influence the cost of a prescribed fire. On the Gila National Forest in the USA, prescribed fire can cost anywhere from $62 to $494 per ha (Lolley and others 2006). Costs have been as high as $1235 per ha on the Santa Fe National Forest and average $741 per acre on the Black Hills National Forest (table 4). A complete analysis of costs for various treatments in the Colorado Front Range was also compiled and can offer valuable cost estimation guidance (Front Range Fuel Treatment Partnership Rountable 2006). Table 4 also refers to the use of fires naturally ignited by lightning to achieve resource benefit. This practice is termed wildland fire use (WFU). WFU events tend to be much less expensive on a per ha basis than management ignited prescribed fires (Lolley and others 2006). Since WFU fires tend to burn over multiple days or weeks, more acres are generally burned in a given event relative to a management ignited prescribed fire. As the number of acres burned increases in an event the cost per acre generally decreases as the same level of resources are used in each case (Wood 1988). WFU fires also do not generally require construction of fuel breaks, which can be costly. However, the places where they can be applied can be quite limited due to population safety considerations, smoke emission, etc..

Part 2. Evaluation of fuel treatment effectiveness

Part 1 of this deliverable has presented the various options and approaches of reducing fire risk through fuel management. Selection of fuel treatments, however, is a complicated task that involves effectiveness and efficiency, especially when the objective is to reduce the probability of large fires. This objective clearly requires that the fire remains, to the extent possible, within the capacity of available resources.

Part 2 of the deliverable utilizes much of the knowledge presented in Part 1. It focuses on carrying out an analysis regarding fuel management scenarios and developing innovative supporting techniques that will support decision making by fire managers. More specifically, a case study is developed involving a large fire in 2017 on the island of Kythera in Greece, where, through computer simulation, four different scenarios of fuel treatments are tried and evaluated. The result of the fuel treatments on fire behavior is assessed regarding fire spread. Most important, the effort is expanded in modeling firefighting demand, through a new innovative method, in order to compare it with the available firefighting resources on the island, making it possible to evaluate their possibility to control the fire before it becomes large. Furthermore, a series of advanced rules and a new method for fire capacity/firefighter safety are employed in order to guide fire management planning. Examples of application of these are provided for other study sites outside of Greece.

The fire of 4 August 2017 on Kythera island, Greece

Kythera island lies south of Peloponnese, in Greece (figures 22 and 23). It covers an area of 278 km². Its location, away from a base of aerial firefighting resources and with ground reinforcements needing many hours to reach the island, make it a prime candidate for examining the value of fuel treatments for averting the probability of a large fire.

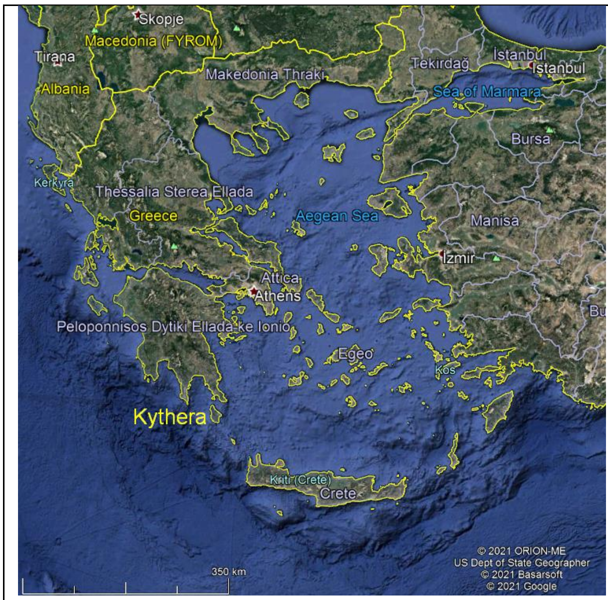

Figure 22. Map of Greece with the island of Kythera (Source: Google Earth).

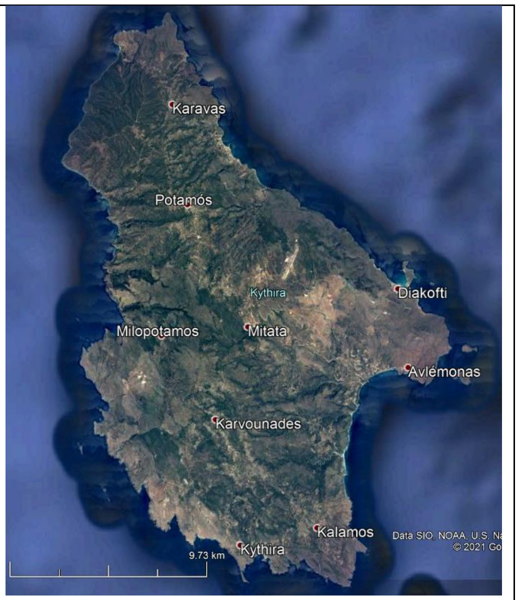

Figure 23. The island of Kythera in detail (Source: Google Earth).

A fire that started close to the Health Center of the island on 4th August 2017, 10:55 am, was not attacked effectively at its first stages and grew to large dimensions. It burned vigorously for three days, threatening homes and a monastery (Moni Mirtidion) (figure 24) and finally reached a size of 2,621 ha. Parts of its perimeter stopped at the sea (Figures 25 and 26).

Figure 24. August 6, 2017, at 17:27 (Photo: Valerios Kalokairinos).

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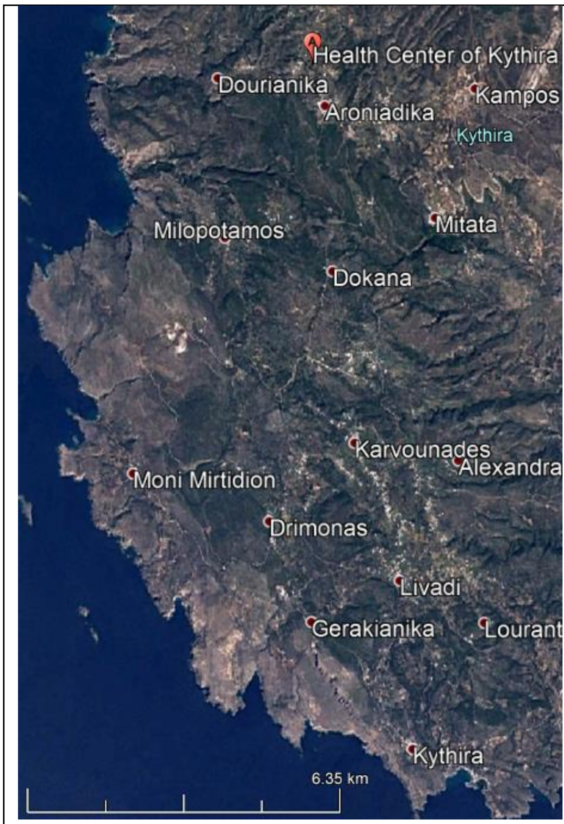
<tr><td>
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<tr><td>Figure 25. Kythera (detail) in December 2016 (Source: Google Earth).</td><td>Figure 26. The same area after the fire of August 4, 2017 (December 2017) (Source: Google Earth).</td></tr>
</table>

Simulation of the fire of 2017

For the purposes of the present work, we documented in detail the fire behavior and the growth of the fire through a combination of interviews with firefighters and locals who fought the fire, time and location-stamped photos and videos from the mass media and social media, official reports, etc. Thus, we were able to reconstruct its evolution with very high accuracy.

We then used fire behavior simulation, which has been proven as an invaluable tool not only for real-time response planning and for wildfire risk assessment, but also for fuel management planning (Ager at al. 2011). Fire spread simulations were carried out using the G.FMIS forest fire simulation system. G.FMIS is based on Rothermel’s (1972) mathematical fire spread model for the estimation of fire behavior, and on the appropriately improved Dijkstra's (1959) shortest path algorithm for the simulation of fire propagation Eftichidis et al. (1988). G.FMIS also integrates the NUATMOS algorithm for simulation of the wind field over the topography (Ross et al. 1988).

Running G.FMIS requires data on fuels, weather and topography. For the fuels, we used a detailed fuel map that had been developed earlier in the frame of another research project (Xanthopoulos et al. 2020). The map was based on fuel models developed specifically for Greece (Dimitrakopoulos et al. 2001, DImitrakopoulos 2002). Meteorological data were obtained from the meteorological station that operates at the Kythera airport. They were used both for calculation of the wind field and for fine fuel moisture content estimation at the time of simulation. We also used as input a digital terrain model. The outputs of G.FMIS are maps of fireline intensity, flame length, and rate of spread, simulated at each point (grid cell), together with the timestep of the simulated fire.

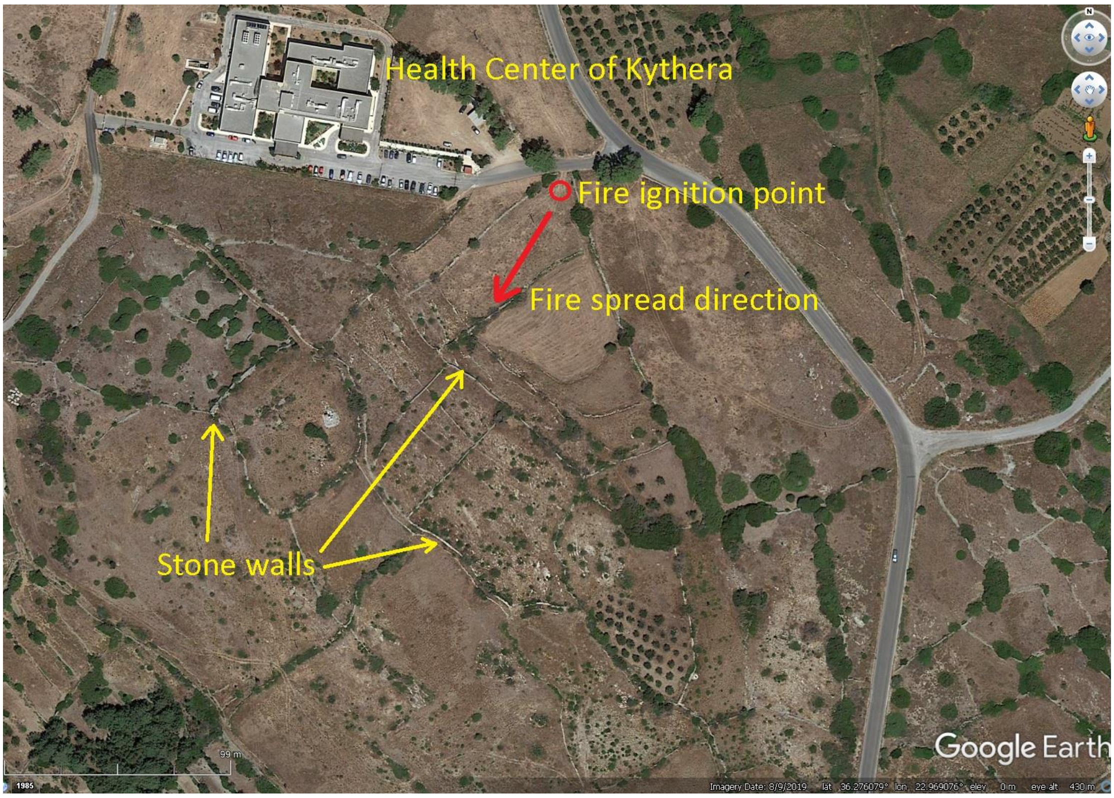

Figure 27. Image showing the area where the 2017 Kythera fire started, the fire spread direction and the presence of a dense series of stone walls that affected fire spread.

We simulated the spread of the fire for the first 6 hours after its ignition. A longer simulation period would be misleading for our purposes because by that time there was already increasing aerial firefighting and there was also a shift in wind direction. Additionally, any (expected) inaccuracies in prediction at each step start to compound reducing confidence to the results.

Initially we studied the conditions regarding the wind and made some necessary adjustments. The mean wind velocity for that period (first 6 hours after its ignition) – according to the local airport measurements – was 4.2 m/sec (at 10 m height: World Meteorological Organization standard used in Europe). It was reduced to 3.5 m/sec which refers to the wind speed at 6.1 m (20 ft) height (Fischer and Hardy 1972, Turner and Lawson 1978, Lawson and Armitage 2008). We then used the latter (3.5 m/sec) as a reference value, and we estimated the midflame wind speed at the height (fuel depth) of each fuel model by utilizing a logarithmic wind profile. The wind adjustment factor (WAF) (Rothermel 1983) for each fuel model was then calculated by dividing the midflame wind speed with the wind speed at 6.1 m (20 ft) height (Table 6).

The WAFs for the vegetation in the area of the burn, were further adjusted for the influence of the successive stone walls interspersed with a high density in the burned area. Stone walls act as permeable barriers slowing down wind over long distances, not being impermeable barriers (Powell et al. 2018). On sloping ground, they are very often combined with terraces whose effect in ROS is also significant. Thus, after determining WAF values for all the fuel types, we introduced an empirical stone wall adjustment factor (SAF) (estimated at 0.9 for tall maquis and at 0.6 for the rest of the fuel types) which was applied on the WAF for the corresponding fuel model, resulting in a WAF(SAF) for that model across the burn area (Table 6).

The WAFs for the vegetation in the area of the burn, were further adjusted for the influence of the successive stone walls which are interspersed with a high density in the burned area (Figures 27 and 28). Stone walls act as permeable barriers slowing down wind over long distances, not being impermeable barriers (Powell et al. 2018). On sloping ground, they are very often combined with terraces whose effect on fire rate of spread (ROS) is also significant. Thus, after determining WAF values for all the fuel types, we introduced a stone wall adjustment factor (SAF). SAF may be applied, either directly on Vmidflame (=1.75 m/sec) resulting in Vmidflame(SAF) or on WAF of choice - if the entire area hosts stone walls - resulting in a WAF(SAF) for that fuel type (model) across that area.

Figure 28. An example photo immediately after the passage of the fire, showing the protective role of the stone walls on vegetation (Photo: Valerios Kalokairinos).

Table 6. The wind adjustment factors (WAF) for the fuel models in Kythera, sorted by their fuel depth value (highest to lowest), the corresponding stone wall adjustment factor (SAF) and the combined adjustment factor WAF(SAF)= WAF × SAF .

Fuel Model	WAF	SAF	WAF(SAF)
Tall maquis	0.56	0.90	0.51
Low maquis	0.50	0.60	0.30
Low Maquis GRAZED	0.48	0.60	0.29
Phrygana	0.41	0.60	0.25
Very low shrubs (KYTH1)	0.36	0.60	0.21
Agricultural (Grass)	0.36	0.60	0.21
Very Low Shrubs (KYTH1) GRAZED	0.20	0.60	0.12
GRAZED Grass	0.14	0.60	0.09
Mowed Grass	0.11	0.60	0.07

The fuels types map that was used for the simulation of the fire is shown in figure 29. The fuel types correspond to fuel models forming the necessary input for G.FMIS.

