TECHNICAL UNIVERSITY IN ZVOLEN
Faculty of Wood Sciences and Technology

MAJLINGOVÁ, Andrea
KAČÍKOVÁ, Danica
KROPIL, Rudolf
HANCKO, Dušan

WILDLAND FIRE PATTERNS AND FIRE-FIGHTING TACTICS IN CENTRAL EUROPEAN COUNTRIES

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Authors:

doc. Ing. Andrea Majlingová, PhD., MSc. — Department of Fire Protection, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovak Republic

prof. RNDr. Danica Kačíková, MSc., PhD. — Department of Fire Protection, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovak Republic

Dr.h.c. prof. Ing. Rudolf Kropil, PhD. — Department of Applied Zoology and Wildlife Management, Faculty of Forestry, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovak Republic

Col. Ing. Dušan Hancko — Regional Directorate of Fire and Rescue Service, Trieda SNP 75, 974 01 Banska Bystrica, Slovak Republic

Reviewers:

Dr. hab. Ágoston Restás, PhD. et PhD. — University of Public Service, Institute of Disaster Management, Budapest, Hungary

prof. Ing. Jaroslav Holuša, Ph.D. — Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Czech Republic

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FOREWORD

Wildland fires are an essential pre-requisite for many ecosystems; however, frequent, and large-scale fires are a significant disturbance agent in many forested landscapes. Frequent and large-scale fires have negative impacts on air and water quality, threaten biodiversity, increase the risks of soil erosion, and spoil the aesthetics of a landscape. Forest fires also represent a threat to climate change mitigation, as they release large amounts of greenhouse gases. Furthermore, forest fires can cause large economic damage and the loss of human lives if they affect populated areas. Nevertheless, forest fires play an essential role in the dynamics of many ecosystems. They are an essential element of forest renewal, they help control insect and disease damage, and they reduce the build-up of fuel and thus the intensity of future fires. [1]

Climate change is expected to have a strong impact on forest fire risk in Europe, as recognised by the EU strategy on adaptation to climate change [2].

Fire risk depends on many factors such as climatic conditions (e.g., humidity, temperature, and wind), vegetation (e.g., fuel load and condition), topography, forest management practices and socio-economic context. According to the European Environment Agency [3] most wildland fires in Europe are ignited by humans, either accidentally or intentionally. However, climatic factors and the availability of fuel determine the conditions under which fires occur and spread, once ignited. The extreme fire episodes and devastating fire seasons of recent years in Europe were, in most cases, driven by severe fire weather conditions. Thus, climate change is expected to have a strong impact on forest fire regimes in Europe.

Climate change has already increased forest fire risk across Europe. Even so, the burnt area of the Mediterranean region has decreased slightly since 1980, indicating that fire control efforts have been effective). However, in recent years, forest fires coinciding with record droughts and heatwaves have affected regions in central and northern Europe not typically prone to fires. An expansion of fire-prone areas and longer fire seasons are projected in most European regions, for high emissions scenarios, so additional adaptation measures are needed. [4]

Many of the recent extreme fire episodes and devastating fire seasons in Europe were driven by severe weather conditions, with record droughts and heatwaves occurring in the spring and summer of 2017 and 2018 for instance. The new EU climate adaptation strategy aims to build a climate-resilient Europe by mitigating the negative consequences of climate change, such as the impacts of forest fires, by 2050.

Wildland fires are also becoming an increasing public health issue. Smoke from wildland fires is currently estimated to be the direct cause of death of 339,000 people annually [5], and there is a well-documented increase in hospital admissions due to smoke-enhanced cardiovascular and respiratory conditions, amongst others [6].

Wildland fires are now an EU-wide concern. In the Mediterranean region, fire is becoming deadlier, while in Central and Northern Europe, unusually dry summers have recently led to forest fires in countries which have historically seen very few. Wildland and mostly the forest fires not only represent a danger for human beings and rural areas, environment, and biodiversity, but also a serious threat to the climate change mitigation potential of forests.

This monograph presents relevant knowledge, completed research results, derived new knowledge and information, concerning not only the factors influencing the behaviour of wildland fires but, especially, the management and tactics applied to fight them.

In addition to the knowledge on fire management and tactics applied in the conditions of the Slovak Republic, it also presents the procedures used abroad, in another Central European countries like Czech Republic, Hungary, and Poland. Although some of them cannot be applied in the conditions of the Slovak Republic due to the current legal situation. For this reason, they should be seen as inspiration for the innovation of existing methodological and tactical procedures in the future.

This monograph is a response to the demand of the practice to summarize and synthesize the existing knowledge in the field of tactics of firefighting in the natural environment not only from the domestic environment, but also from abroad and to convey them to a wide range of professionals and the public.

CONTENT

1. INTRODUCTION TO WILDLAND FIRES

Wildland fires occur in open land covered with grass, brush, or timber are often termed wildland fires. Although they are often terrifying in their destructive power and intimidating in their coverage, they begin, like almost every other fire, with suitable fuel and a small, localized source of ignition.

Uncontrolled wildland fires of forest vegetation, grassland and agricultural cultures are a global phenomenon [7,8], which can be related to the expected climatic and meteorological conditions. They represent a complex phenomenon involving many processes (e.g., the process of burning, releasing, and transferring energy) that occur in a wide range of spatial and temporal scales [9,10].

The characteristics of the fuel particles and the fuel structure itself partly determine the amount of energy that will be released in the combustion process and describe the way in which the burning and heat transfer process itself takes place [7,11]. Knowledge of the relevant characteristics of fuel occurring in the wildland affecting fire behaviour is essential for informing and supporting the decision -making of relevant persons, also as an input for a wide range of applications designed to control fires as well as the development of preventive measures aimed at mitigating the occurrence of large fires [12,13]. These applications may be aimed at determining fire hazards and issuing fire warnings [14-16], assessment of the risks of ignition in the wildland [17,18], modelling the behaviour of fires occurring in different types of vegetation (e.g. grasslands, forests, shrubs), planning of fire tactics procedures, calculation of emissions of fire-induced combustion products [7] and anticipation of the impacts of fire in several aspects [19,20].

1.1 Wildland fires classification

According to the landscape type, the wildland fires can be classified into the categories: forest fire; grassland, and other grassland (eels, gardens, etc.) fire; and agricultural areas and crops fires.

Abroad, these are supplemented by the category of peat fires, fires arising within the wildland-urban interface area, bushfires, etc.

These categories of fires differ, among other characteristics, by the type of fuel consumed during a fire which results in differences also in the rate of fire spread.

1.1.1 Forest fires

Forest fire (Figure 1) can be considered as part of the forest ecosystem. In historical times, under the influence of lightning or spontaneous combustion, fires have been set which have had a destructive effect on the forest. However, it cannot generally be said that forest fire is only a negative factor for the forest ecosystem. In some areas (e.g., North America), it is forest fires that have given rise to communities that use fire competitively to their advantage and are totally dependent on it. Finally, man is also indebted to forest fires for fire, which has facilitated much of his evolution.

Figure 1 Forest fire in locality Horny Tisovnik (Slovakia) in March 2022
(Source: District Directorate of Fire and Rescue Service in Zvolen, 2022)

Today, however, we look at forest fires a little differently. In a landscape that has been altered by anthropogenic activity and is largely used for the needs of society, forest fires pose a great risk of causing enormous damage to humans. The origin of forest fires has also changed. Today, the most common cause of forest fires is man himself. Fire is mainly caused by inattention to the use of open fire source (burning dry grass, hiking, camping, smoking).

Based on these facts, forest fires are nowadays considered to be anthropogenic or of natural origin in Central European conditions.

A forest fire is a sudden, partially, or completely uncontrolled, temporally, and spatially limited emergency that has an adverse impact on all social functions of the forest.

In forestry terms, a forest fire is defined as an extremely damaging agent of anthropogenic or natural origin that damages all components of forest biocenoses, both the habitat and the plant and animal component.

In Slovakia, Act No. 314/2001 Coll. on Fire Protection [21] and in the Czech Republic, Decree No. 246/2001 Coll. on Fire Prevention [22], defines fire as "*any unwanted combustion that kills or injures persons or animals, damages material values or the environment, and unwanted combustion that endangers persons, animals, material values or the environment*".

From the point of view of combustion dynamics, it is a complex of physico-chemical phenomena based on non-stationary combustion processes (varying in space and time) of combustion, gas exchange and heat transfer.

Forest fire can also be characterised as the combustion of the entire suite of organic materials that make up a forest stand. This is due to the inhomogeneous composition of the forest as such, which is divided into several levels (stages) by horizontal division.

To understand the forest fire, it is necessary to characterize the basic thermal interfaces during the burning of the individual parts and the influence of temperatures on the living organic matter, which in this case is a living tree, shrub, grass, but also a forest duff.

1.1.2 Grassland fires

Grassland ecosystems occur in areas of the world that have an annual precipitation between 150 and 1,200 mm and mean annual temperature between 0 and 25 °C [23]. Along precipitation gradients grasslands are located between forests and deserts.

Grasslands are not entirely natural because they have formed and developed under natural and anthropogenic pressures. Their importance now is to the variety of ecosystem services that they provide: livestock grazing areas, water catchments, biodiversity reserves, tourism sites, recreation areas, religious sites, wild food sources, and natural medicine sources. An important function of grasslands is their sequestration and storage of carbon (C). Mollisol soils of grasslands have deep organic matter horizons that make this vegetation type almost as important as forests for C fixation and storage.