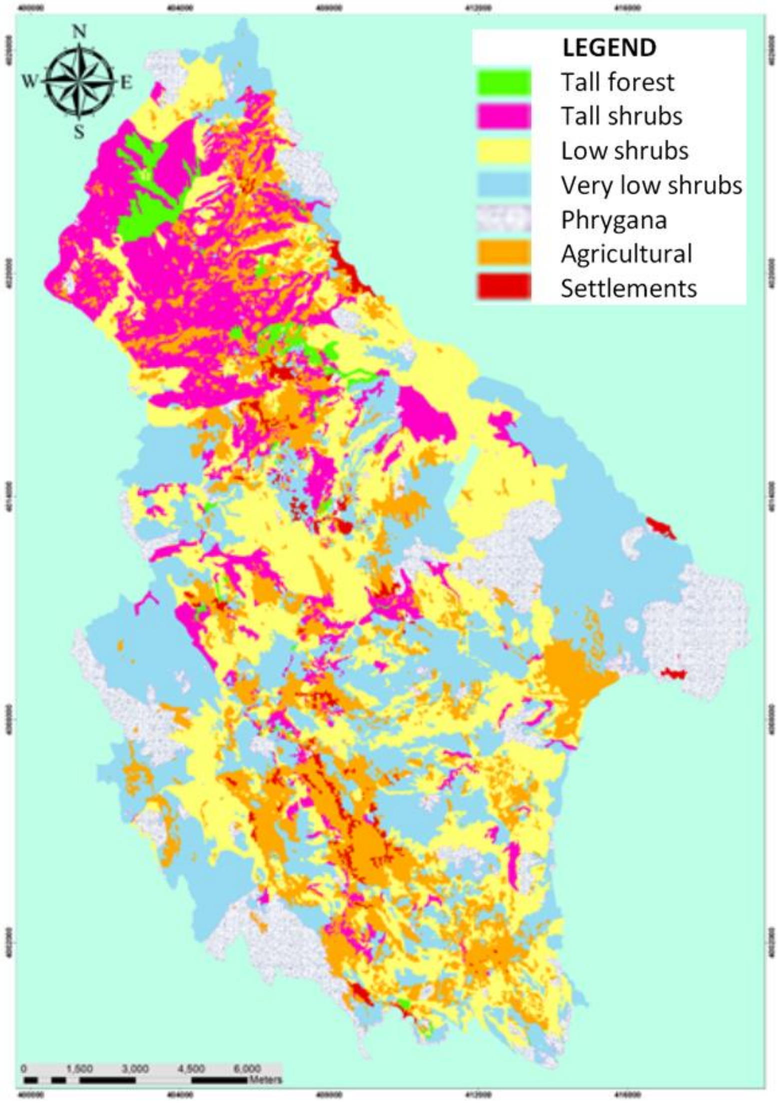

Figure 29. The fuel map for Kythera island (Source: Xanthopoulos et al. 2020).

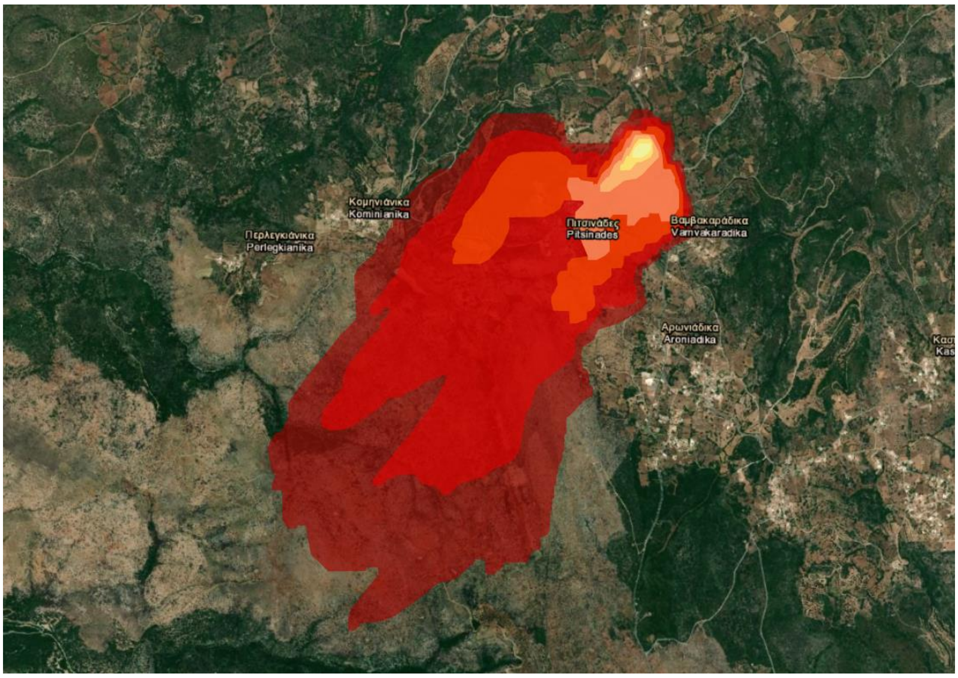

Figure 30. Simulation of Kythera fire, based on the existing fuels, with a step of one hour. The image shows the burned area per fire step.

The simulation of the fire spread of the 2017 fire with the existing fuels, for six hours, using a step of 1 hour is shown in Figure 30. Figure 31 shows in yellow the real fire contours with time as documented through our investigations. The result show a very good agreement between the actual fire spread and the simulation, encouraging the next step which is use of G.FMIS for simulation of fire treatment scenarios.

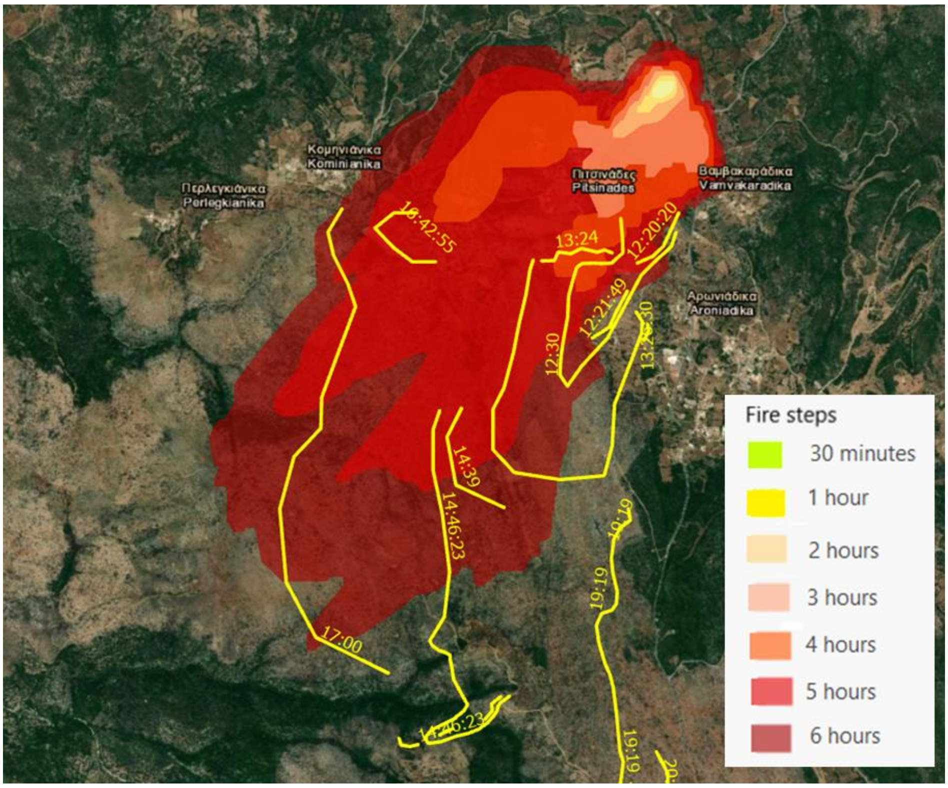

Figure 31: Real fire documented contours super-imposed over the simulated fire spread based on the Kythera fuel map.

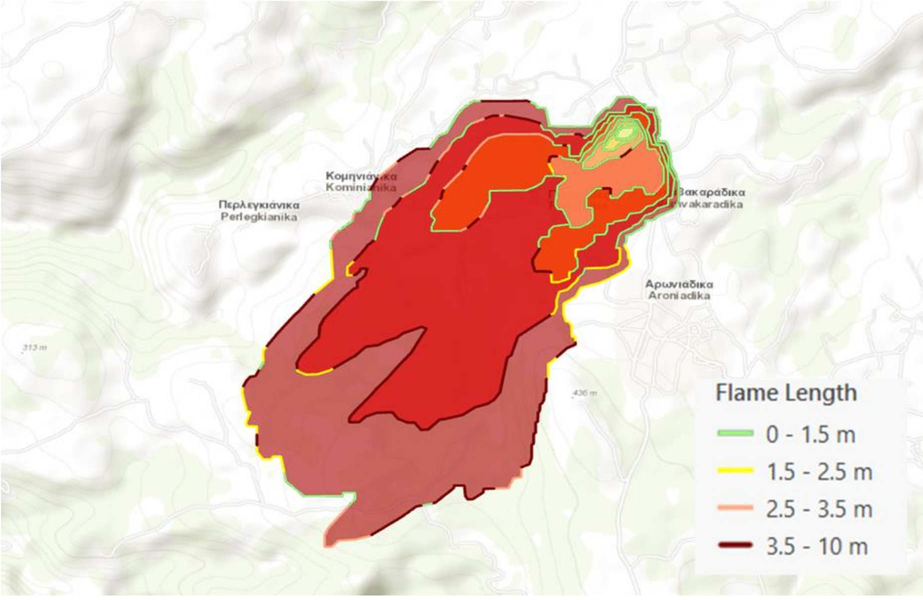

Figure 32: Simulation of Kythera fire based on existing fuels, showing the flame length classes along the perimeter at each (hourly) simulation step.

Figure 32, shows the fire perimeter at each simulation step, based on simulation with the existing fuels map, indicating through different colors the flame length along the perimeter. The classes correspond to the broadly accepted limits for firefighting. It is noted that at no point across the perimeter a flame length over 10 m is predicted. Firefighting is virtually impossible on flame lengths longer than 10 m (Tedim et al. 2018).

Simulation of the results of fuel management

After simulation of the real fire, G.FMIS was used for simulation of four fuel management scenarios, in order to discover what would be the result on fire spread if they had been applied to the area that burned prior to the fire event. The four scenarios were:

- Scenario 1: Mechanical treatment (tractor) only in agricultural areas
- Scenario 2: Mechanical treatment (hand tools) only in agricultural areas
- Scenario 3: Grazing everywhere (in all types of vegetation)
- Scenario 4: Intense grazing everywhere (in all types of vegetation)

The Influence of each of the four fuel treatment scenarios on fire perimeter growth and flame length, was tested.

The fuel treatments alter fuel conditions. Grazing reduces the amount of herbaceous fine fuels, the shrub component, the fuel depth (height) and the fine fuels while mechanical treatment breaks the horizontal continuity and changes the fuel depth (height) of the vegetation.

Treated fuels are the potential outputs of the treatment of choice and they were used as input data for the simulations. To describe those transformations (changes) we estimated the characteristics of the fuels after each one of the selected treatments. We present the fuel models which describe the untreated (initial) fuels versus the fuel models which we estimate that describe the treated fuels after treatment (method) of choice. The selected treatments and possible changes in Fuel Models (F.M.) are presented in Table 7, in the form: “Untreated Fuel (initial)” –> Applied Treatment –> “Treated Fuel”. The biomass of grass, live leaves and fine twigs along with the depth (height) of the fuels may be sufficiently different in grazed and ungrazed areas.

Table 7: Possible fuel treatments and consequent changes in Fuel Models (F.M.)

Untreated Fuel Model (initial)	**Treatment**	**Treated Fuel Model (potential after treatment)**
Forest with tall maquis understory	Mechanical *(Low thining decreasing a) the continuity between surface and canopy fuel strata and b) the horizontal continuity)*	Deep litter (KYTH2)
Forest with tall maquis understory	Grazing	Low Maquis
Forest with tall maquis understory	Prescribed burning	Grass
Forest with tall maquis understory	Grazing (*intense*)	Low Maquis GRAZED
Tall maquis	Prescribed burning	Low Maquis
Tall maquis	Grazing	Low Maquis
Tall maquis	Grazing (*intense*)	Low Maquis GRAZED
Low maquis	Prescribed burning	Very Low Shrubs (KYTH1)
Low maquis	Grazing	Very Low Shrubs (KYTH1)
Low maquis	Grazing (*intense*)	Very Low Shrubs (KYTH1) GRAZED
Very Low Shrubs (KYTH1)	Prescribed burning	Phrygana
Very Low Shrubs (KYTH1)	Grazing	Very Low Shrubs (KYTH1) GRAZED
Very Low Shrubs (KYTH1)	Grazing (*intense*)	Very Low Shrubs (KYTH1) GRAZED
Phrygana	Prescribed burning	Phrygana or Grass
Agricultural (Grass)	Mechanical (tractor)	Bare Ground
Agricultural (Grass)	Mechanical (hand tools)	Mowed Grass
Agricultural (Grass)	Prescribed burning	Grass
Agricultural (Grass)	Grazing	GRAZED Grass
Agricultural (Grass)	Grazing (*intense*)	Bare Ground

Note:

- The term “maquis” is used interchangeably with the term “shrubs” (which could also be written as “Evergreen sclerophyllous shrublands”).
- Low maquis is F.M. I (Dimitrakopoulos et al 2001).
- Tall maquis is F.M. II (Dimitrakopoulos et al 2001).
- Very Low Shrubs (ΚΥΘ1) [or Very Low Shrubs (KYTH1) in English], is the local F.M. for Kythera (Xanthopoulos et al. 2019) in which the term “shrubs” is maintained.
- We have assumed that phrygana cannot be grazed.

Calculations for the fuel models after the treatments

Regarding the quantification of the effects of the treatments on the fuels, we utilized the research of Papanastasis et al. (2006) and Mantzanas et al (2018), to calculate the values of the ratio “Grazed Area to Ungrazed Area” (GA/UA) for herbs’ fuel load in phryganic areas and grasslands. The findings of Mancilla-Leyton et al. (2021) supported the calculations of GA/UA ratio values for fuel height (depth) and live woody load of evergreen sclerophyllous shrublands and areas covered by phryganic species (Table 8). The values of the parameters of the models describing the initial and treated fuels are summarized in tables 9 and 10.

Table 8. GA (Grazed Area) to UA (Ungrazed Area) ratio values for various fuel types and categories. Leaves + twigs < 6mm equals to Live Woody (LW).

Site - treatment	Fuel type, category (source)	Fuel Parameter	(unit)	GA/UA Value
Psiloreitis - grazing	Herbs in phryganic areas (Papanastasis et al. 2006, Table 2)	Load	(g/m^2)	0.225
Psiloreitis - grazing	Herbs in grasslands (Papanastasis et al. 2006, Table 3)	Load	(g/m^2).	0.367
Oite – intense grazing	Herbs in grasslands (Mantzanas et al 2018, Table 6)	Load	(kg/0.1ha)	0.489
Donana, Spain - high browsing pressure	Cistus salvifolius leaves + twigs < 6mm (Mancilla-Leyton et al. 2021, Table 1)	Load	(g/m^2)	0.449
Donana, Spain - high browsing pressure	Cistus salvifolius height (Mancilla-Leyton et al. 2021, Table 1)	Height	(cm)	0.485
Donana, Spain - high browsing pressure	Halimuim halimifolium leaves + twigs < 6mm (Mancilla-Leyton et al. 2021, Table 1)	Load	(g/m^2)	0.420
Donana, Spain - high browsing pressure	Halimuim halimifolium height (Mancilla-Leyton et al. 2021, Table 1)	Height	(cm)	0.830
Donana, Spain - very high browsing pressure	Myrtus communis leaves + twigs < 6mm (Mancilla-Leyton et al. 2021, Table 1)	Load	(g/m^2)	0.425
Donana, Spain - very high browsing pressure	Myrtus communis:height (Mancilla-Leyton et al. 2021, Table 1)	Height	(cm)	0.667
Donana, Spain - medium browsing pressure	Pistacia lentiscus leaves + twigs < 6mm (Mancilla-Leyton et al. 2021, Table 1)	Load	(g/m^2)	0.528
Donana, Spain - medium browsing pressure	Pistacia lentiscus height (Mancilla-Leyton et al. 2021, Table 1)	Height	(cm)	0.767

Table 9. Values of the parameters of the Fuel Models (F.M.) that were used for the description of the initial and treated agroforestry vegetation.