Fire has been and continues to be an important disturbance in grassland evolution and management (Figure 2). Natural wildland fires have been a component of grasslands for over 300 million years and were important in creating and maintaining most of these ecosystems. Humans ignited fires over many millennia to improve habitat for animals and livestock. Prescribed fire practiced by humans is a component of modern grassland management. The incidence of wildfires in grasslands continues to grow as an issue as droughts persist in semi-arid regions.

Figure 2 Grassland fire in locality Klokoc (Slovakia) in March 2022
(Source: District Directorate of Fire and Rescue Service in Zvolen, 2022)

Fire can produce a wide range of changes in landscape appearance but the degree of change and duration in grasslands is usually much less than in forested ecosystems [24]. Grass recovery is usually so rapid that the occurrence of fire is masked within 1 year by rapid regrowth. The fire-induced changes coupled with burn intensities generate varied responses in the water, soil, flowers and fauna of burned ecosystems due to the co-variation between fire severity and ecosystem resonance.

1.1.3 Agricultural areas and crops fires

Wildland fires can affect agriculture (Figure 3) by damaging crops, orchards, livestock, farm infrastructure or affecting soil composition. Wildfires typically directly impact agricultural production and yield. While irrigated crops can be viewed as a "buffer" during a wildfire, wind-driven wildfires can easily burn well-irrigated crops. The heat from wind-driven fires can burn into multiple outer rows of crops, causing singeing, burning, and even killing crops. Heat radiating directly from flames can damage sprinklers, fences, and other agricultural infrastructure. Crops that are harvested when at a low moisture content, such as wheat and other grasses, can be especially susceptible to wildfires and many times fuel wildfires to a raging burn.

Figure 3 Agricultural area fire (Source: [25])

Also, farmers in many parts of the world set fire to cultivated fields to clear stubble, weeds, and waste before sowing a new crop. While this practice may be fast and economical, it is highly unsustainable, as it produces large amounts of the particle pollutant black carbon and reduces the fertility of soil. [26]

Responsible for more than a third of all black carbon emissions, open burning is the single largest source of black carbon, a short-lived climate pollutant that contributes to air pollution, climate change, and increased melting in the cryosphere (regions of snow and ice). Open burning also represents one of the largest causes of air pollution-related illnesses and deaths after cookstoves. [26]

Over time, the repeated practice of open burning becomes costly to farmers. Successive fires destroy the organic matter that makes soil fertile, causing crop yields to decrease over time and increasing the need for costly fertilizers. Smoke and spreading flames also pose a risk to neighbouring communities, buildings, and fields. [26]

1.1.4 Classification of wildland fires according to the location of occurrence

Ground fires

Ground fires (sometimes called underground or subsurface fires) occur in deep accumulations of humus, peat and similar dead vegetation that become dry enough to burn. They can also occur outside of these organic and inorganic substrates, so that the roots of healthy trees not covered by soil or forest duff can burn. Subsurface fire spreads slowly beneath the surface through glowing channels. An example of an underground fire and how it compares to other fire types is shown in Figure 4.

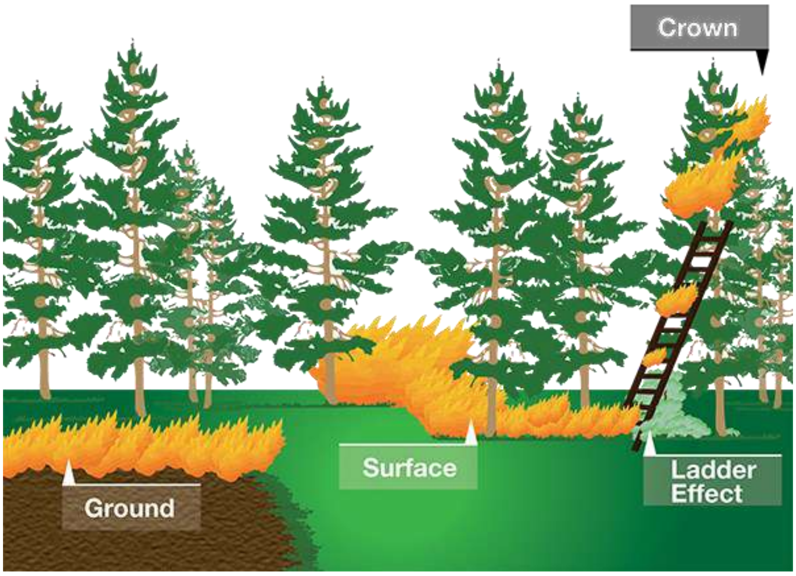

Figure 4 Types of Forest Fire (Source: [27])

These fires move very slowly, but can become difficult to fully put out, or suppress. The rate of spread is small, not exceeding 2 to 5 m per day, and the fire manifests itself in tiny wisps of smoke.

Underground fires are dangerous. They occur in countries where coal seams, peat, etc. are close to the surface. They are dangerous fires that can become a ground fire.

Depending on the depth at which the underground fire is active, fires are divided into: light: up to 250 mm deep, medium: 250 to 500 mm deep, severe: deeper than 500 mm.

Surface fires

Surface fires (Figure 4) burn only surface litter and duff. These are the easiest fires to put out and cause the least damage to the forest. They occur most frequently, and their source of fire is dry grass or fallen leaves from trees, dry needles, low trees, snags, bark waste, lying sticks, lying logs and dry wood - ground cover.

Ground fires are divided into [28]: lethal, persistent.

Lethal ground fires occur mainly in spring and summer and spread at a rate of less than 0.5 $m \cdot min^{-1}$.

According to the rate of spread, fires are classified as: light (up to 1 $m \cdot min^{-1}$), moderate (from 1 to 3 $m \cdot min^{-1}$, and severe (more than 3 $m \cdot min^{-1}$).

They are also distinguished by the flame height: light (up to 0.5 m), medium (from 0.5 - 1.5 m), severe (over 1.5 m).

Crown fires

Crown fires (Figure 4) burn trees up their full length to the top. These are the most intense and dangerous wildland fires. Their danger lies mainly in the high speed of fire spread; the difficulty of control due to the turbulence generated.

They start in neglected stands with tall weeds and grasses and deep-trunked trees. They are mostly preceded by ground fires. The crown fire front precedes the ground fire front.

Crown fires are divided into [28]: lethal overstory, perennial standing.

In a lethal fire, the fire is moving through the tree canopy in a wave-like motion like water. In strong airflow, both trunks and roots of trees are usually affected by this fire. Trees are also uprooted. In a persistent standing fire, the fire forms a straight wall, and the fire is slow moving.

Crown fires are classified according to the rate of spread of the fire: light (3 $m \cdot min^{-1}$), medium (from 3 - 100 $m \cdot min^{-1}$) and severe (more than 100 $m \cdot min^{-1}$).

For all these types of fires, prevention, cultivation, and the quality of maintenance of forest stands are most important. Forest fires depend on the type of soil substrate, terrain configuration, forest type, flammability of the material, and weather. The accessibility of the terrain is also decisive for extinguishing, given the existence of a sufficiently dense network of roads.

However, if a fire does occur, monitoring, the organisation of the firefighting and the availability of effective technical means are crucial, but the rapid transport and conveyance of firefighting equipment to the fire is also an important factor.

In Slovakia, there are distinguished other two types of forest fires: the hollow tree fire and disaster disturbed area fire.

Hollow tree fires

Such fires are rare. Unlike other types of fires, fires involve individual trees, so it is not a problem to extinguish them from the firefighting point of view, especially if they are solitary trees. If it is in a forest, it may be the cause of another type of fire.

The cause of a fire can be human activity or a lightning strike and, in the case of a wandering tree, spontaneous combustion.

An example of a hollow tree fire is shown in Figure 5.

Figure 5 Hollow tree fire
(Source: District Directorate of Fire and Rescue Service in Zvolen, 2022)

Disaster disturbed area fires

In the case of a disaster disturbed area fire, the area of the potential fire area is not differentiated in height, but is formed by breaks, uproots, standing trees, remains of decomposing trees (dead wood), herbaceous cover, and a ridge. The distribution of the wood mass is often uneven, and the wood is piled up in layers of several km. After the processing of calamity timber, a large amount of logging waste remains, which has a high-risk potential for fire start-up and spread. Burning after the fire is ignited can be widespread, long lasting in time (even several days), throughout the whole area of the fire, not just at the head of the fire (the fire pit principle). The area of the calamity area, compared to other types of fire, is difficult to access due to the temporary disabling of the forest road network; in the case of extinguishing, due to the impassability of the terrain, it is not possible to use the basic methods of forest fire suppression (tactics), which has an impact on the spread of the forest fire [29].

An example of a disaster disturbed area fire is shown in Figure 6.

Figure 6 Disaster disturbed area fire in High Tatras Mts territory in November 2005
(Source: District Directorate of Fire and Rescue Service in Poprad, 2005)

1.2 Wildland fire parameters

Characteristic (anatomical) parts of a wildland fire include (Figure 7): spot fire, head, tail, flanks, fingers, and island, pocket.