F.M. / PARAMETER	Low maquis (I)	Tall maquis (II)	Sarcopoterium spinosum (V)	Grass (VI)	Very low shrubs (KYTH1)	Low maquis (I) GRAZED	Very low shrubs (KYTH1) GRAZED	Grass (VI) Grazed	Grass (VI) Mowed
1 HR (MTON/HA)	9.91	17.88	3.50	4.82	5.81	8.82	5.13	2.06	4.82
10 HR (MTON/HA)	6.80	13.30	1.02	0.49	0.86	6.12	0.77	0.49	0.49
100 HR (MTON/HA)	3.60	8.5	0.28	0	0.00	3.60	0.00	0	0
LIVE HERB (MTON/HA)	0	0	0	0	0.00	0	0.00	0	0
LIVE WOODY (MTON/HA)	7.70	10.60	0.85	0	9.79	3.67	4.25	0	0
1 HR S/V (1/CM)	55	55	65	78	55	55	55	60	60
LIVE HERB S/V (1/CM)	-	-	-	-	-	-	-	-	-
LIVE WOODY S/V (1/CM)	55	55	65	-	55	55	55	0	0
FUEL BED DEPTH (CM)	102.19	203.58	40.00	27.53	31.41	73.27	20.64	13.35	7
EXT MOISTURE (%)	34	34	20	14	36	32	34	12	12
HEAT CONTENT (J/G)	20000	20000	19054	18600	19050	20000	19050	18600	18600

Table 10 (Part 1). Values of the parameters of 5 untreated (initial) Fuel Models (F. M.) and 4 treated F. M. that were used for the description of the untreated and treated agroforestry vegetation respectively, in Kythera (values are given horizontally). The table refers only to the fuel models present in the burned area.

Fuel Model	SV1h	SV10h	SV100h	SVhb	SVwd	L1h	L10h	L100h	Lhb
Tall maquis	55	3.57	0.98	0	55	1.788	1.330	0.850	0
Low maquis	55	3.57	0.98	0	55	0.991	0.680	0.360	0
Low Maquis GRAZED	55	3.57	0.98		55	0.882	0.612	0.360	0
Very low shrubs (KYTH1)	55	3.57	0.98	0	55	0.581	0.086	0.000	0
Very Low Shrubs (KYTH1) GRAZED	55	3.57	0.98	0	55	0.513	0.077	0.000	0
Phrygana (Sarcopoterium spinosum)	65	3.57	0.98	0	65	0.350	0.102	0.028	0
Agricultural (Grass)	78	3.57	0.98	0	0	0.482	0.049	0.000	0
GRAZED Grass	60	3.57	0.98	0	0	0.206	0.049	0.000	0
MOWED Grass	60	3.57	0.98	0	0	0.482	0.049	0.000	0

Table 10 (Part 2).

Fuel Model	Lwd	MXdead	Sigma	PR (β)	PROPR	Heat	Depth	WAF(DS)
Tall maquis	1.060	0.34	55	0.00481	0.038	20000	203.58	0.51
Low maquis	0.770	0.34	55	0.00534	0.042	20000	102.19	0.30
Low Maquis GRAZED	0.367	0.32	55	0.00591	0.047	20000	73.27	0.29
Very low shrubs (KYTH1)	0.979	0.36	55	0.01022	0.081	19050	31.41	0.21
Very Low Shrubs (KYTH1) GRAZED	0.425	0.34	55	0.00959	0.076	19050	20.64	0.12
Phrygana (Sarcopoterium spinosum)	0.085	0.20	65	0.00275	0.025	19054	40	0.25
Agricultural (Grass)	0.000	0.14	78	0.00376	0.040	18600	27.53	0.21
GRAZED Grass	0.000	0.12	60	0.00372	0.032	18600	13.35	0.09
MOWED Grass	0.000	0.12	60	0.01479	0.126	18600	7	0.07

The simulations of the four scenarios of fuel treatment for six hours at one hour time steps regarding perimeter growth and flame length along the perimeter are shown in figures 33 to 40 and can be directly compared with the result of the simulation of the actual fire with the real fuels map.

Simulations of Kythira fire based on treated fuels scenarios

Scenario 1: Agricultural fuels treated with mechanical tools

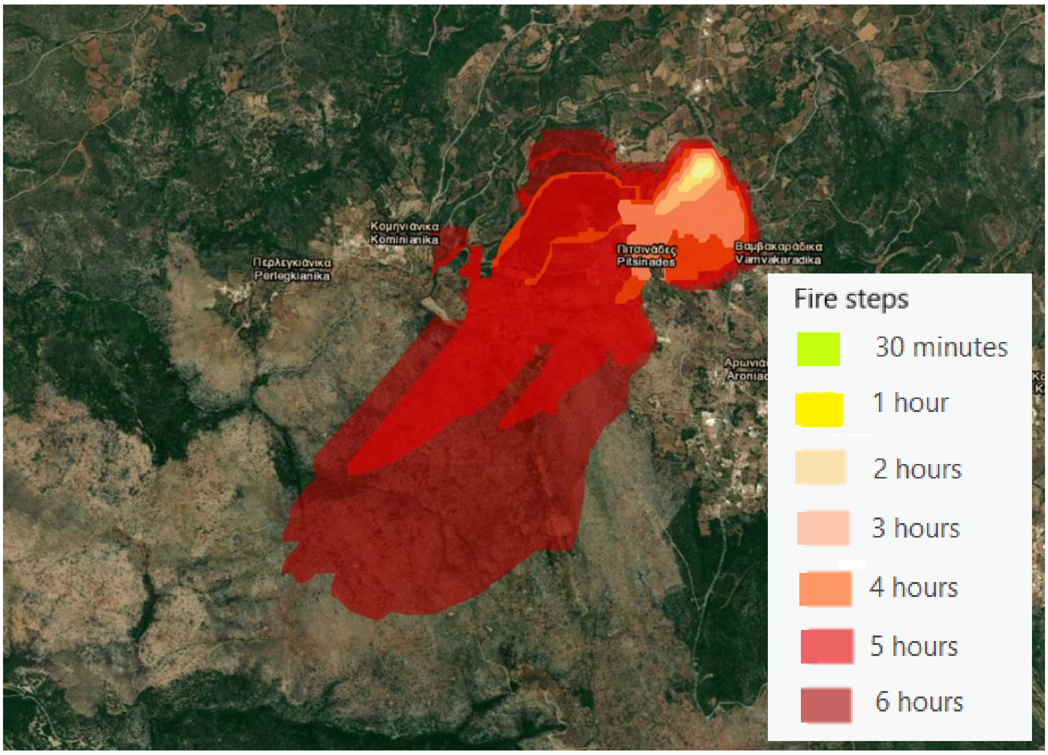

Figure 33. Simulation of Kythera fire, based on scenario 1 fuel treatment . The image shows the burned area per fire step.

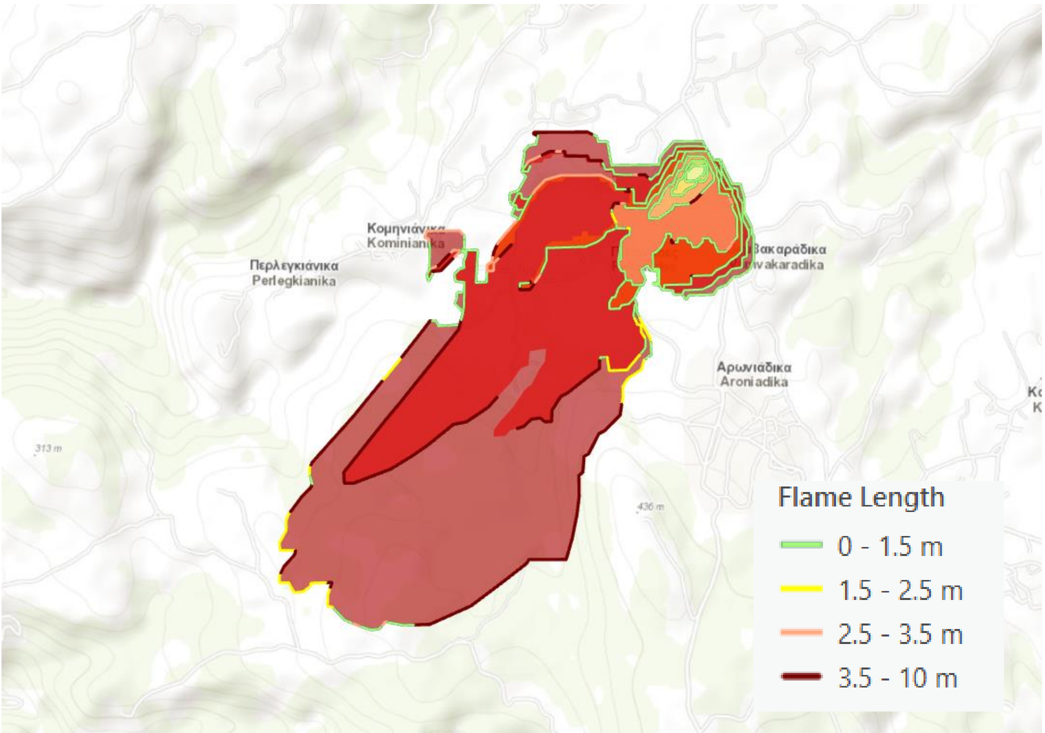

Figure 34. Simulation of Kythera fire based on scenario 1 fuel treatment showing the flame length classes along the perimeter at each (hourly) simulation step.

Scenario2 : Agricultural fuels treated with hand tools

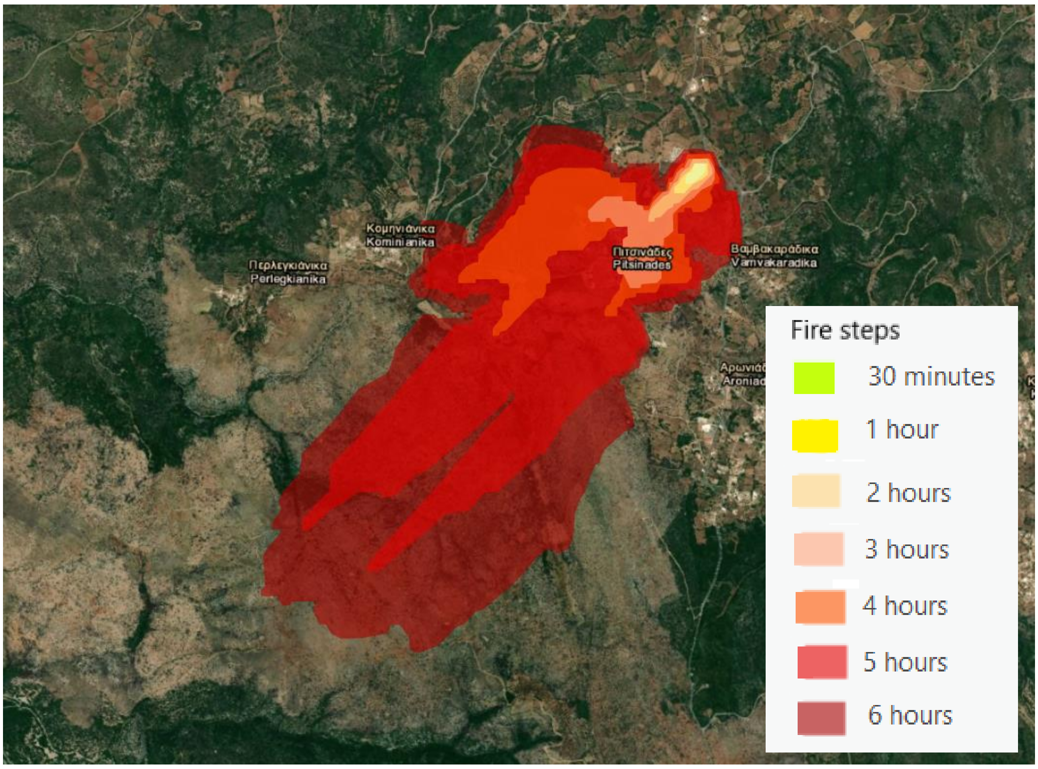

Figure 35. Simulation of Kythera fire, based on scenario 2 fuel treatment . The image shows the burned area per fire step.

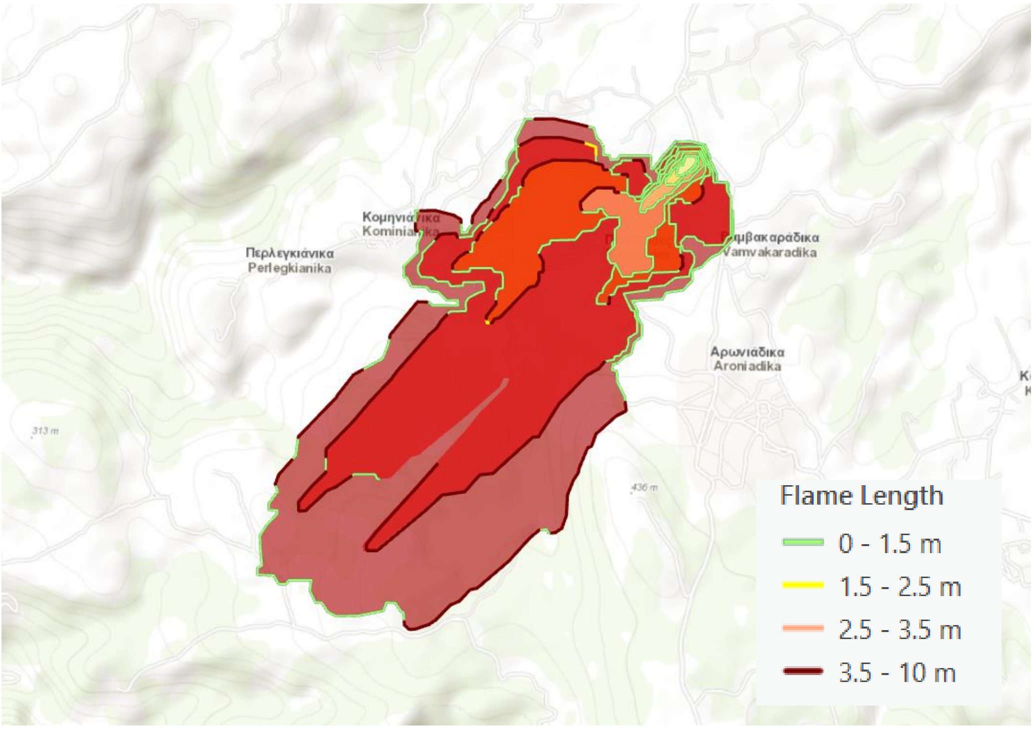

Figure 36 . Simulation of Kythera fire based on scenario 2 fuel treatment showing the flame length classes along the perimeter at each (hourly) simulation step.

Scenario 3: All fuel types treated with grazing

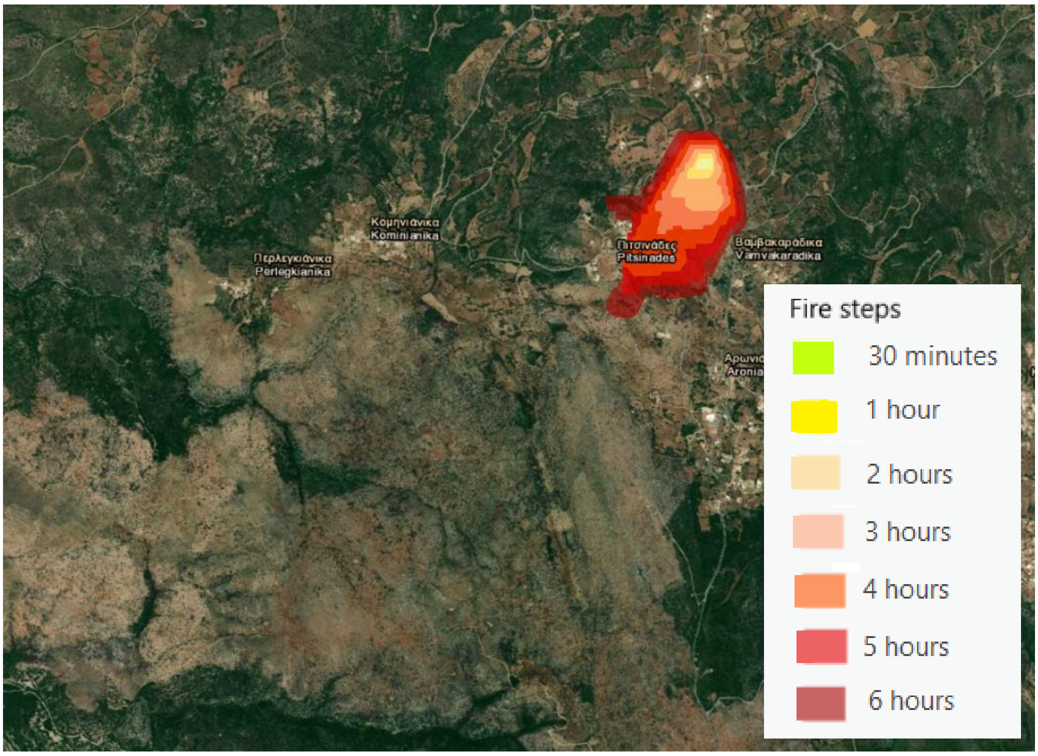

Figure 37. Simulation of Kythera fire, based on scenario 3 fuel treatment . The image shows the burned area per fire step.