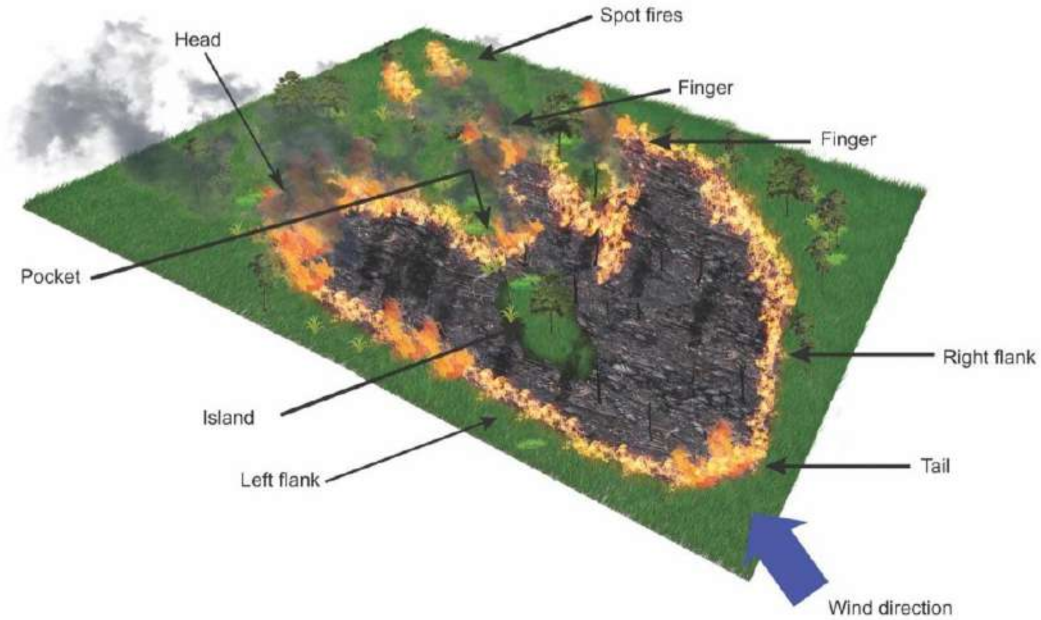

Figure 7 Characteristic parts of a fire area (Source: [30])

The point of origin (or origin of a fire) is the place where the fire originated or the point from which the fire started to spread. It can be located near urban areas, roads, but also in very remote and inaccessible areas in the mountains.

The fire head (or front) is the part of the fire that is usually on the opposite side of the direction from which the wind is blowing. It spreads fastest in the direction of the wind, burns intensely and usually causes the most damage. Usually, the key to fighting a fire is to control the front and prevent a new fire front being formed.

The tail (or base, heel, rear) is on the opposite side to the fire front. The tail of the fire usually burns downhill or upwind. It usually burns slower, quieter, and easier to control than the fire head.

The flanks are the sides of a wildland fire, roughly parallel to the main direction of fire spread. The right and left wings separate the head from the tail of the fire. Wind deflection can cause a flank to become a fire head and vice versa, in which case the opposite flank becomes the tail.

Fire fingers are long narrow fire strips that spread out from the main fire parallel to the wind direction. In an uncontrolled wildland fire in windy weather, fire fingers can create new fire forms.

Islands are unburned areas that are inside the fire area. They need to be kept under control because they contain potentially flammable substances that could start burning again and spread the fire.

Pocket (or bay) is a marked indentation in the fire perimeter, usually located between two fingers.

The perimeter is the outer boundary or distance around the outer zone of burning and preparation. It is also called the edge of the fire. The perimeter enlarges gradually. This condition usually lasts until firefighting begins.

1.3 Fuel types relevant to the wildland fire types

Fuel in this case is perceived as a general term used to describe the characteristics of vegetation, which relate mainly to fire behaviour and are essential for gaining control of the fire [31].

A fuel complex is a set of individual layers of fuel in space, e.g., tree canopies, undergrowth including shrubs and fuel contained in the ground layer [32]. These layers are characterized by certain homogeneous properties. They are defined mainly by the specific characteristics of their particles. The different layers differ in vertical distance from the ground and the orientation of the fuel. Understanding the impact of this multi-layered fuel arrangement on fire behaviour requires the study of the physical properties defining each fuel layer, its vertical and horizontal continuity. [33]

The fuel that occurs in the wildland is stored in three stacked layers: underground fuel, surface fuel and crown fuel. Depending on which of the layers or components of the forest burns in the fire, the fire is classified as underground, surface, or crown fire. These are generally three types of fire that can be encounter in the wildland.

Underground fuel consists mainly of decomposing vegetation - humus and soil wood, which form decomposing dead roots and stumps. This combustible material is located between the litter and the soil itself, which no longer contains sufficient organic material. This topmost layer of soil is also called raw overlying humus (duff). If a fire also spreads with this layer of fuel, it contributes to its more difficult manageability. Roots may be damaged, and trees die, even if the area has not been hit by a crown fire [34].

Surface fuel represents all living and dead vegetation above the raw overlying humus, starting with the tree litter and ending with the canopies of small trees that do not interfere with the crown closure. Surface fuel is much more diverse than underground and crown fuel. It includes fallen leaves and needles, lichens, and mosses, fallen woody material as fallen trunks, branches and twigs, live and dead parts of herbs and grasses, shrubs, and small trees. Also, a surface/ground fire spreads primarily through fine surface fuel (grass, needles, and small wood material smaller than 2.5 cm in diameter). A greater amount of fuel contributes to greater intensity and length of fire burning. The intensity of a surface fire is the most important indicator of the probability of whether a crown fire will also occur.

Crown fuel is made up of large trees and shrubs that reach the height of the treetop [34]. In a crown fire, the main source of energy are leaves, twigs, and small branches. In a very intense crown fire, a large part of the woody biomass of large branches burns. For the emergence of a crown fire, the intensity of surface fire, the height of the deposit of tree crowns and the humidity of leaves and branches are decisive. Crown biomass density [35] is important for the spread of crown fire. Usually, a fire arises in a layer of surface fuel [34] only subsequently can spread, and only if it is supported by enough fuel and favourable weather [36]. The duration and intensity of the ground fire then decides whether a crown fire will also occur. The fire can also spread to underground fuel, which is located directly in the soil, thus passing into an underground fire [34].

Due to its complexity and the key role of surface fuel which plays in a fire, it is of the utmost importance in research [34] and great emphasis is also placed on the study of its fuel characteristics [37]. This type of fuel is present in all identified categories of fires occurring in the natural environment.

As it is well known, the fire environment defines the three key elements influencing fire initiation, propagation, and effects: weather, topography, and fuel [11]. Fire behaviour is highly dependent on fuel (vegetation) characteristics, which is the only variable that can be managed to reduce fire propagation. In addition, fuel properties play a critical role in fire ignition and spread [38], as well as in the smouldering-flaming ratio of fire behaviour [39], which in turn affects fire emissions.

Vegetation types with similar fire behaviour are grouped into fuel types and models [32]. The former indicates the classification of vegetation into categories with similar characteristics from a fire behaviour perspective. The latter refer to the specific parameters required to model their fire behaviour (height, load, particle size, etcetera). Fuel types can refer to surface or canopy fuels. Forest understory and low vegetation formations are surface fuels, while elevated fuels, normally forest crowns, represent canopy fuels. Fire usually starts in surface fuels but may transfer to canopy fuels, causing crown fires, which are more dangerous than surface fires as they release more energy and propagate in larger fronts, being harder to control [40].

Therefore, fuel type mapping is an essential tool in fire risk prevention, planning, and real-time fire management across multiple spatial scales [41] because it allows to spatially describe a key factor over which fire managers have control on [42]. Fire scientists require accurate and updated fuel maps to support fire strategic planning within a comprehensive fire danger assessment system. However, fuel mapping is challenging due to the high temporal and spatial variability of fuels [41].

The starting point of fuel type mapping is to define the fuel classification system to be used, which includes the fuel types and models (parameters). Many fuel classification systems have been developed [43]. All phases in their development process have heavily involved expert knowledge, from suppression specialists to researchers [41], because of the high diversity of fuels, their temporal and spatial variability, and the lack of comprehensive fuel data across regions [42].

The most used fuel classification systems are the Northern Forest Fire Laboratory (NFFL) system [44], the Fire Behaviour Fuel Models (FBFM) [45], the Fuel Characteristic Classification System (FCCS)

[46], all created for the United States; the Canadian Fire Behaviour Prediction System [47], and the Mediterranean-European Prometheus system [43,48]. Many of them include default parameters and only refer to surface fuels, limiting their capability to prevent and manage crown fires (the most severe). Although they have been developed for specific regions and conditions, they have been widely used to map fuel types in other regions [49-52].

Fuel types have been usually mapped through fieldwork, aerial photointerpretation, ecological modelling, existing datasets and/or remote sensing [43]. Remote sensing methods previously applied to fuel type mapping include a wide range of techniques and input data, from medium [50-53] to high spatial resolutions [54,55]. Both passive [52,53] and active [56,57] sensors have been used, as well as a combination of sensors [49-51,58].

Fuel maps exist for continental scales, such as South America [59] and Africa [60]; and global scales [61]. However, in Europe, fuel mapping has been mostly developed for local and regional scales [49,62,63].

The only European-level fuel cartography is the EFFIS fuel map [64], based on land cover and vegetation maps and using the NFFL system. Other works have mapped FBFM fuel models [45] for the European subcontinental scale, such as the Iberian Peninsula [52].

The lack of an adapted-to-Europe fuel classification strategy is limiting since fuel models are site-specific and should be applied to the region for which they were developed to obtain the most realistic fuel mapping and modelling [43]. In this context, the ArcFuel project [65] aimed in 2011-2013 to conceive a methodology to enable consistent fuel mapping production over Europe to support fire and emissions simulation scenarios, and the design of effective fire prevention and mitigation strategies. For this, it constructed a hierarchical vegetation fuel classification system adapted to Europe [66]. Nevertheless, fuel cartography was only created for southern European national (Portugal and Greece), and regional (Spain and Italy) scales and no European fuel map was generated [65].

For forest fire modelling in Slovakia, a more detailed classification of forest surface fuels has already been developed in the past using GIS tools. The forest area of Slovakia was classified (Figure 8) into 10 fuel models [67]: mosses and lichens (FM 21), grasses up to 30 cm (FM 22), grasses and herbs up to 30 cm (FM 23), herbs, grasses, mosses up to 30 cm (FM 24), herbs up to 15 cm (FM 25), herbs up to 30 cm (FM 26), tall herbs up to 100 cm (FM 27), without dominants of herbaceous synusia (cover) - pauper (FM 28), grasses, herbs up to 30 cm of drier SLT D series (FM 29), grasses, herbs up to 30 cm of wetter SLT D series (FM 30)

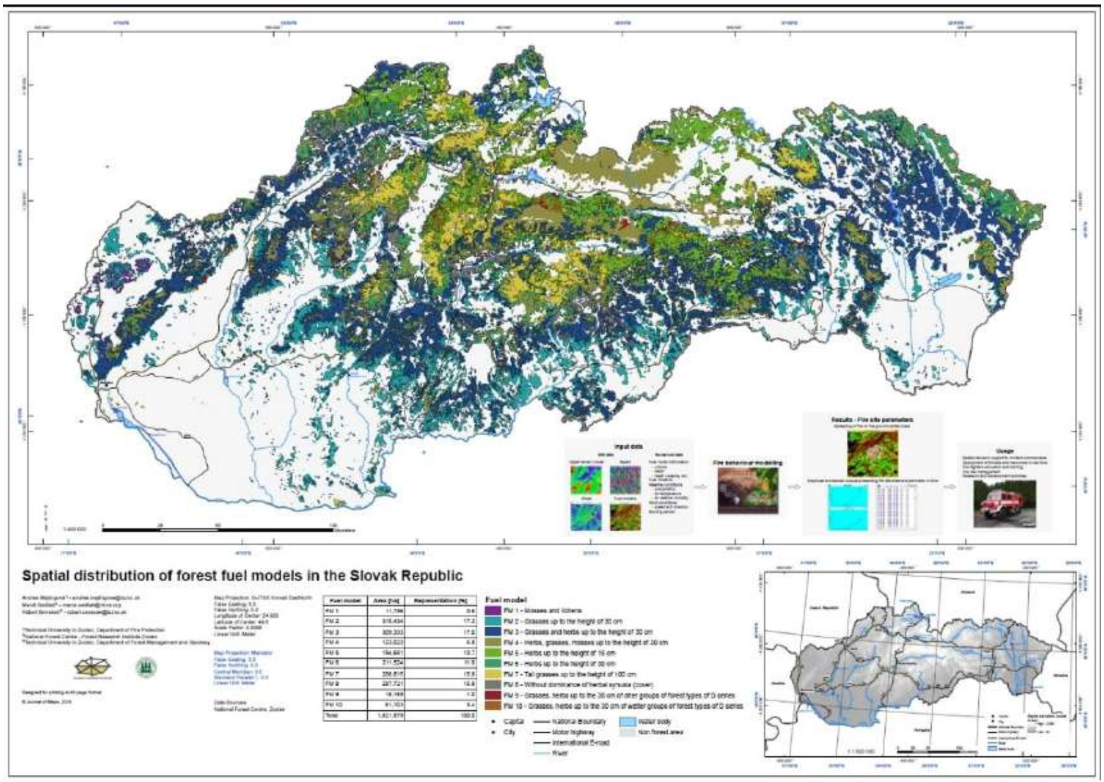

Figure 8 Spatial distribution of surface fuel models in Slovakia (Source: [67]

Due to the high ecological biodiversity of the area, the approach through the geobiocenological classification of forests in Slovakia was chosen as appropriate. The basic typological unit is the forest type, which is basically a type of permanent ecological conditions. It is a unit with a narrow ecological range for tree growth, production, and regeneration and, therefore, for the desirable species and spatial composition of stands. Permanent production conditions exist within a forest type. The superordinate unit of the forest type is the forest type group (acronym SLT), which is a set of forest types grouped together based on their ecological similarity, and, in managed forests, based on the similarity of undergrowth synthesis. It is a unit of the natural distribution of tree species within their range in the territory and, by comparing them with their present state, indicates their past transformations.

The group of forest types (SLT) was chosen as the basis for the classification of fuel models for the following reasons: the smaller number of SLT compared to the number of forest types simplifies the subsequent quantification of the parameters of fuel models; availability from the Forest Management Plan (FMP) database, which is regularly updated for all forests; commonly used in forestry practice as a characteristic describing the forest phytocenosis; it considers abiotic and habitat conditions in addition to biotic ones to a large extent.

The aim was to divide the SLT into associations based on the occurrence of dominant herbaceous species, their physiognomy and partly based on their cover, tree species composition and moisture conditions (edaphic-trophic ecological series D). The SLTs thus divided into SLT associations represent initial fuel models that represent areas with similar surface fuel herbaceous synthesis and similar natural tree species composition.

Information on fuel quantity ($t \cdot ha^{-1}$) is also important for modelling purposes. This is determined by field survey in the case of surface fuel, and by deriving from forestry data in the case of crown fuel, i.e., detailed description of the stands as part of the forest management plan or forest management plan and permanent research plots. For fuel quantification, the adapted methodology of Brown [68] has been applied. This methodology is based on destructive field surveys (measurements) of characteristics related to the following fuel types - humus, litter, live herbaceous and herbaceous vegetation, understory vegetation and dead (dry) fuel. Material is taken from each sampling plot for laboratory surveys to determine the moisture content and physical (fire) properties of this fuel. The initial moisture content of each type of forest fuel is already determined during the field survey. For this purpose, a moisture meter for measuring the moisture content of the fine fuel ME 2000 from Wiltronics is used. It determines the percentage moisture content of leaves, twigs, and bark on the forest soil surface as well as of live and dead wood fuel (e.g., shrubs) as quickly and accurately as possible. The measuring principle of this moisture meter is based on electrical resistance. The moisture meter measures resistance up to 10 tera-ohms (10×10^{12} ohms), which corresponds to a moisture content of at least 2% by weight in the fuel after drying in the hot air oven.

1.4 Legal framework for wildland fire prevention and fire prevention measures adopted

In this subchapter, there is introduced the legal framework concerning the wildland fire protection in four selected Central European countries, i.e., Slovakia, Czech Republic, Hungary, and Poland, as well as the measures adopted to prevent the fire.

The European Union actively supports forest fire prevention projects through its Regional Development Fund. Furthermore, the European Union Solidary Fund provides support to help EU countries tackle major natural disasters such as forest fires. [69]

The European Union Civil Protection Mechanism ensures the rapid deployment of resources and personnel to any country in the world that requests assistance during crises such as forest fires. At the core of this mechanism is the Emergency Response Coordination Centre, which monitors forest fire risks and emergencies across Europe. This centre is supported by national and European monitoring services, including the European Forest Fire Information System. [69]

In 2019, to strengthen the mechanism, the EU established a new European reserve of capacities. Known as rescEU, it includes firefighting planes and helicopters. For the 2022 forest fire season, Croatia, France, Greece, Italy, Spain, and Sweden put a total of 12 firefighting planes and 1 helicopter at the disposal of other EU countries in case of an emergency. The European Commission will decide jointly with these EU countries on the deployment of the planes and helicopter. [69]

To the relevant legislation and documents belong:

- Regulation (EEC) No 2158/92 of 23 July 1992 on protection of the Community's forests against fire [70].
- Regulation (EC) No 2152/2003 of 17 November 2003 on the monitoring of forests and environmental interactions in the European Union (Forest Focus) [71].
- European Parliament resolution on forest fires and floods (September 2006)(P6 TA (2006) 0349) [72].
- LIFE+ Regulation (EC) No. 614/2007 on the Financial Instrument for the Environment (LIFE+) [73].
- Commission Communication (COM(2008)130 final) on reinforcing the Union's disaster response capacity [74].

Slovakia

The generally binding legal regulations concerning the wildland fires prevention, is the Act No. 314/2001 Coll. of the National Council of the Slovak Republic on Fire Protection, as amended [21], and the Decree of the Ministry of the Interior of the Slovak Republic No. 121/2002 Coll. on Fire Prevention, as amended [75].

The Decree of the Ministry of Interior of the Slovak republic No. 121/2002 Coll. on fire prevention, as amended, besides others, lays down further details concerning prevention of forest and other wildland fire types, too.

The President of the Fire and Rescue Service in the form of an order (Order of the President of the Fire and Rescue Service no. 8/2007 on protection of forests against fires [76]) issued measures to ensure a unified procedure in the implementation of tasks related to the protection of forests against fires; measures to ensure the protection of forests against fires in localities affected by disaster disturbance; conditions and procedure of the district directorate of the Fire and Rescue Service in carrying out ground monitoring and patrolling activities (monitoring); guidelines for the evaluation of the implementation of measures to ensure the protection of forests against fires; templates of forms for the evaluation of the implementation of measures to ensure the protection of forests against fires.

Forest fire prevention is also integrated in the forestry legislation.

The Act of the National Council of the Slovak Republic No. 326/2005 Coll. on Forests [77], as amended, regulates, preserve, improve, and protect forests as a component of the environment and natural wealth of the country for the fulfilment of their irreplaceable functions; to ensure differentiated, professional, and sustainable forest management; to reconcile the interests of society and forest owners; to create economic conditions for sustainable forest management.

The Decree of the Ministry of Agriculture of the Slovak Republic No. 453/2006 Coll. on the Forest Management and Forest Protection [78], as amended, lays down details on forest management and forest protection. Besides others, it provides the principles of forest protection against the impact of pollutants, abiotic and biotic harmful agents, and forest protection measures, including forest protection against fires.