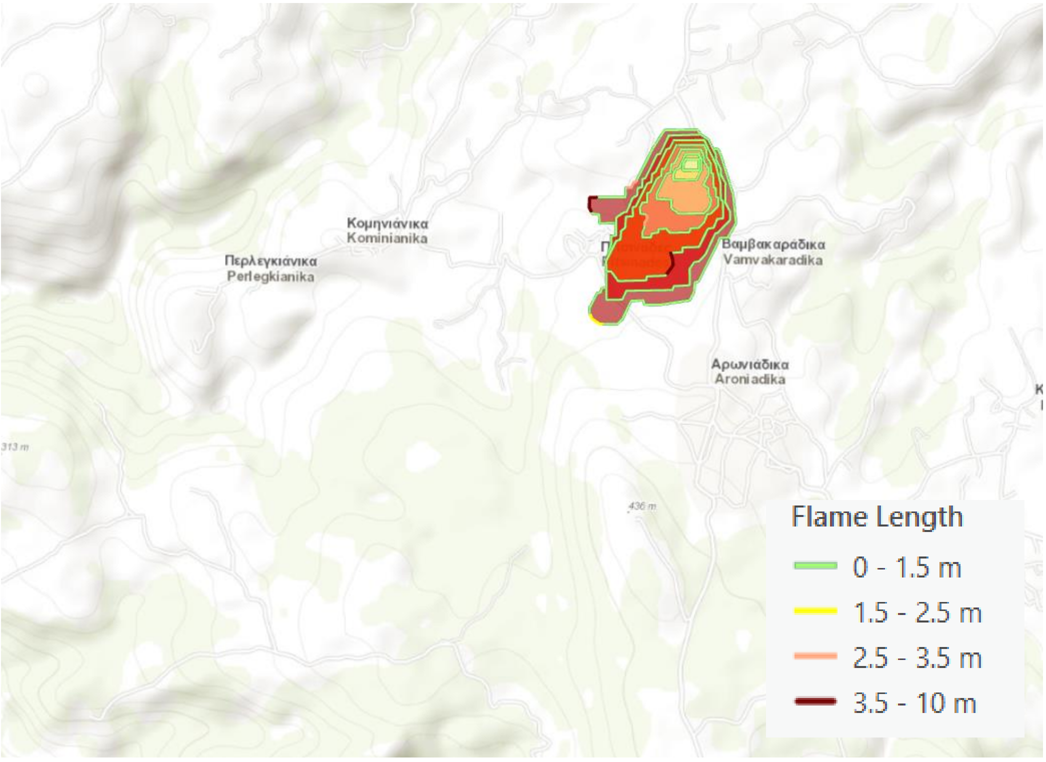

Figure 38 . Simulation of Kythera fire based on scenario 3 fuel treatment showing the flame length classes along the perimeter at each (hourly) simulation step.

Scenario 4: All fuel types treated with intense grazing

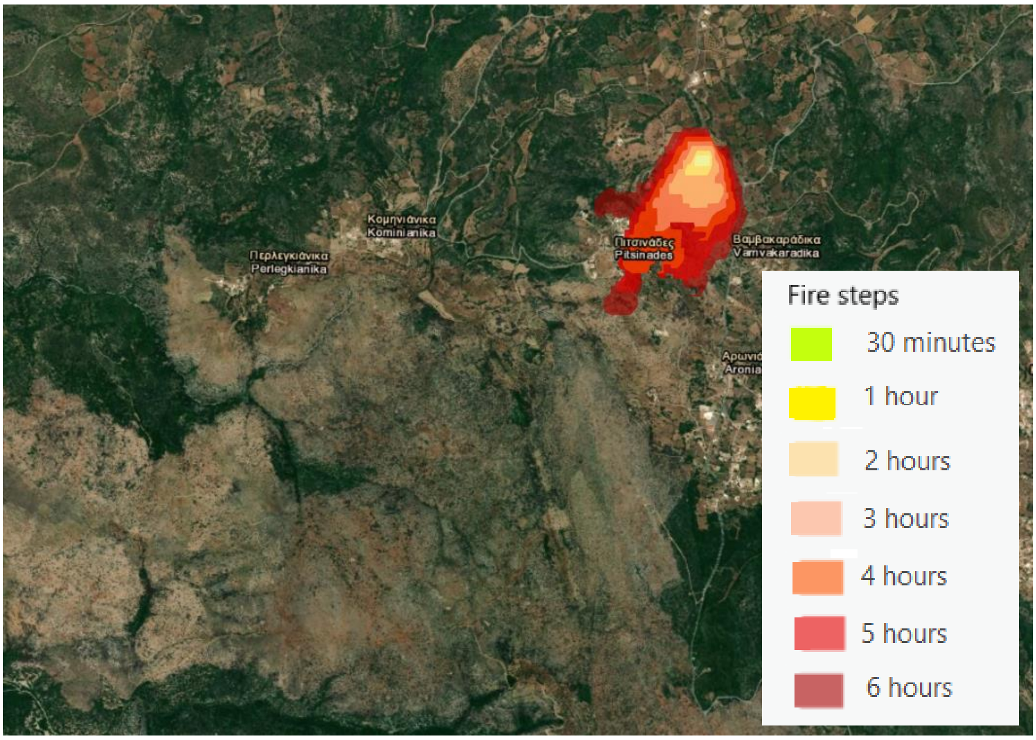

Figure 39. Simulation of Kythera fire, based on scenario 4 fuel treatment . The image shows the burned area per fire step.

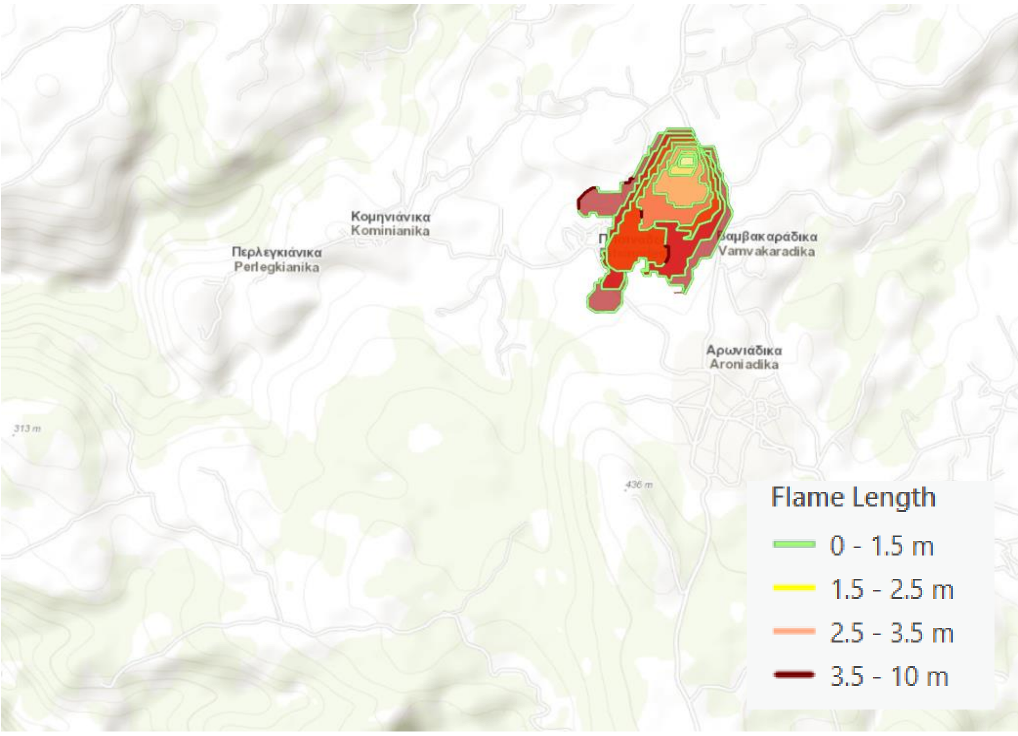

Figure 40 . Simulation of Kythera fire based on scenario 4 fuel treatment showing the flame length classes along the perimeter at each (hourly) simulation step.

Figures 41 and 42 summarize the simulations for the four scenarios regarding burned area and flame length along the perimeter for easier comparison.

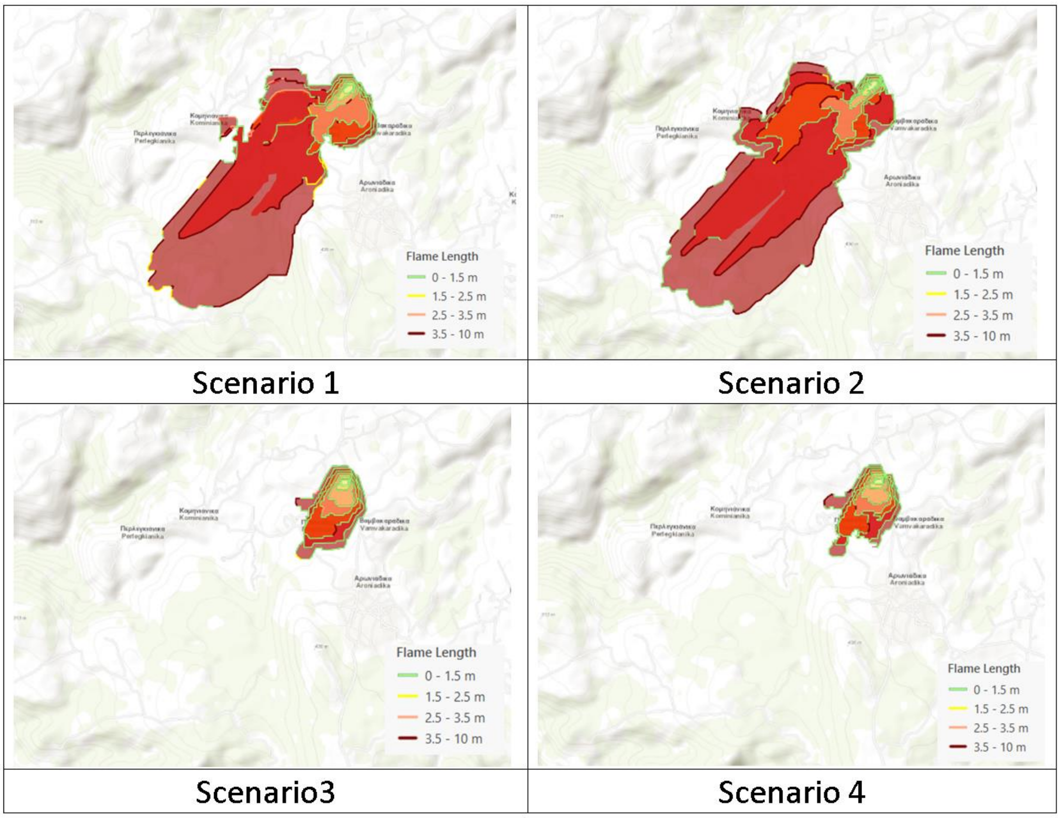

Figure 41. Influence of the four fuel treatment scenarios on burned area (simulation of 6 hours)

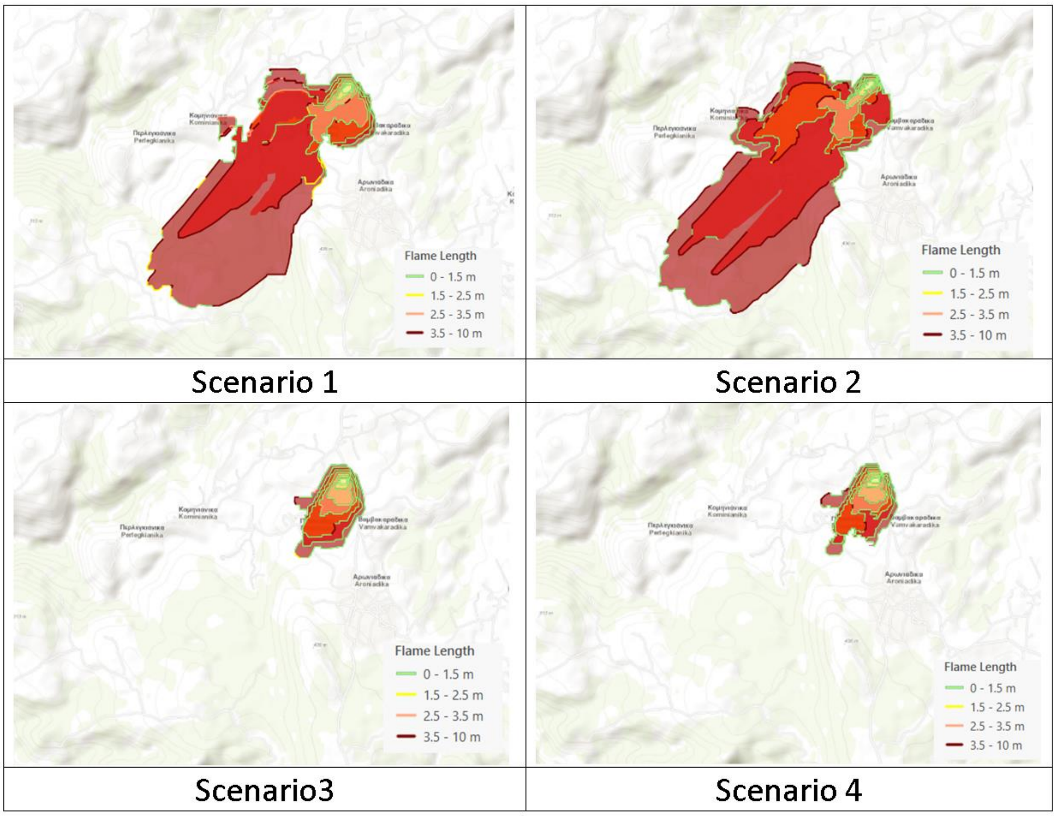

Figure 42. Influence of the four fuel treatment scenarios on flame length along the perimeter (simulation of 6 hours)

The effect of fuel treatment on fire growth and flame length

Figure 41 illustrates the effect that the four fuel treatment scenarios would have on the burned area for six hour of simulation. Table 11 summarizes the perimeter length at each hour of the 6-hour simulation, including the simulation with the real fuel situation and the simulations for with the four fuel treatment scenarios. The significant effect of grazing (treatments 3 and 4) is obvious. On the other hand, treatments 1 and 2 seemingly have little effect. However, this is the result of the relatively small percentage that agricultural areas occupy within the burned area. To be exact, the final burned area after six hours in the simulation with real fuels is 281.1 ha, while the agricultural area within this area, which is the only one receiving fuel treatment under scenarios 1 and 2, is 20.28 ha, or 7.19% of the total.

Table 11. Simulated fire perimeter length for each of the 6 1-hour time steps.