It should also be pointed out that the burning of vegetation is strictly prohibited under the Act on Fire Protection. When breaching this prohibition, a natural person is liable to a penalty of up to 331 EUR or a fine of up to 33 EUR in block proceedings, while a legal entity or a natural person-entrepreneur may be fined up to 16,596 EUR by the fire brigade.

To prevent wildland fires, there are provided several activities in Slovakia. There is provided information on the forest fire index through the internet page of the Slovak Hydrometeorological Institute during fire season. When the forest fire index is of high value, i.e., the fire danger is high, the information on fire danger is provided via TV (news) or radio broadcasting. There were implemented several Information campaigns to citizens and scholars on fire prevention and self-protection against fire. There is also implemented a stationary CCTV fire detection and early warning system in three high risky regions of Slovakia (High Tatras Mts., Slovak Paradise National Park, and Zahorie region). Except it, there are also ground patrols used to monitor the fire in the field during fire season. Those are composed as for firefighters as for foresters.

Czech Republic

The generally binding legal regulations concerning the wildland fires prevention in Czech Republic is the Act No. 133/1985 Coll. On Fire Protection [79], as amended. The Act addresses, among others, the prevention of fires, the fundamental obligations of natural persons, legal persons, and natural persons entrepreneurs, as well as the roles of the state administration and self-government in the field of fire protection and, through a range of complementary legal regulations, the suppression of fires.

The operating regulation to the Act No.133/1985 Coll. is the Decree of the Ministry of the Interior No. 246/2001 Coll. on the specification of fire safety conditions and the performance of state fire supervision [80], as amended.

Likewise in the Slovak Republic, forest fire prevention is also integrated in the forestry legislation. There is Act No. 289/1995 Coll. on Forests and on the amendment and supplementation of certain acts (Forest Act), as amended by later regulations [81], which regulates the obligations of forest owners in the field of fire prevention. This Act prohibits behaviour that may lead to a forest fire.

Fire prevention on the territory of regions, towns and municipalities may be further regulated by the regulations of these entities, e.g., prohibitions on burning in dry periods, etc.

The prevention of wildland fires in the Czech Republic relies mostly on the education of citizens, scholars. An important activity according to the forest fires, is the activity of foresters who are responsible for reporting the slash or slash piles burning in forests to firefighters` headquarters. For early fire detection purposes, also the activity of the Air Fire Service is important. However, the number of flights of the Air Fire Service has steadily decreased in recent years. [82]

The information on forest fire danger is provided by the Czech Hydrometeorological Institute under the Integrated Warning Service System, which is a jointly provided warning service of the Czech Hydrometeorological Institute in cooperation with the meteorological service of the Czech Army in the field of operational meteorology and hydrology for the territory of the Czech Republic. The second information that is provided is information on drought, which is used as an indicator of the fire danger. A Fire Danger or High Fire Danger warning is issued if the fire risk calculated based on the landscape aridity level, predicted precipitation model, air temperature and humidity and wind speed is medium or high. [83]

Hungary

Forest fire prevention is carried out in cooperation with the forestry authority and the National Directorate General for Disaster Management, based on community and national legislation. The forestry authority also participates in the work of the Forest Fire Working Group of the National Fire Prevention Committee. [84]

Fire prevention in Hungary is the duty of the land (forest) owners. According to the Act No. XXXVII of 2009 on Forests, on the Protection and Management of Forests [85], „the forest owner must provide for conditions of forest fire prevention".

More specific regulations are integrated in the Decree No. 153 of 2009 (XI.13.) FVM of the Ministry of Agriculture and Rural Development [86] implementing Act No. XXXVII of 2009 on forests, and on the protection and management of forests.

According to the Decree No. 12 of 1997 of the Ministry of the Interior on the protection of forests against fire [87], „the forest owners must organize early warning systems and initial attack crews in the high fire risk periods."

This law environment was sufficient when the state forest ownership was close to 99 %. Under the actual ownership structure, however, it is not adequate anymore.

In 2011 a special type of forest fire hazard maps was developed for fire fighters by forest departments. Maps can be printed and stored in their IT system also. For improving the map system, a Web Map Service (WMS) developed by forest authority based on that special forest maps, was launched in 2012. WMS contains some special types of forest thematic layers. Fire Service has been using them in their GIS system. Use of data derived from FWI developed by the Joint Research Centre (JRC) was integrated in the fire ban system in 2012. Its values were considered, and they were analysed throughout the whole fire season supported by JRC.

In 2012 National Fire Prevention Committee was established by the government where representatives of forest authority became members also. It is required for the committee to monitor recent fire prevention activities and fire awareness raising campaign materials. Fire prevention and firefighting activities were presented very well by spokesmen and members of National Fire Prevention

Committee in the media in the frame of awareness-raising campaigns in the last fire season. Media events such as press conferences, short reports, and announcements in newspapers and on the radio and TV were organised accordingly. Supplying data from fire database is daily task to forest owners, managers, and media. [88]

In 2018, the forestry authority has proposed a review of previous forest fire prevention plans at the national and county levels. The criteria and content of reviews has been compiled by the forest authority following the suggestions and best practices published in the issue of the European Commission Expert Group on Forest Fires in 2021.

Expert presentation and demonstration about forest fire prevention and suppression are organised by forest departments for fire fighters. The webpage of Forestry Directorate is continuously updated with fire prevention information. [89]

Poland

The wildland, i.e., forest fire prevention issue is integrated into several national regulations. One of them is the Forest Act 1991 [90], that lays down principles of preservation, protection, and expansion of forest resources.

The Regulation on forest fire prevention (1999) [91] establishes that fire prevention depends on the following risk levels: category I (high risk); category II (medium); and category III (low). Details on the assessment of the risk level are explained. The types of fire-fighting equipment for the given categories are specified. When the admittance to the forest shall be forbidden is also specified. The Regulation amending Regulation on forest fire prevention (2010) [92] establishes the way of classifying forests according to the categories of forest fire risk. The category of forest fire risk includes forests with similar level of susceptibility to fire, based on incidence of fires, stand and climatic conditions and anthropogenic factors.

The information on forest fire risk degree is provided two times per day, i.e.., at 9.00 and 13.00 h for designated diagnostic zones covering the whole country area. [93]

The owners, managers or users of the forests organize observation and patrolling of forests early to detect the fires; build and maintain water sources for fire-fighting purposes; maintain roads, fire escape routes marked in the forest management plan, mark the water intake points using signs, furnish and maintain bases of equipment for forest firefighting in the appointed places. [93]

Existing observation and alarm system consists of constant terrestrial observing system, fire patrols, alert and disposition points, CCTV Camera systems alerts, and disposition telecommunication network. Fire prevention relies also on conducting informative and warning activities [93]

2. DYNAMICS OF WILDLAND FIRES

3.1 Introduction to wildland fire dynamics

Wildland fire, also called forest, bush or vegetation fire, can be described as any uncontrolled and non-prescribed combustion or burning of plants in a natural setting such as a forest, grassland, brush land or tundra, which consumes the natural fuels and spreads based on environmental conditions (e.g., wind, topography). Wildland fire can be incited by human actions, such as land clearing, extreme drought or in rare cases by lightning.

There are three conditions that need to be present for a fire to burn: fuel, oxygen, and a heat source. Fuel is any flammable material surrounding a fire, including trees, grasses, brush, even homes in wildland fires. The greater an area's fuel load, the more intense the fire. Air supplies the oxygen a fire needs to burn. Heat sources help spark the wildland fire and bring fuel to temperatures hot enough to ignite. Lightning, burning campfires or cigarettes, hot winds, and even the sun can all provide sufficient heat to spark a wildland fire.

In many ways, wildland fire behaviour is much more complicated than is the case with other types of fires. The variables that influence the burning process change almost continuously as the conditions in the fire area itself change. Each of these changes can be either an advantage or disadvantage to gaining control of the fire and to the actual fighting of the fire [94].

The success or failure of localization and eradication operations in the context of a wildland fire depends on the ability of the incident commander to interpret the situation or, in many cases, to anticipate what will happen when various influences, both internal and external, interact.

The process of wildland fire combustion and its suppression directly depends on the fastest and most effective interruption of the combustion process. However, in the case of wildland fire, in addition to the traditional triangle of burning, the "fire tetrahedron" (Figure 9) is also used because of the greater complexity of the burning process [94].

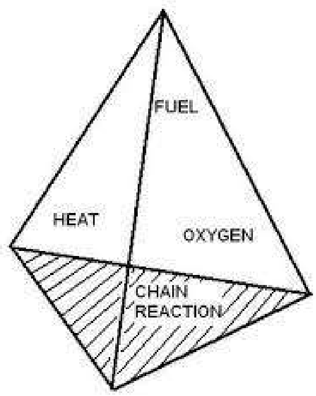

Figure 9 Fire tetrahedron (Source: [94])

The elements of the fire tetrahedron are fuel properties, meteorological situation, topography, and fire period (from initiation to extinction). When a fire develops, these elements are continuously modified in their interrelationships.

Figure 10 shows the dominant factors influencing wildland burning at the flame, wildland fire, and fire regime scales. This shows an extension of the traditional concept of the burning triangle for indoor fires to include the so-called three-level triangle, which incorporates a wide range of other variables that influence the origin, spread and prediction of fire regimes [95].