	Total perimeter (m) at each time step					
Fuel treatment	1.0	2.0	3.0	4.0	5.0	6.0
REAL FUELS	505.8	864.3	2271.4	4572.6	7117.3	8302.3
SCENARIO 1	504.3	867.4	2516.8	4118.6	6654.9	8153.4
SCENARIO 2	438.1	841.2	2093.8	4703.6	7084.1	8275.3
SCENARIO 3	394.0	875.9	1292.2	1839.0	2060.6	2629.0
SCENARIO 4	388.6	917.7	1292.7	2328.8	2379.6	3190.1

Additionally, it should be pointed out that perimeter reduction is not the only outcome of the fuel treatments. The treatments also have an effect on flame length along the perimeter, which influence the effectiveness of firefighting as analyzed next.

The effect of fuel treatment on firefighting demand

In order to assess the effect of the fuel treatments on the required firefighting effort, we used a published formula for calculating the length of the flank of a fire that can be extinguished by a firetruck with a capacity of 2500 l, as a function of flame length (Simos and Xanthopoulos 2014). The formula is as follows:

$$EXT_{2500L\_Flank} = 20.756 + 57.493 / FL_{flank}$$

Where the extinction length EXT_{2500L_Flank} and the flank flame length FL_{flank} are expressed in meters.

Using the equation we developed table 12 which allows to estimate perimeter extinction (m) per truckload (2,500 l), taking flame length into consideration.

Table 12. Length of the fire perimeter of a fire (EXT_{2500L_Flank}) that can be extinguished by a 2500 l firetruck, as a function of flame length.

Flame length class	FL value used in simulation	Extinction of perimeter (m) per 2500l firetruck load
1: up to 1.5 m	1.2	68.7
2: up to 2.5 m	2.2	46.9
3. up to 3.5 m	3.5	37.2
4. up to 10 m	10.0	26.5
5. more than 10m	20.0	23.6

In order to develop a more realistic firefighting requirement estimation, the reduction in the effectiveness of the firetrucks due to the need for refilling with water needs to be taken into consideration, as well as the average time for emptying the load of a firetruck to the fire. Recognizing the typical conditions at Kythera (typical distance to water (km), fire truck travel speed at the islands road network, we made the following calculations regarding the truck loads that can be achieved by a firetruck per hour:

Average distance (km)	4
Firetruck speed (km/h)	50
Water loading time with delays (min)	5
Travel time (min)	14.6
Time for using-up one water load (min)	15
Total time required per truckload for each round (min)	29.6
Fight & reload rounds per hour (LOADS_PER_HOUR)	**2.0**

We traced the fire perimeter of the simulated fires under the four scenarios for each time step and calculated the perimeter length for each of five classes of flame length (m) as illustrated in Figure 42. a) 0-1.5 (1.2), b) 1.5-2.5 (2.2), c) 2.5-3.5 (3.5) d) (3.5-10) (10.0) e) >10 (20.0)

The more intense flame length (and fire intensity) class e) was not present in the simulations.

The required firetruck loads (T) for extinguishing a length of the perimeter of each flame length class is estimated by dividing the length by the corresponding EXT_{2500L_Flank} for that flame length. The results of the calculation for all the simulations are summarized in table 13.

Table 13. Estimated requirement of 2500 l firetruck loads (T) for extinguishing the fire perimeter at each time step, taking the flame length of the all the parts of the perimeter (in classes) into consideration.

	1.0	T	2.0	T	3.0	T	4.0	T	5.0	T	6.0	T
REAL	505.8	7.4	864.3	14.2	2271.4	38.4	4572.6	88.2	7117.3	204.0	8302.3	202.4
SCENARIO 1	504.3	7.3	867.4	14.1	2516.8	40.8	4118.6	76.7	6654.9	162.3	8153.4	175.9
SCENARIO 2	438.1	6.4	841.2	12.3	2093.8	36.2	4703.6	102.8	7084.1	183.5	8275.3	189.6
SCENARIO 3	394.0	5.7	875.9	12.8	1292.2	19.3	1839.0	29.0	2060.6	30.0	2629.0	41.4
SCENARIO 4	388.6	5.7	917.7	13.4	1292.7	19.7	2328.8	36.2	2379.6	34.7	3190.1	51.2

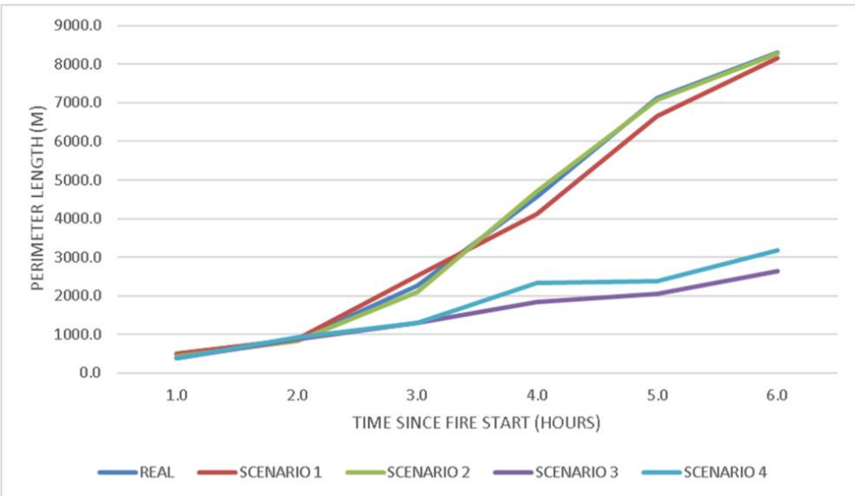

Figure 43. Fire perimeter length growth with time for the simulations with the real fuels and under four fuel treatment scenarios.

At each time step (1, 2 3… hours), the loads that can be achieved by a firetruck in this step's hours is the product of the hours times the LOADS_PER_HOUR (calculated at 2 loads per hour according to the example shown above). Thus, dividing the required firetruck loads (T) for each by the loads that can be achieved for the same duration result in an estimate of the required firetrucks. Figures 43, 44, and 45, present the estimated perimeter growth and firefighting demand for 6 hours.

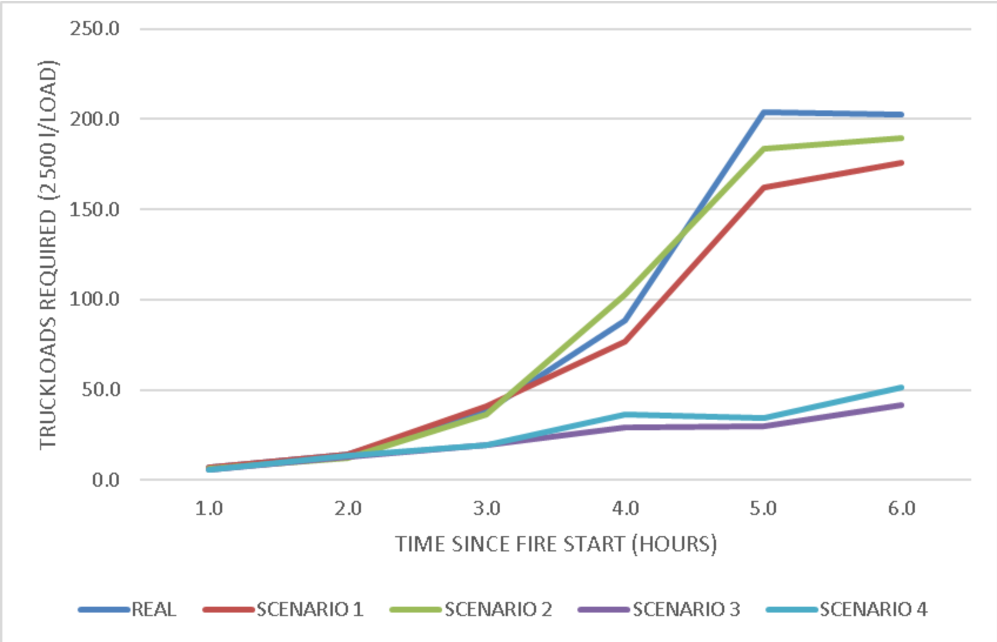

Figure 44. Number of required truckloads of 2500 l for extinguishing the fire perimeter with time for the five simulations.

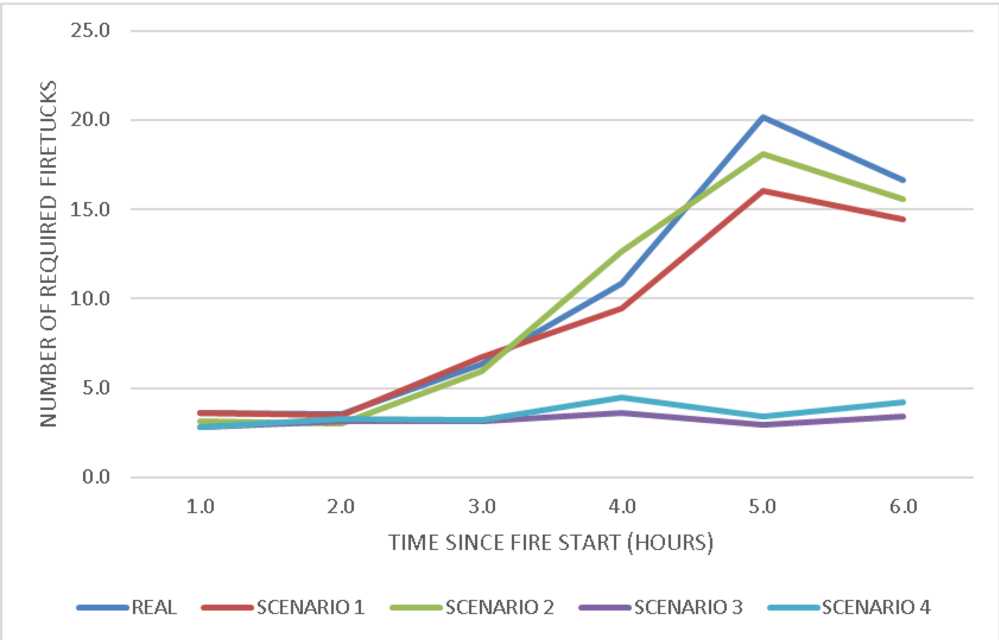

Figure 45. Evolution of the required number of firetrucks for controlling the perimeter of the fire as a function of time, for the five simulations.

Conclusions

In conclusion, scenarios 1 and 2 (treatments only in agricultural areas) do not affect the length of fire perimeter but reduce the required firefighting effort through the reduction of flame length along many parts of the perimeter. The capacity of the available firetrucks on the island (13) is exceeded after roughly 4 hours. It is unlikely that reinforcements will arrive by boat by that time (as it happened in 2017).

Scenarios 3 and 4 reduce both perimeter growth rate and flame length, thus reducing the needed firefighting effort. The number of firetrucks on the island is not exceeded. Broadcast fuel treatment through grazing over all of the land is much more effective (and cost free, actually producing income) than scenarios 1 & 2.

Part 3. Optimization of fuel treatments

Part 2 has demonstrated the value of fuel treatments and revealed the value of treatments, such as grazing, that can be applied over the landscape at little or no cost, while also producing income. However, broadcast treatments are not always possible as they depend on many factors including presence and cooperation of the population. In many areas of Mediterranean Europe, as mentioned in the literature review, free range grazing is in decline. Also, in many forest types, grazing is not enough to reduce fire hazard to acceptable levels and it has to be combined with other fuel treatments. Thus, it is often necessary to resort to other methods, usually manual or mechanical, which need to be applied at specific locations. Decisions at such cases are challenging as the treatments, the locations and the dimensions (area, width) have to be selected very carefully in order to achieve both effectiveness and efficiency.

Thus, this part of the deliverable introduces some tools that can be used in support of decision making, being complementary to the decision making framework developed in Deliverable 5.1

Based on literature and experience, we developed a small number of rules that can be applied in a GIS environment in support of where to apply and where not to apply fuel treatments.

Rule #1: Dangerous topography avoidance

This rule recognizes the need to avoid places where steep topography, canyons, etc. increase fire intensity and potentially lead to development of erratic behavior, making firefighting very dangerous. At the same time working on such slopes is very difficult and costly. Thus, we consider fuel treatment at such locations as non-feasible.

In a GIS environment, the rule is applied on basins polygons layer, as follows:

IF Altitude_Range >= 200 m AND Average_Slope % >= 25 AND Volume/SurfaceArea >= 50

THEN Fuel_management is Non-feasible

In Figure 46 the resulting map for Kythira island after the application of Rule #1 is presented. This rule was applied on the basins polygons layer of the area and the attributes table of this layer) which includes Average_slope (%) and Volume/SurfaceArea attribute values. The basins that are highlighted in cyan color are those that are selected after the application of this rule as areas where Fuel_management is non-feasible.

Figure 46. Map of selected areas on Kythera island (highlighted in cyan), where Fuel management is non-feasible according to the Rule #1 applied.

Rule #2: Steep slopes avoidance

The explanation of this rule is similar to Rule #1 and has to do with the fire behavior and the cost. The slope limit is set at 50%.

In a GIS environment, the rule is applied on the Slope (%) raster layer, as follows:

If Slope(%) >= 50 THEN Fuel_management is Non-feasible

This analysis is applied only on the slope (%) layer of the Area of Interest (AoI) in order to select the locations that have slope(%) values > 50%.

The resulting map, after the application of rules #1 and #2 for Kythira island is presented in figure 47, where the areas that fulfill the criteria of either rule #1 or #2 or both are presented in red color.

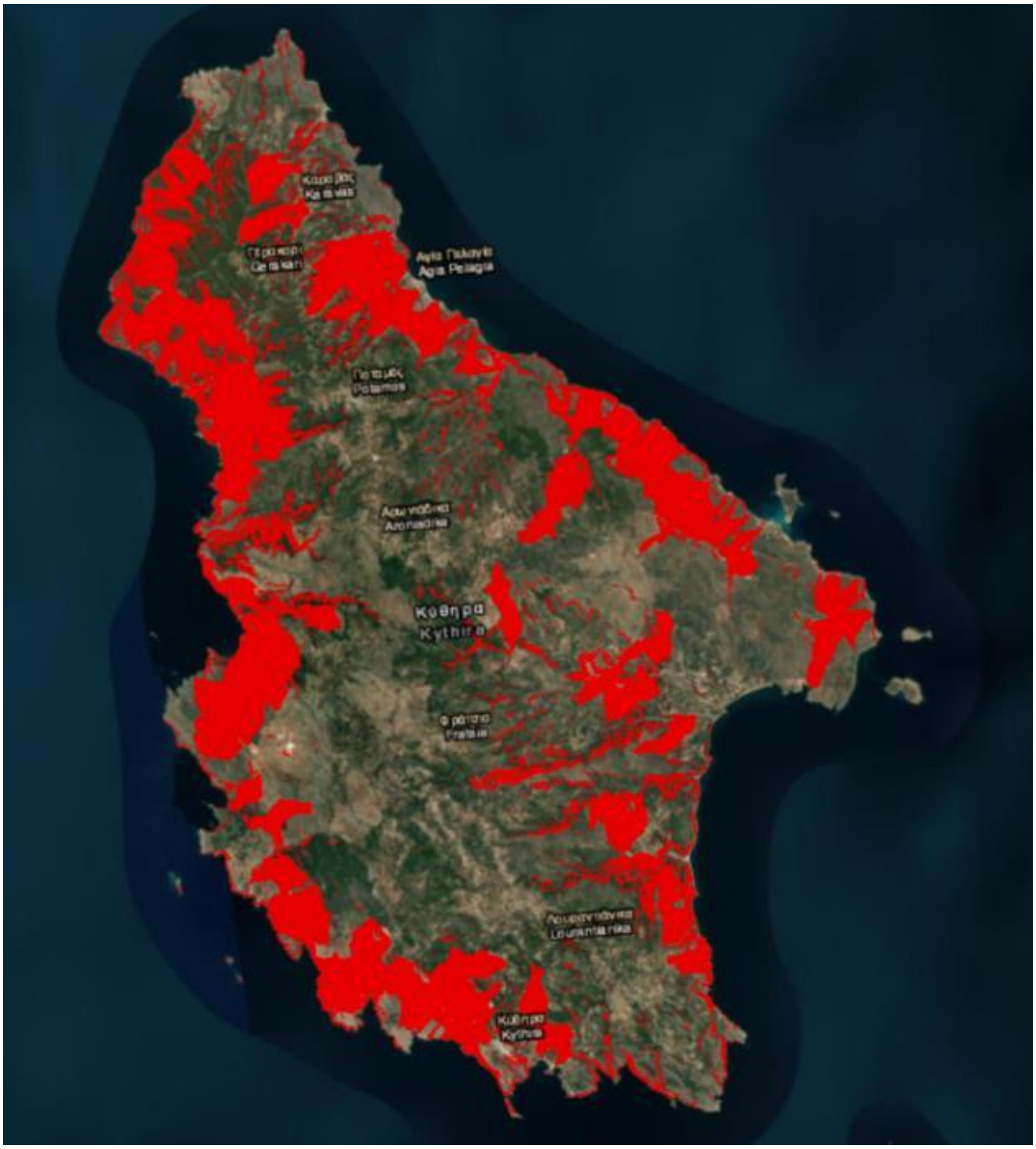

Figure 47. Areas in Kythira island where fuel management IS considered as non feasible after the application of rules #1 & #2

Rule #3: Areas where fuel management is proposed

This rule uses a number of spatial criteria which are applied on the slope raster layer, 100m buffered Roads layer, 100m buffered agricultural areas, and selected vegetation type layer.

In a GIS environment, the rule is applied as follows:

If Slope% <=10 and Distance_from_Roads <=100 m and Distance_from_Agricultural <=100 m AND [vegetation is LowShrubs OR Vegetation is Phrygana] then Fuel Management is Proposed

Figure 48 presents the area in Kythira island which is selected after the application of the first criterion regarding slope. The transparent area on this map shows the areas with slope % < 10.

Figure 49 presents in green color the area which is selected after the application of the criteria concerning distance from roads and agriculture (i.e 100m buffer zones around them).

In figure 50 the final output of this rule is shown, mapping the areas where fuel management treatments are proposed in green colors shades.

Figure 48: Area with Slope <= 10% (transparent area) in the central part of Kythera.

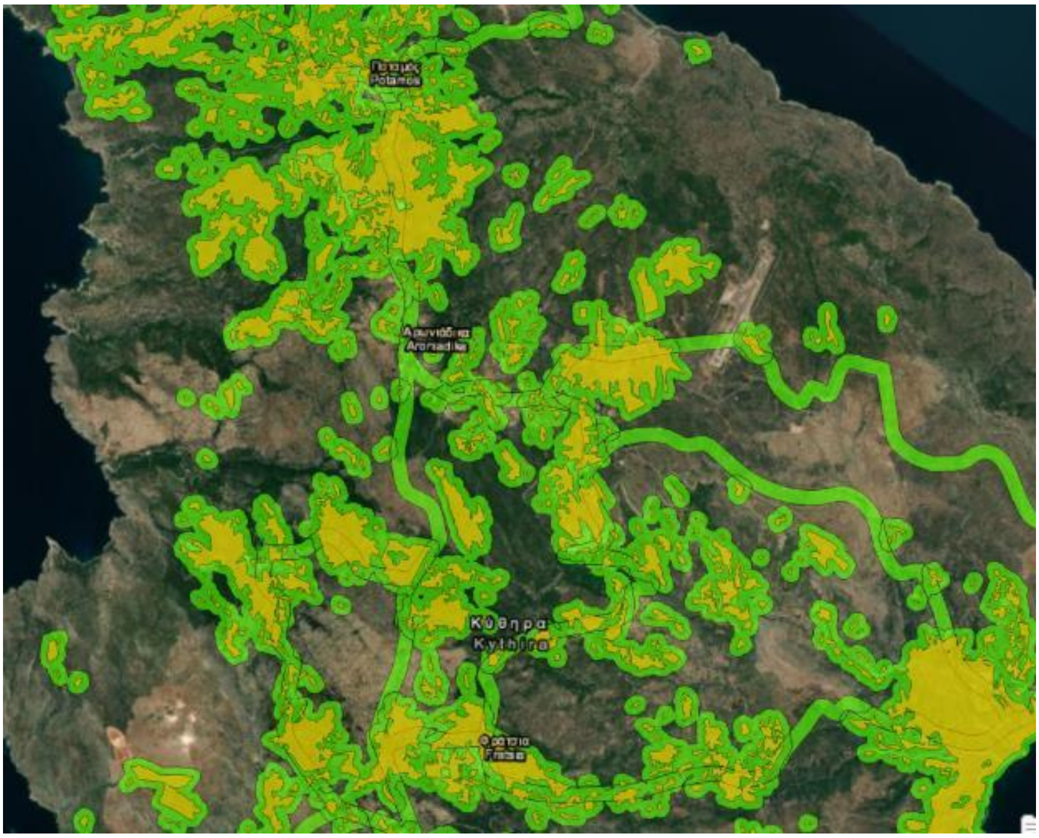

Figure 49: area (green coloured) 100 m from roads network and agriculture in Kythera.

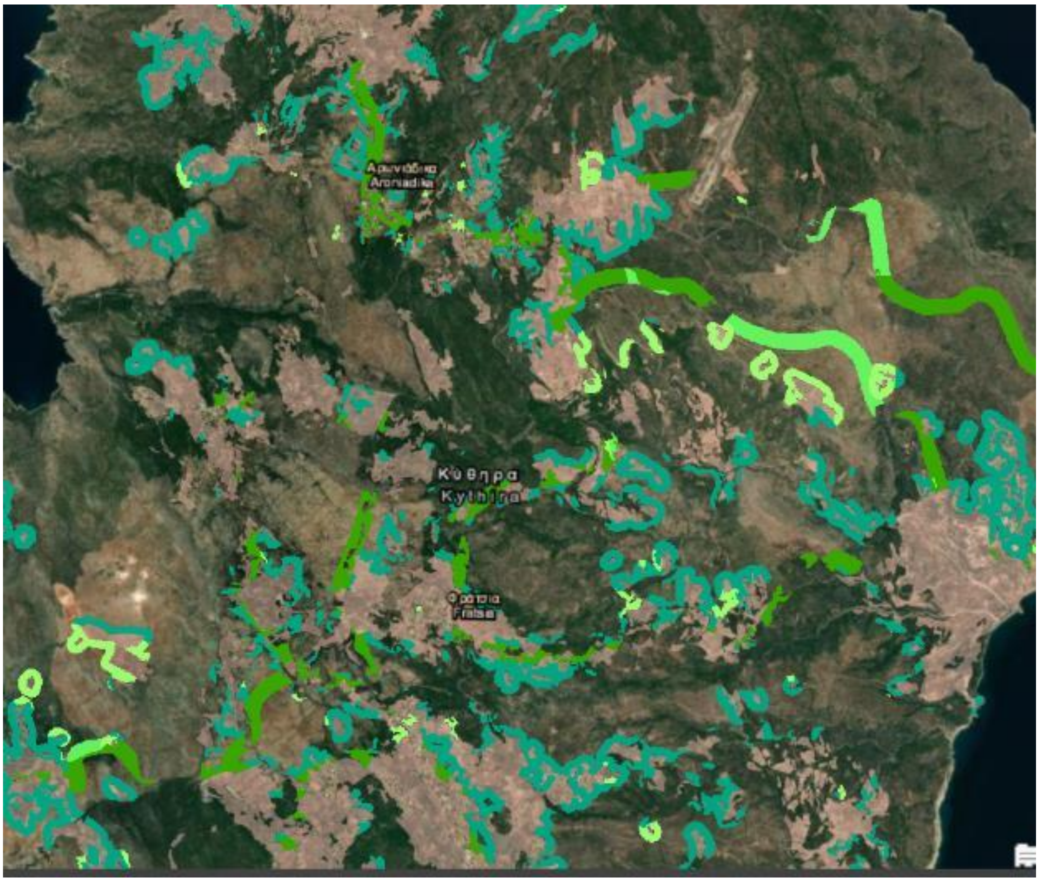

Figure 50: area (green coloured) where fuel management is proposed , after the application of all the criteria of rule #3

Rule #4: Taking fire behavior into consideration: Safe Separation Distance (SSD) analysis

The potential fire behavior of a specific type of vegetation, in a particular topography and under particular (adverse) weather conditions, also needs to be taken into consideration when determining where a fuel treatment should be located. It also affects the necessary width/size of the treatments in order to allow safe and effective firefighting, and accordingly it affects the associated cost.

Rule #4 for selecting fuel treatment location and width, involves determination of a Safe Separation Distance (SSD) between the flames and the firefighters that optimally would be provided by the treated area. Thus, this rule, is based on the work of Butler (2015) who, following-up on earlier work where the proposed SSD was 4 x Flame height (Fh) (Butler and Cohen 1998, Butler 2014), introduced a 'slope-wind' factor (Δ) to adjust SSD calculation for the influence of slope and wind, which was later also reported in a table by Campbell et al (2016). SSD can be expressed by the following equation:

$SSD = 4 \times Fh$ or

$SSD = 8 \times Hv \times \Delta$, (assuming that $Fh = 2 \times Hv$),

where, Hv is the vegetation height and Fh is the flame height

Table 14 is based on Campbell et al (2016), but we made some adjustments regarding the units and the wind speed at different heights. The gaps between the four classes of the wind speed values were "filled". So the initial "0-3", "4-7", "8-13" and ">13" (m/sec) classes were modified.

Table 14. Table of proposed slope-wind factor values (shown in red fonts) (modified from Campbell et al (2016)).

	Wind speed						Slope (%)			
	10 m			6.1 m (20 ft)			<20	21-30	31-50	>50
	Km h^{-1}	m s^{-1}		Km h^{-1}	m s^{-1}					
Light	**0-12.7**	**0-3.5**		**0-10.8**	**0-3**		**1**	**1**	**3**	**5**
Moderate	**13.1-29.6**	**3.6-8.2**		**11.2-25.2**	**3.1-7**		**1.5**	**2**	**4**	**6**
Strong	**30.1-55.1**	**8.4-15.3**		**25.6-46.8**	**7.1-13**		**3**	**3**	**6**	**7.5**
Very strong	**>55.1**	**>15.3**		**>46.8**	**>13**		**4.5**	**5**	**7**	**9**

Factor Δ was calculated in the GIS, for every raster cell from the combination of wind speed and slope values in that cell. The fuel depth (Hv) is considered equal to the fuel bed depth of the fuel model in the cell. Thus:

$SSD = 8 \times Hv \times \Delta$

Example:

Wind=30 km/h at 6.1 m and slope=40%, therefore Δ=6 (from table 14)

The fuel depth of the fuel model "Tall shrubs" (Hv) is 2 m.

$SSD = 8 \times 2 \times 6 = 96$ m

Analysis for Safe Separation Distance in Kythera

The SSD calculation methodolgy decribed above, was used in a GIS raster-based spatial analysis on the island of Kythera, in order to map SSD in six (6) classes over the whole island. The SSD maps for Kythira Island were based on the wind field estimation for prevailing wind conditions during summer in the area, according to historical meteorological data analysis. The NUATMOS software [Ross et al, 1988] which is incorporated in G.FMIS fire simulator was used for the estimation of a wind field map.

For the calculation of SSD in the spatial dimension, a classified Slope (%) map was combined with the wind speed map (figure 51) for the intermediate calculation of a Delta factor map (figure 52).

Then, three SSD output maps were calculated (figure 53, 54, 55) based on Delta mapping and fuel depth maps for the area of Interest, corresponding to the existing fuels (figure 52), scenario 2 fuel treatment and scenario 3 fuel treatment respectively.

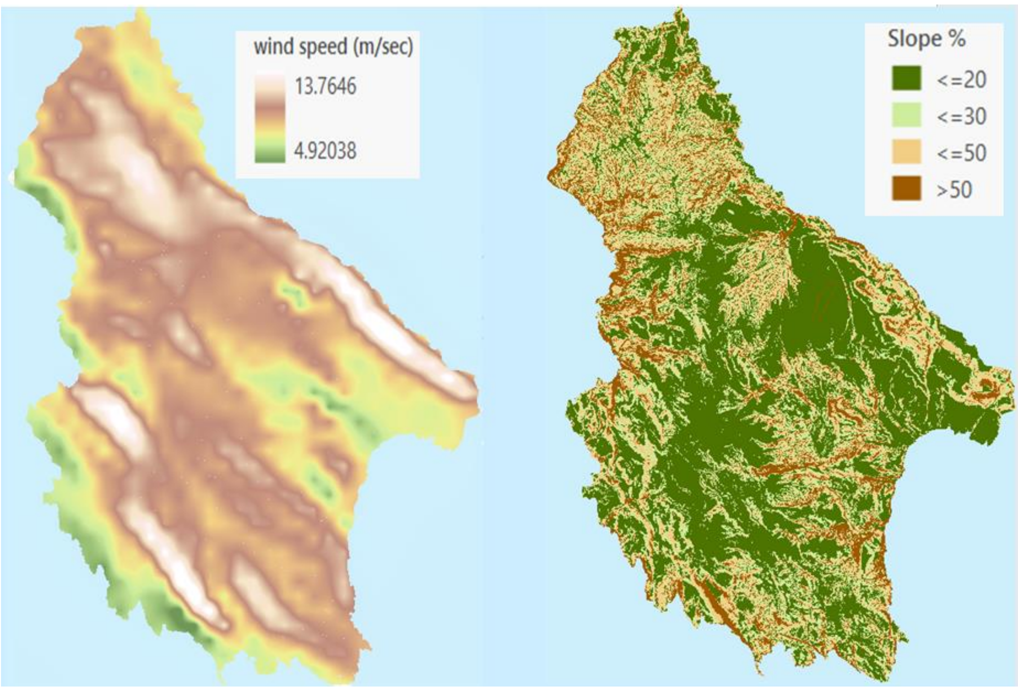

Figure 51. Wind speed map for prevailing wind conditions during the summer in Kythera island (left) and slope (%) map classified in four (4) classes (right)

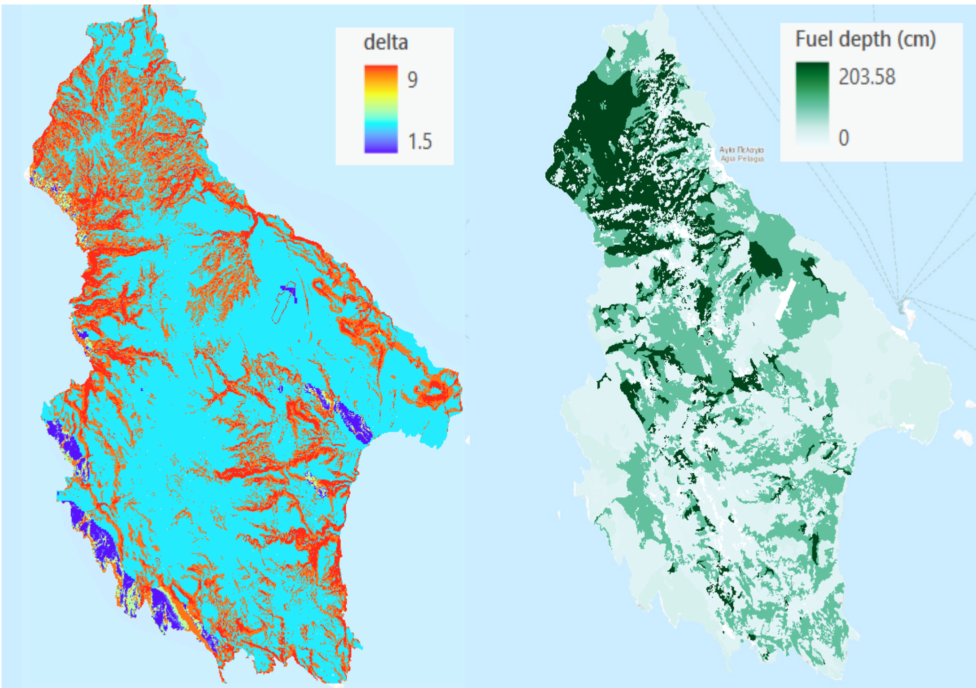

Figure 52. Maps of estimated Delta factor (left) and fuel depth of the existing fuels (right) on the island of Kythera.