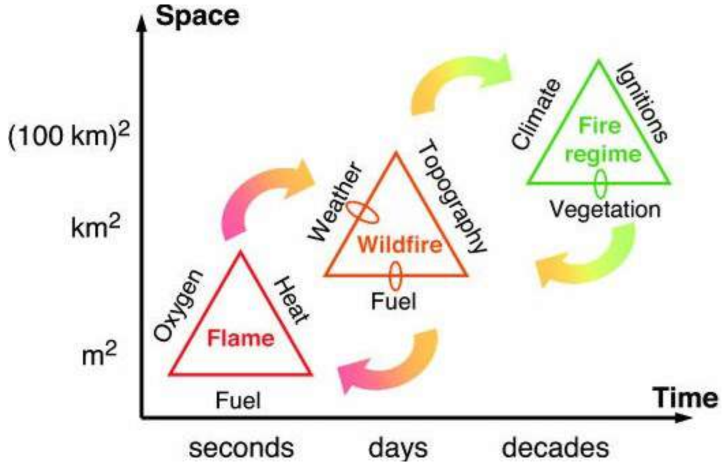

Figure 10 Combustion triangle parameters influencing fire behaviour in a wildland area (Source: [95])

2.1.1 Fuel properties

During a fire, several essential fuel parameters are required to be monitored. Each of these parameters influences the intensity, duration and spread of a surface fire. These factors include fuel composition, fuel quantity, fuel spatial distribution and fuel moisture content.

Fuel composition describes how detailed the fuel is classified in relation to its quantity. Almost all surface fuels can be classified into one of the primary categories: grasses (light fine fuels), shrubs or dense brush, deciduous or coniferous forests (bulky or heavy fuels). Light fine fuels are easy to ignite but do not release much heat. Bulky fuels, on the other hand, are more difficult to ignite, but if they burn, the rate of release and the amount of heat released are high.

Fuel composition also has a significant effect on the rate and direction of spread of a woodland fire. As already mentioned, light fine fuels are very easy to ignite and therefore it is most common for fires to occur on grassland. This is because it is a fast-igniting material that requires only a small amount of heat to reach the ignition temperature. Once ignited, it generates enough heat to ignite other fuels.

In general, the finer the surface fuel, the easier it is to ignite and the faster it spreads across the surface. However, on the other hand, these fires cause much less damage than is the case with bulky heavy fuels (crown fires).

In forest fires, multiple fuels burn simultaneously, which also affects the rate of spread of the fire within that area. For example, if a fire is assumed to spread from a bush and shrub fuel (fuel model) towards a grass fuel model (fine fuel), the fact that the rate of spread may increase up to twice as fast must be considered. If the fire spreads or changes from a crown fire to a surface fire, it is necessary to consider the acceleration of the fire spread up to three times [94]. The height of the fuel is also a very important factor related to the fuel composition, which is particularly important because of the transition from surface fire to crown fire.

The amount of fuel is a clear factor in retaining the heat required to ignite another fuel. This involves the determination of the amount of fuel contained within a specific area and is measured as a mass per unit area, usually in units of $t \cdot ha^{-1}$.

The volume of fuel is directly related to other fuel parameters such as fuel density or fuel distribution. Surface fuel can be distributed irregularly or uniformly in space, regardless of its quantity. Furthermore, the spatial relationship between fuels is not only horizontal (from grasses to shrubs to trees) but also vertical (from low understory to tall trees).

In the case of vertical fuel structure, shrubs and bushes can be considered the most hazardous fuel type, posing a hazard particularly in terms of surface to crown fire or vice versa. This is often the reason for the spread of grassland fires, often caused by deliberate burning in the spring season, to forest stands. This phenomenon is particularly common in areas on the boundaries of urbanized and wildland areas.

The amount of fuel is also closely related to the fire loading in the wildland area. The fire loading of the wildland area varies with soil type, plant species found, rainfall, climatic conditions, hillside exposure and human activity.

In general, fuel parameters such as fuel composition, fuel quantity and fuel distribution are static parameters. Dynamic fuel parameters, i.e., those that change over time, include fuel moisture content.

Fuel moisture content can be determined as the water content of the fuel, expressed as a percentage of the weight of the fuel after drying in the dryer. Fine fuel (grasses, but all fast-drying fuel that is less than 6 mm in diameter: leaves, ferns, mosses, pine needles and small twigs) is most susceptible to changes in fuel moisture values.

The moisture content of the fuel is a key factor in determining the fire danger. A scale has been constructed for this purpose [94]. This scale was established by experimental observation, weighing a specified amount of fuel at different moisture contents. Subsequently, another scale, called the fire spread factor, was constructed based on the input of fire growth rate values for the same type of fuel and other conditions unchanged. These are provided in Table 1.

Table 1 Effect of fuel moisture on the rate of fire spread (Source: [94])

Fuel moisture content (%)	Fire spread factor
25	1
20	2
15	3
10	7
5	20
3	32

From the values shown in Table 1 it is seen how the gradual drying of the fuel leads to an increase in the rate of spread of the fire.

Several agencies and institutions responsible for fire protection in the field of wildland fire prevention use fuel moisture data for the purpose of determining the fire danger index and developing fire warning systems.

In addition to the fire danger index, a flammability index is also provided abroad. This index is used to determine the relative effects of different weather types on the rate of spread and intensity of a fire.

The combination of the fire danger index and the flammability index is called the fire loading index. This index is not dependent on the fire loading itself but is instead a different relative measure of the effect of weather on the probability of fire occurrence, the rate of spread and its impact on the effectiveness of firefighting activities. It is expressed, for e.g., in the form of a 5 to 10 scale, where 5 or 10 represents the highest fire danger.

2.1.2 Weather and wind situation

Meteorological parameters such as air temperature and relative humidity can significantly influence the probability of a fire. Weather affects not only the rate of spread of the fire (the rate of fuel consumption in a fire) but also the direction of the fire spread. Due to changes in weather and wind conditions, long-lasting fires can occur and may be sustained for weeks. These situations are particularly typical for countries around the Mediterranean, Australia, and the U.S.

The most important weather parameter in terms of fire is wind. Wind is a direct result of the cooling and heating of the earth's surface, which creates varying air pressure. Therefore, wind is the movement of air from an area of higher air pressure to an area of lower air pressure.

From the point of view of fire location and suppression operations, wind has either positive or negative effects, depending on whether it slows down the progress of the fire or, on the contrary, stimulates it.

As mentioned above, the main effects of wind on fire include changing the rate of fire spread and the direction of fire spread. However, it should also be mentioned that a doubling of wind speed does not automatically mean a doubling of the acceleration of fire spread. In this case, the fire spread rate increases in a geometric sequence. Thus, when the area of the fire area increases rapidly, the effect of the wind on the continuous spread is multiplied by a power.

The prevailing weather conditions are in fact an expression of a set of wind directions and wind speeds that are typical for the area, even in the absence of a fire. It is the unequal heating of the geographical area, combined with the topography of the area, that produces them.

The results of long-term observation of firefighters during the fighting and eliminating of wildland fires show that the wind speed increases with sunrise, while its speed gradually decreases with sunset. Since the earth's surface heats up fastest between six and nine o'clock in the morning and cools down between five and seven o'clock in the afternoon, it is also currently that the wind strength is greatest.

Another phenomenon associated with wind is wind turbulence, which forms on ridges, in canyons, valleys and other faults on the Earth's surface. These also have a significant influence on fire behaviour, on the direction of spread and intensity.

Another meteorological parameter that needs to be mentioned is the inversion. This is a meteorological phenomenon in which the air temperature in some layer of the lower atmosphere does not decrease with increasing altitude but increases. The inversion layer in a fire creates an impenetrable layer on the fireground, which can cause abnormal migration of smoke, heat and flying embers. Below the inversion layer, the fire burns very slowly, due to the reduction in wind speed, because of its limited movement in the atmosphere. One sign of the existence of an inversion layer is a column of combustion products rising into the atmosphere, which cannot penetrate this cold layer of air and therefore form a mushroom-shaped column. If this column is spotted, attention must be paid to it because if the fire reaches sufficient intensity in the convective column to break through the inversion layer, an opening effect is created that suddenly lets air into the fire environment below the inversion layer. This causes the spread of the fire to accelerate dramatically. Subsequently, the rapidly rising temperature column can create a low-pressure zone that causes an increase in localised surface winds that can reach gale parameters within minutes. Alternatively, the fire may burn to higher altitudes and penetrate the edge of the inversion layer with similar results, causing the fire to spread downslope. For these reasons in particular, the occurrence of inversion needs to be monitored and the possibility of these phenomena needs to be considered in the management of fire localization and suppression operations, especially in relation to the safety of the intervening persons.

The reliability of weather conditions is almost always linked to the reliability of predictions of fire behaviour. Changes in topography and weather inevitably create variability in fire behaviour. High and fast-moving clouds, in conditions where surface winds are not present, can be the origin for wind return. If shadows are falling on the slopes and rapid cooling is occurring, this is also a precursor to the return of downslope winds. Changes in the direction of the smoke columns at different levels can be a sign of unstable air movement.

2.1.3 Topography

Terrain features represent another factor that influences fire behaviour. If fires occurred on perfectly flat terrain the influence of topography on fire behaviour would be minimal, but this is not the case in real conditions. On the contrary, the forest fires occur mainly in areas that are rugged in height and covered with tree vegetation.