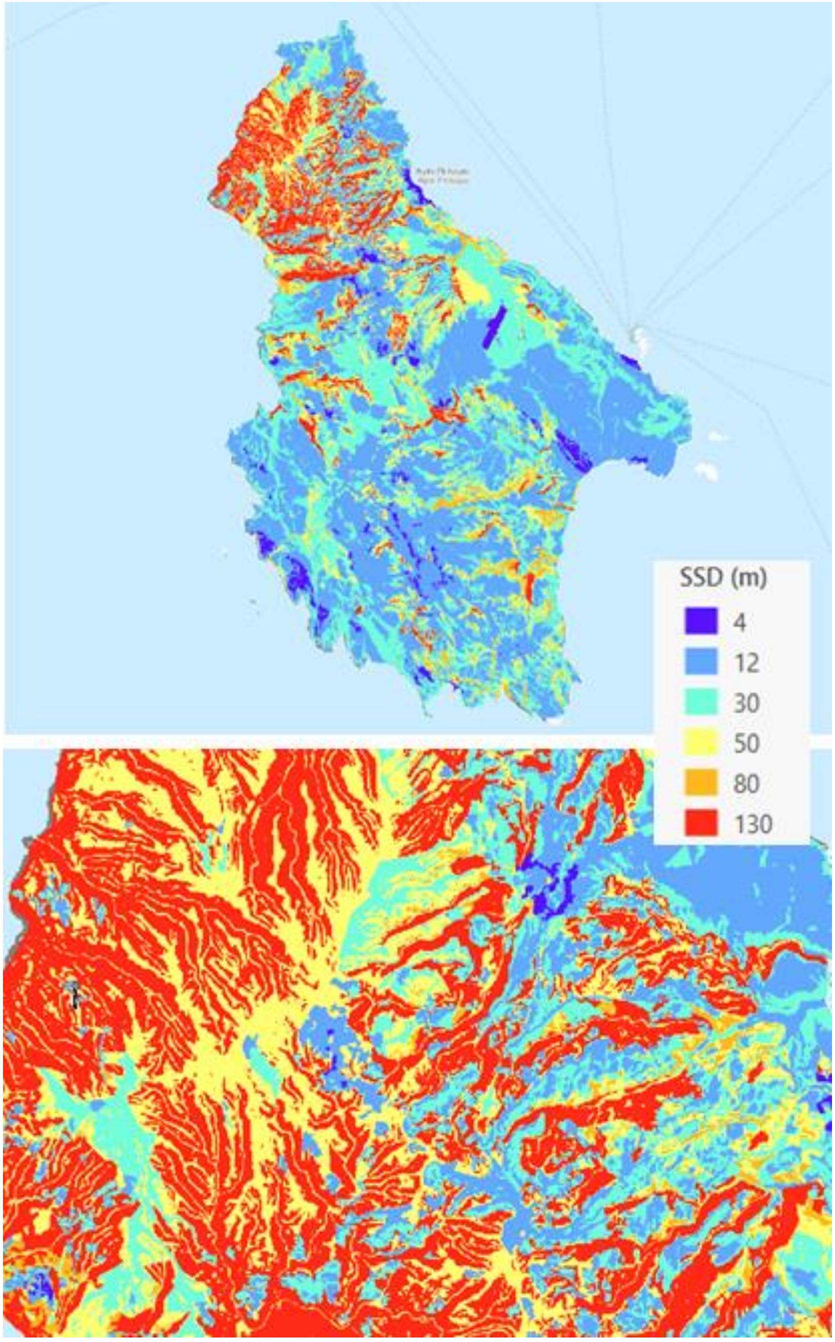

Figure 53. SSD mapping based on the existing fuels (whole area and detail of the northern part of the island)

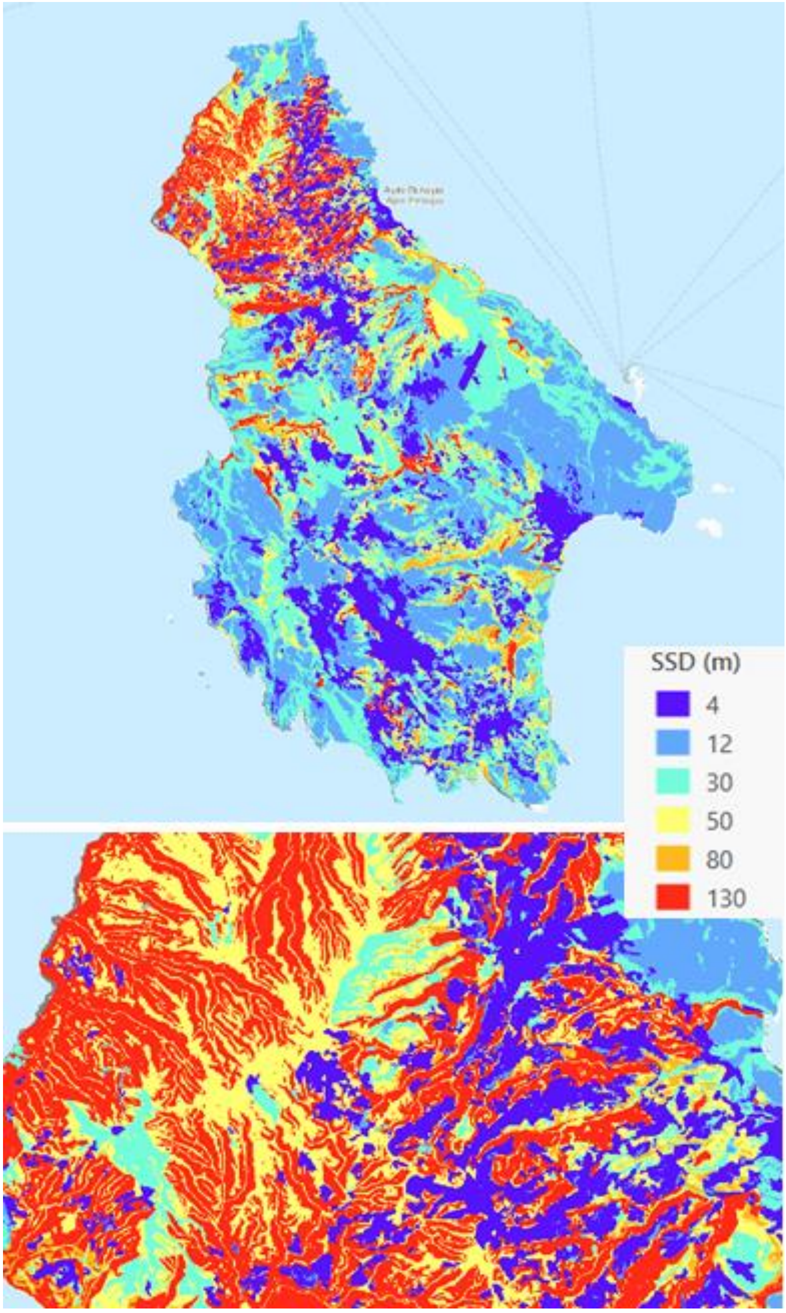

Figure 54. SSD mapping based on ‘Scenario 2’ fuel treatment (whole area and detail of the northern part of the island)

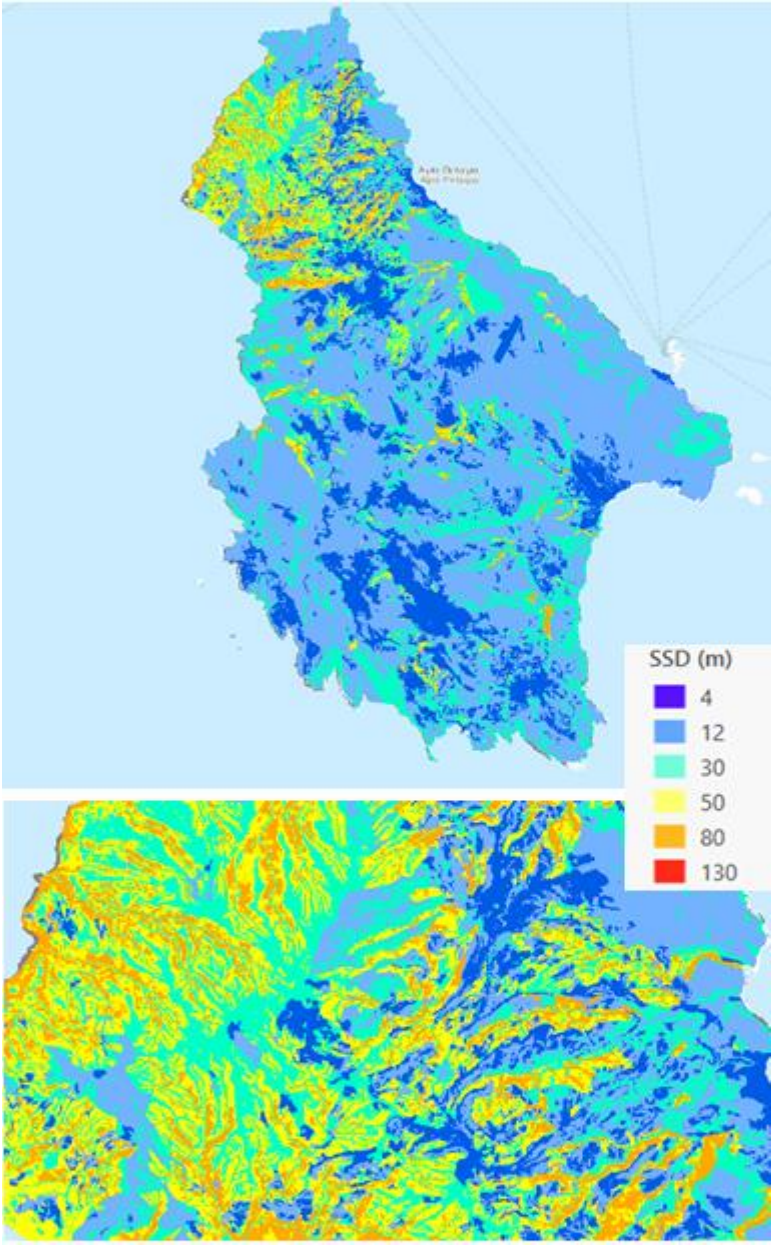

Figure 55. SSD mapping based on ‘Scenario 3’ fuel treatment (whole area and detail of the northern part of the island).

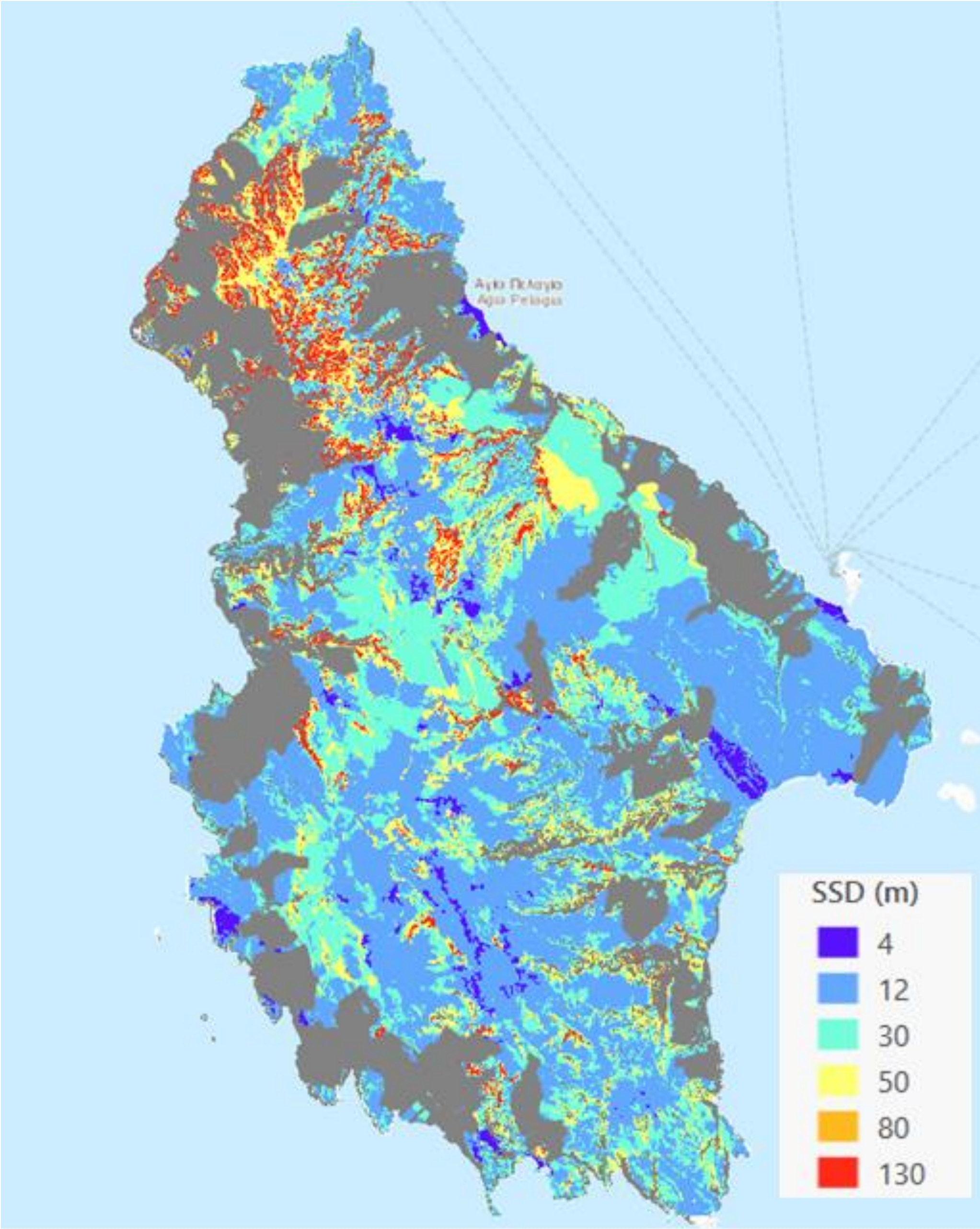

Figure 56. Map of SSD based on existing fuels and areas where fuel treatments are not feasible according to rules #1 & 2 (shaded in grey color).

Figure 56 presents the culmination of the whole procedure for determining where fuel treatments can be positioned effectively and efficiently for controlling forest fires on the island. It shows in grey color the areas where according to rules #1 and 2 fuel treatments are not feasible. Taking as a criterion that firefighters can reach the flames with their hoses roughly at a distance of 12 m and using this as a criterion, 12 m wide fuel treatment can be applied effectively in the non-grey areas where SSD is in class 12. Areas with SSD in the 4 m class are smaller but they could also be used very efficiently. Obviously, these rules do not preclude fuel treatments to locally protect high value assets. In that case, the SSD estimates for the fuel treatment scenarios can guide the required width of fuel treatment.

An example of application of the methodology in the Monchique Area in Portugal

In the following figures (57-61), the application of the methods developed in Kythera in the Monchique Area in Portugal. It is a demonstration of the possibility of the proposed approach to be applied in different places, becoming a valuable decision support tool.