The most important topographical factor influencing fire behaviour is the slope gradient, which, in the context of the actual weather and wind situation, together with the fuel parameters, poses a real problem. The influence of terrain features, such as ridges and canyons, on wind flow has already been described above. However, slope effects can also cause other problems in relation to fire development. They can affect its intensity and rate of spread in a very dramatic way. A fire that starts on a flat or very long valley will spread at a constant rate unless the parameters of the other factors are altered. But if a fire starts on a slope and spreads up or down the slope and is influenced by other factors (change in fuel type, change in wind flow, etc.), it will spread at a rate in terms of these changed conditions (its rate of spread will slow down or, conversely, accelerate because of the wind flow stimulating its burning).

In general, we can describe 4 aspects of slope gradient that influence the behaviour of a forest fire or a wildland fire [94]:

- slope gradient, or slope elevation (angle or degree),
- connecting points, where ridges, valleys, and canyons occur,
- tops of ridges, also called chimneys,
- exposure of slopes to the sun and the effects of weather.

A front of flames moving across flat terrain creates a heat radiating zone in front of it. As the fire moves across the flat surface this radiation preheats the fuel until its ignition temperature is reached and subsequent fire spread occurs. If the fuel is unevenly distributed and there is no wind, the fire spreads uniformly. In this case, the rate of spread of the fire is controlled by the volume of unburnt fuel exposed to the heat radiation zone (fire front). If the same fuel is located on a 20° slope, heat can be transferred by convection or radiation, which significantly increases the preheating zone. This expansion allows the fire to spread much more easily. The steeper the slope, the higher the rate of spread of the fire. In general, the rule is that the rate of spread of a fire will increase by a factor of two as the slope angle is increased by a factor of two [94]. This means that if a fire spreads down a 10° slope and spreads up a 20° slope, its rate of spread can be expected to increase twofold. If the fire spreads down a 10° slope and affects a 30° slope, the rate of spread may increase up to four times.

Knowledge of these laws is particularly important for the localization and suppression of wildland fires and for the safety of intervening personnel, as the rate of spread of a fire spreading down a slope can increase by a factor of 16 to 20 compared to a fire spreading on flat ground.

Another effect that should be mentioned that effects the fire behaviour in terms of topography is the chimney effect.

Connections between hillsides are created by ridges, valleys, or canyons. The valley portions of canyons are the most suitable environment for fire formation as they are often populated and equipped with transportation infrastructure. This area can be likened to the heating area of a wood stove. If the canyon is wide and the slope of the canyon slopes is gradually increasing, then the influence of topography is minimal. But if the canyon is narrow, with steep slopes, these serve as exhaust channels for the fireplace during a fire. The tops of these steep slopes are then called chimneys. Like a wood stove, chimneys are used to vent hot gases and smoke and transfer heat by convection. As the gases move up the chimney, they accelerate the flow of air into the base of the fire, thus providing oxygen to the fire, which leads to its further growth [94]

Also, fuels are often denser in canyons as they retain most of the moisture. This fact increases the heat production and the height of the flames in a fire. Heat conduction preheats the slopes before the fire front reaches them. Through sparks, embers and local air currents created by convection, other combustible material can be ignited gradually before the fire front reaches it. This causes the formation of post-local spot fires which appear before the fire front, giving the appearance of the fire spreading up the slope. Heat, smoke, and gases spreading through the previously mentioned chimneys can make conditions at the top of slopes or these chimneys unsuitable for intervening firefighters. The higher the chimneys are above the fire front, the greater the impact of their effects.

In addition to the slope gradient, fire behaviour is also influenced by the exposure of the slopes, i.e., their orientation with respect to the cardinal directions. North-facing slopes tend to have higher fuel moisture content than others because north-facing slopes typically receive less direct sunlight and therefore can hold more moisture. Vegetation is often greener and burns much more slowly. On the other hand, southern slopes have less moisture content, and the vegetation is not as green. When a fire starts, this factor can cause changes in the rate of spread.

2.1.4 BURNING PERIOD

Burning period indicates the time since the fire was started. In the context of forest or wildland fires, a burning period of 24 hours is usually considered. This is because, under ordinary conditions, the area is subject to at least a 24-hour cycle of wind effects, exposure to sunlight, relative air humidities and changes in fuel moisture contents. As the fire burns and spreads across the area, changes in fuel parameters occur, as well as changes in topography and weather conditions.

If a fire starts at 9.00 AM and is not located by 2.30 PM, there is a realistic expectation that higher afternoon temperatures, lower fuel moisture content levels and the weather situation during the day will support the spread of the fire.

As a rule of thumb [94], the burning period is set between 10.00 h on the first day and 10.00 h on the following day. This rule is supported by the fact that severe fires can be fought mainly between midnight and two or three o'clock in the morning. If a fire is burning and not under control before sunrise, it can be assumed that its development will continue well into the morning and into the morning hours of the following day.

Thus, the total time elapsed from the start of the fire to its elimination is an indication of the interaction of the factors of fuel, weather, and topography. If the development of the fire indicates that it will be a long-lasting fire (several days or even weeks), it can be assumed that the requirements for the forces and resources needed to carry out the localization and elimination operations at the fire scene will also increase, especially if the fuel parameters and terrain conditions indicate that the fire will continue to spread in multiple fronts.

3.2 Experimental study of surface forest fire dynamics

There are introduced two experimental studies focusing the surface forest fire initiation and spread. Testing material was the forest litter.

Determination the critical moisture values of oak litter affecting the initiation and subsequent propagation of forest fire

The aim of the study, experiments provided, was to determine the critical moisture values of oak litter affecting the initiation and subsequent propagation of forest fire. It was necessary to find moisture content values at which ignition still occurs when the most common sources of initiation are used. In the experiments, there were used the ignition sources which are most often occurring in the fire statistics kept by the Fire Research Institute of the Ministry of the Interior of the Slovak Republic. The experiments were performed under laboratory conditions, in the laboratories of the Technical University in Zvolen.

The ignitability testing of the litter consisted of the following parts: sampling (fuel) in the field, adjusting the samples to the required moisture content, performing a fuel ignition experiments, recording and processing data.

On 23.07.2019, sampling of the oak (*Quercus sessilis*) litter took place as part of a field survey from research plots established in oak stand (365a) (Figure 11) located in the territory of the University Forestry Enterprise which is situated in the Central part of Slovakia (Figure 12). Basic characteristics of the stands were as follows: tree species composition – *Quercus sessilis* (100 %), stand age was 110 years, stand area was 5.59 ha, stem density was 0.8, aspect was north, slope was 30 %, altitude was 320-380 m above sea level.

Figure 11 Location of stand 365a and view of a research plot

Figure 12 Location of the University Forest Enterprise

Laboratory pre-treatment phase was aimed at adjusting the samples to the required moisture content. The litter sample was dried to a dry state in the Memmert hot air oven at a temperature in the range of 103-105 °C. The dried material was placed in a polyethylene bag and weighed. The weight of the sample in the dry state was determined. Subsequently, according to equation (5), the amount of water to be added to achieve the desired moisture content of the sample was calculated. The desired moisture content of the sample was achieved by sprinkling it in the form of a fine mist to achieve uniform wetting of the sample (e.g., the sample dried in an oven to 100 g was moistened to 120 g to reach the desired moisture content value of 20 %). Prior to the experiment, the moistened sample was homogenized in a polyethylene bag by mixing it and allowed to stand in a closed bag for 24-48 h to allow complete absorption of water. The fuel in the bag was also mixed continuously to achieve a uniform moisture content. To calculate the sample moisture content, the following equation was used (1):

$$w = \frac{w_m - w_s}{w_s} \cdot 100 \quad (1)$$

Where:

w – absolute fuel moisture content (%),
w_m – mass of wet fuel (g),
w_s – mass of dry fuel (g).

The experiments were performed in a laboratory digestor using reconstructed bedding of tested litter with uniform moisture content and mass. All samples were arranged in such a structure as to reflect their natural occurrence with approximately the same proportion of each fuel type.

The aluminium dish used for the experiments was circular in shape with a diameter of 20 cm and a depth of 3 cm. This size was chosen because of its suitability for observing not only the ignition of a fire, but also the propagation. The dish was filled with the litter evenly to the brim, the weight of the dish with the sample being in the range of 40 g ± 0.2 g. The dish was then placed in a laboratory digestor with a slight suction set. To check the real moisture content of the sample, 30 g of sample was taken from each bag and the moisture content was verified back by gravimetric method.

The fire was initiated by 3 initiators. Figure 13 shows the types of fire initiators used.

Figure 13 Three types of fire initiators: lighter, flame burning wooden cube, and cigarette butt-end

As the first initiator, a kitchen pull-out lighter was used, which initiated the burning of litter for a period of max. 30 s. Then, an oak wooden cube with dimensions of 2.4 x 1.8 x 1 cm was used. An electric spiral cooker was used for heating-up the wooden cube. After gentle heating, it was ignited by the lighter flame to initiate the flame burning. Finally, Winston Classic cigarette butts 5.4 cm long (with filter) and 3 cm (without filter) with a diameter of 0.8 cm were used. The cigarette was lit and when it had a length of 3 cm (without filter), its tip was placed at a depth of 1 cm inside the fuel at an angle of 45°.

To perform airflow experiments, a SilverCrest Ship 2000 A1 home Profi hair dryer with a constant temperature and constant airflow rate was used as the wind flow source. The temperature was set to 37 – 39 °C to simulate warm summer air. Required wind speed was set by changing the distance, or by increasing the air flow speed. The Laserliner AirflowTest-Master anemometer was used to measure wind speed. This also served to record ambient temperature and relative air humidity.