Application of Rule #1

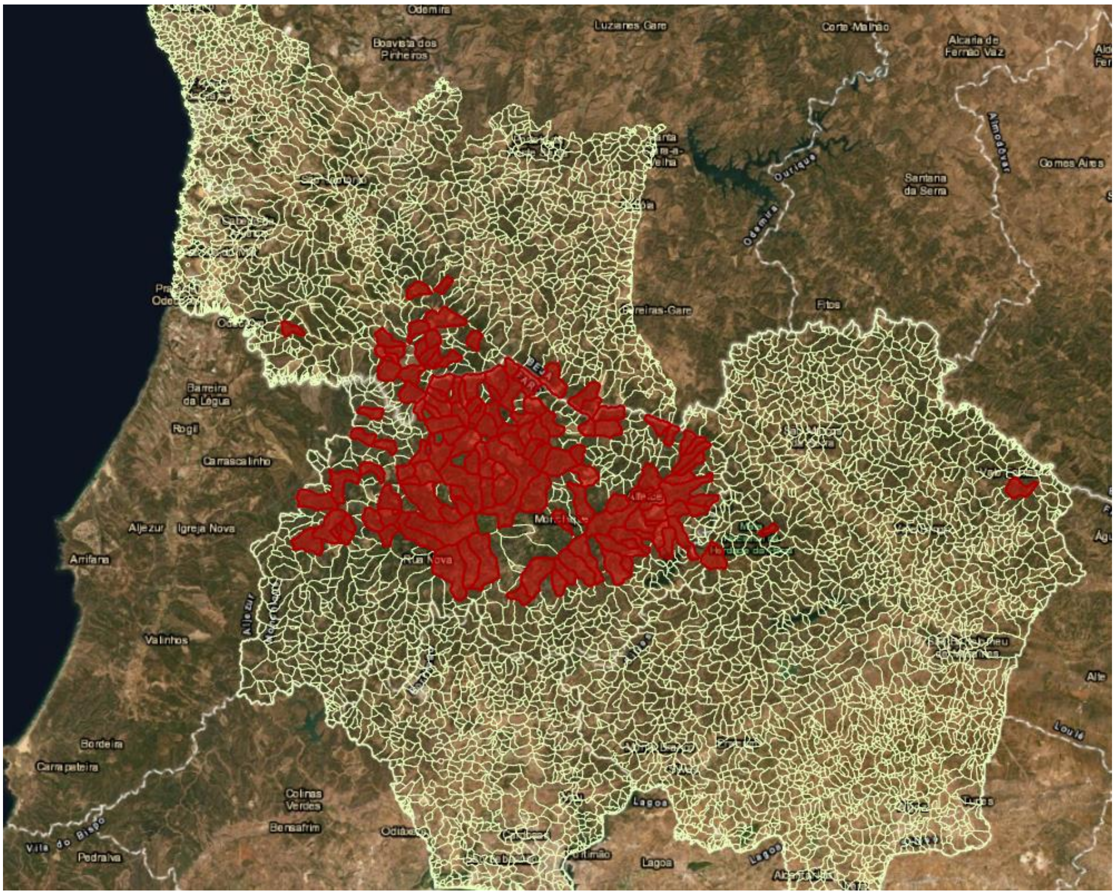

Figure 57: Application of rule # 1 on basins polygons for Monchique Area in Portugal. The areas where fuel treatment is considered as not-feasible are presented in red colour.

Application of Rule #2

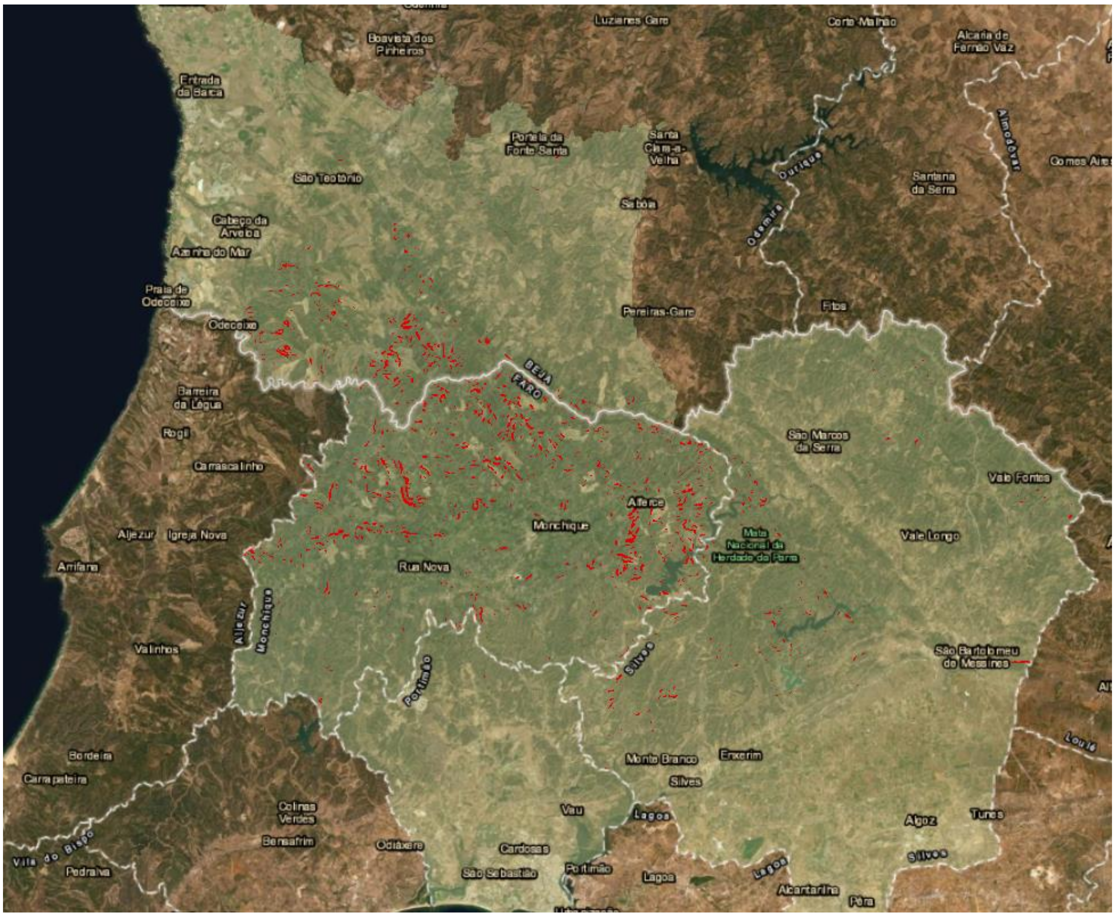

Figure 58: Application of rule # 2 on the slope% map of Monchique Area in Portugal. The areas where fuel treatment is considered as not-feasible are presented in red colour.

Application of combination of rules #1 & 2 for mapping areas where fuel treatment is non-feasible

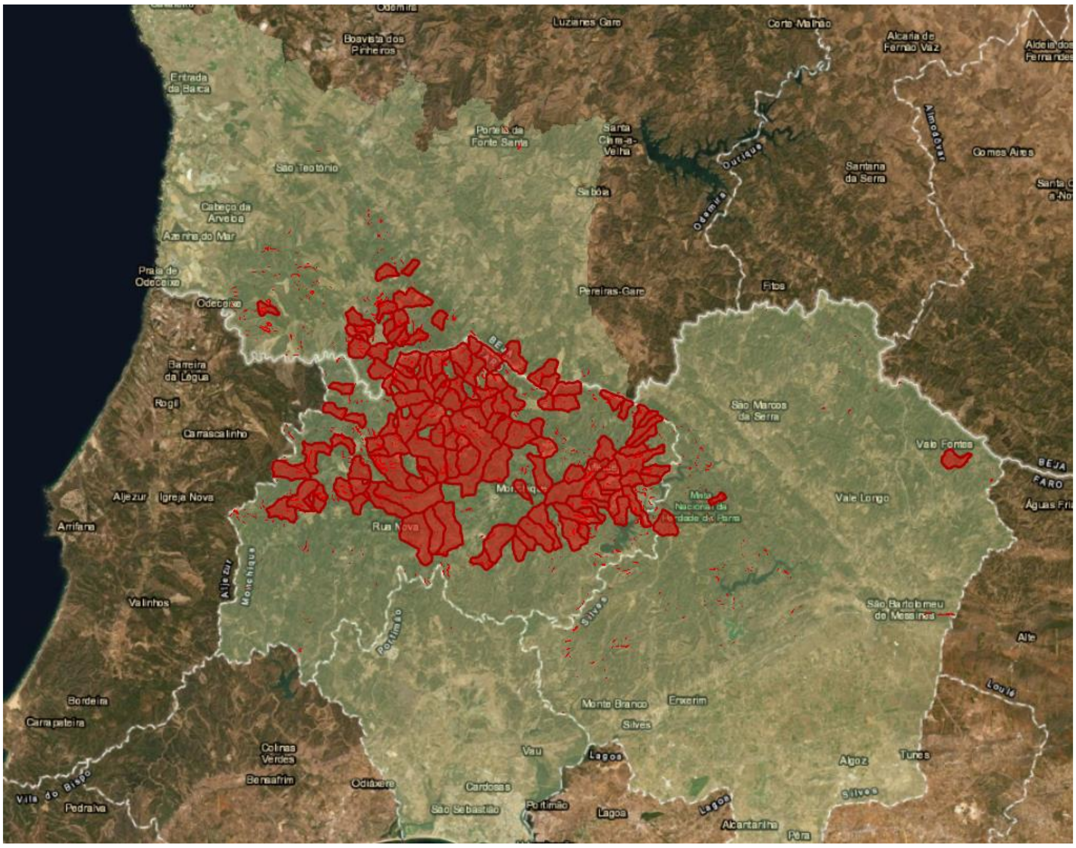

Figure 59: Application of rules # 1 & 2 on Monchique Area in Portugal. The areas where fuel treatment is considered as not-feasible are presented in red colour.

SSD Calculation (based on strong wind scenario classes for the estimation of Delta factor)

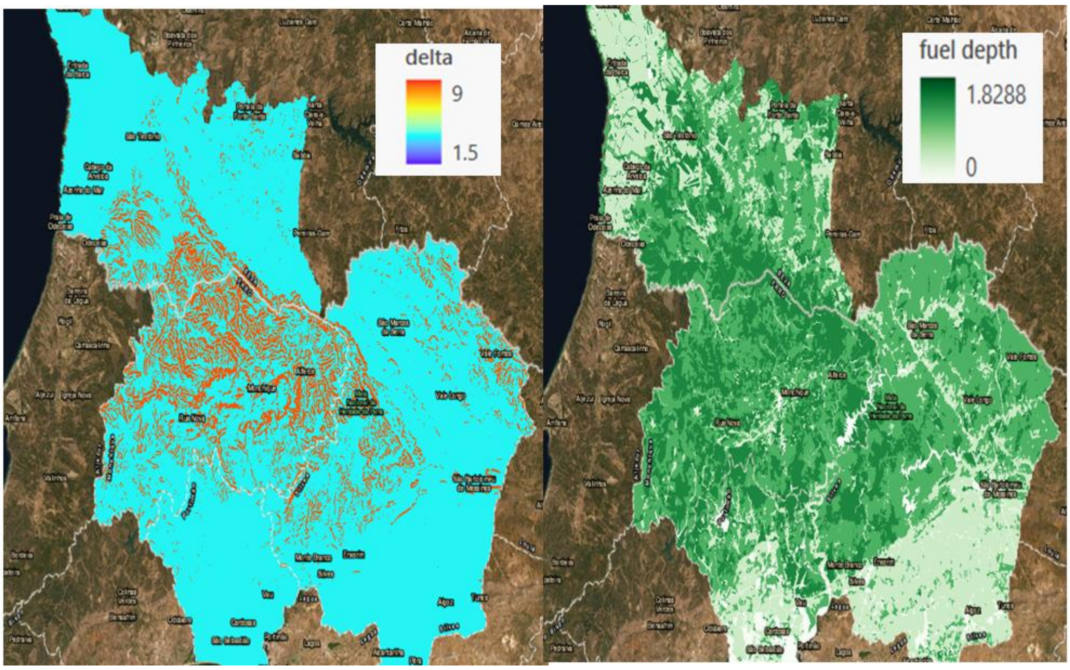

Figure 60: Delta factor for strong wind scenario and fuel depth of NFFL fuel models for Monchique Area in Portugal

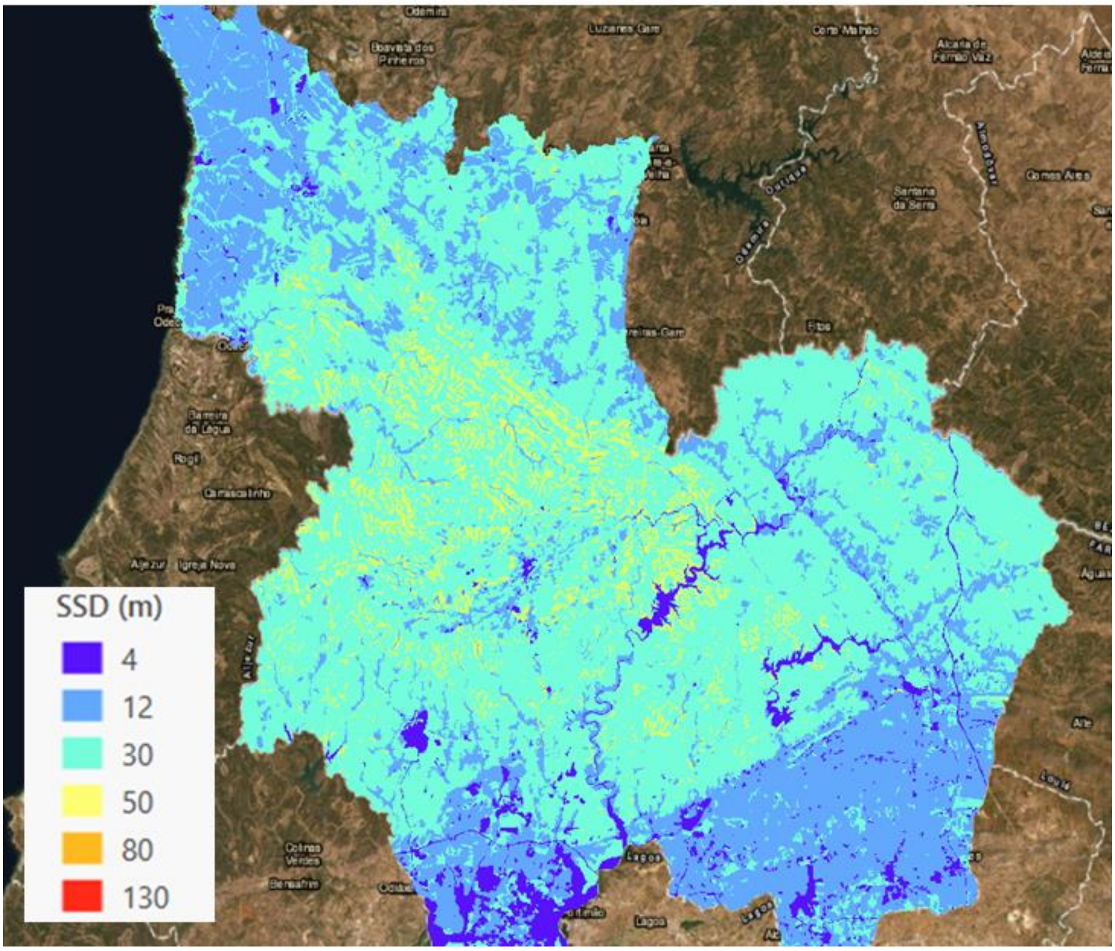

Figure 61: SSD mapping for Monchique Area in Portugal

Conclusions

The work presented in Part 3 of the deliverable presents new ideas, in the form of rules, that can support decisions on fuel treatment. Applied across large areas, this methodology helps to identify in which areas fuel treatment is not feasible and which areas are preferable. Application of SSD contributes to that greatly while it is also a very valuable tool for planning of firefighting.

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