To evaluate the capability of the initiators to ignite the test sample and allow the propagation of fire, a classification scale was created, namely: level 0 - the initiator goes out by the wind; stage 1 - burning of the initiator only; stage 2 - burning only around the initiator; level 3 - burnt area at least 15 %; level 4 - burnt area at least 30 %; level 5 - burnt area at least 45 %; level 6 - burnt area at least 60 %; level 7 - burnt area at least 75 %; level 8 - burnt area at least 90 %; level 9 - the burnt area represents 100 % of the area of the test dish. The classification scale used was created for the purposes of this study, resulted from the course of individual experiments, and was used to express and describe the course of combustion when different individual sources of ignition are used.

Based on the findings of experiments carried out in the initial research phase, the following values of fuel moisture content and wind speed were determined for the determination of the limit value of forest fuel moisture content for initiation and subsequent propagation of fire, for which laboratory tests were performed (Table 2).

Table 2 Values of fuel moisture, wind speed and fire initiator for each type of litter used in the implementation of laboratory tests

Material	Moisture content (%)	Initiator	Flow rate ($m \cdot s^{-1}$)
Oak litter (*Quercus sessilis*) Stand 365a	0	Wooden cube Lighter	0
	5 – 6%		0.3 – 1.5
	10 – 11%		1.6 – 3.3
	14 – 15%		3.4 – 5.4
	20 – 21%		5.5 – 7.9
	–		8.0 – 10.7
	–		10.8 – 13.8
	0	Butt-end	0

All experiments for each type of fuel, fuel moisture content, initiator and wind speed were repeated 3 times for period of 10 min. The average value of these repeated measurements was used to calculate the analysed parameters. If the result of the experiment was significantly different from this average, the experiment was repeated.

Ambient temperature, relative air humidity and fuel temperature were also recorded during laboratory tests. The air temperature was in the range of 18 °C – 23 °C and the relative air humidity in the range of 28.5 % – 43 %.

Results and Discussion

For predicting the fire potential and fire frequency is necessary to understand the climate change effects, especially at regional and local scales. Fire occurrence is strongly dependent on weather conditions which have direct effect on fuel moisture. This parameter is critical in predicting the ignitability of fuel. Regarding this, the most important information is the information on fuel moisture content critical value.

Here are presented the results of determining the critical values of oak litter (fuel) moisture content, at which ignition and the subsequent propagation of fire occurs. A total of 235 experiments were performed at different wind speeds and fuel moisture contents.

Figure 14 shows the course of the fire initiation and propagation process (expressed in degrees) as a function of fuel moisture content and wind speed using a lighter flame as an initiation source. It is clear from Figure 14 that a fuel with a moisture content of 20 % - 21 % could not be ignited by the lighter flame for 30 s at any of the simulated wind flow rates. By fuel with a moisture content of 14 % - 15 %, no fire was initiated at any of the simulated wind flow rates (1, 3, 4, 5, 6). In the absence of wind, the fuel was ignited and further propagated, resulting in an average burned area of up to 30 %. At a wind flow rate of 2.5 m·s^{-1} (stage 2), only 15 % of the area burned down. Furthermore, at a wind flow rate of 9.5 m·s^{-1} (stage 5) and higher, it was not possible to ignite due to the going out of the lighter flame or the early flaming out of the flame immediately after the lighter was removed and the air flow was allowed to access the fuel bed. Based on the results of experiments, it can be stated that the moisture content of the fuel at which a fire is propagated into the surroundings is in the range of 10 % – 11 % at an average wind speed of 6.5 m·s^{-1} (stage 4). At lower wind speeds, the fire was unable to spread further.

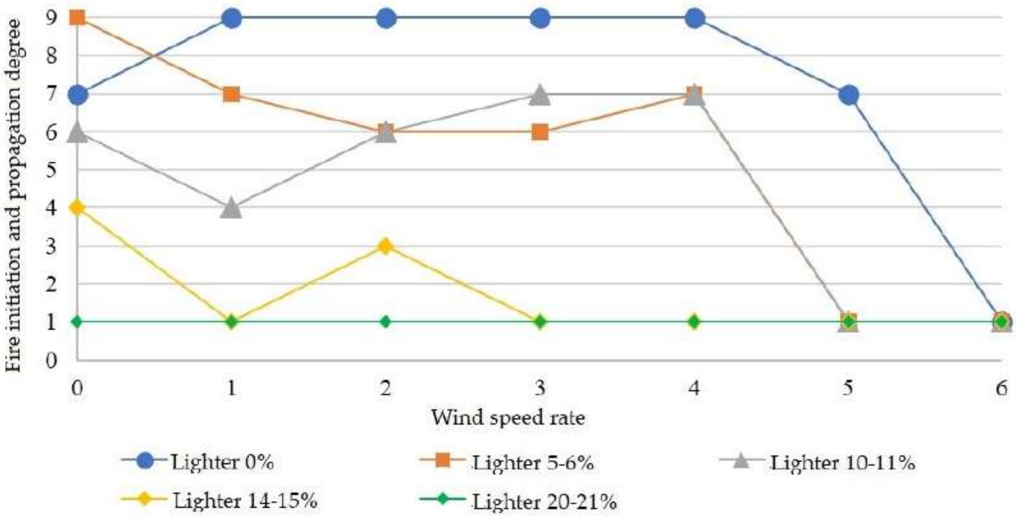

Figure 14 The course of the fire initiation and propagation process (expressed in degrees) as a function of fuel moisture content and wind speed – lighter flame

Figure 15 shows the course of the fire initiation and propagation process (expressed in degrees) as a function of fuel moisture content and wind flow rate using a flame burning cube as the initiation source. At fuel moisture content of 20 % - 21 %, only the cube burned. Any propagation and spread of the fire from this source did not occur. As the wind flow rate increased, only the fuel around the source of initiation place burned. At fuel moisture contents of 10 % and 15 %, with increasing wind flow rate, the proportion of burned area increased up to 75 %. At an average wind flow rate of 9.5 m·s-1 (stage 5), the cube went out due to laminar airflow, before it could initiate the fuel, unless the fuel has been in a dry state.

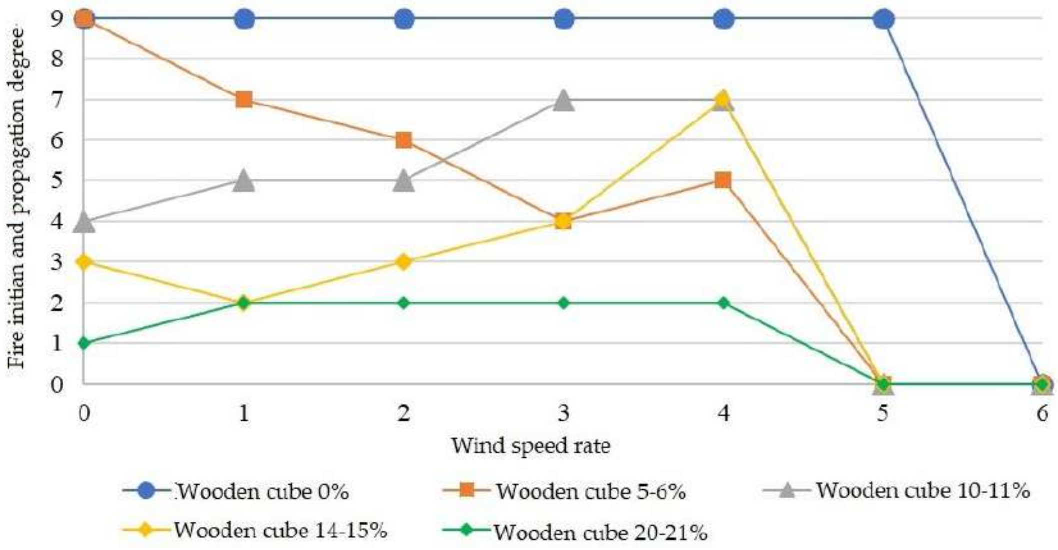

Figure 15 The course of the fire initiation and propagation process (expressed in degrees) as a function of fuel moisture content and wind speed – flame burning wooden cube

In the case of smouldering cigarette butt-end used as the initiator, the fuel did not ignite even in totally dry state. After about 324 s, the smouldering part of the cigarette reached the filter and then went out.

Curt et al. [96] performed similar experiments in which they lit Kermes oak (*Quercus coccifera*) leaves with a kitchen match in the absence of wind. The results showed that out of a total of 39 experiments, 23 experiments were initiated. At a moisture content of 1 % - 2 %, the leaves were lit 15 times, at a moisture content of 2 - 2.5 %, 4 times. No ignition occurred at fuel moisture content above 2.5 %. They performed a similar experiment with a cigarette butt, which was placed at a depth of 1 cm inside the fuel at an angle of 45°. Just in 20 experiments with completely dry fuel, it did not lead to ignition, even though the initial fuel temperature was of 30-35 °C.

The experiment with cigarette butt and leaves of Mongolian oak (*Quercus mongolica*) was performed by Sun et al. [97]. In this case, they simulated throwing a cigarette butt from a height of 1.5 m to the specific point on the fuel bed. Experiment results showed that the moisture content of the fuel, the wind speed and their interaction had a significant effect on the probability of ignition. The probability of ignition was zero when the wind flow rate was of 0 $m \cdot s^{-1}$ and 6 $m \cdot s^{-1}$. At wind flow rate ranging from 1 to 5 $m \cdot s^{-1}$, the probability of ignition decreased with increasing fuel moisture content, and the relationship between fuel moisture content and wind flow rate changed from exponential to linear, and then back to exponential. The maximum moisture content of the leaves at which the leaves can be ignited was set at 15 %.

Satoh et al. [96] found the maximum moisture value of oak leaves that could be lit by cigarette butts at 14 %. The probability of fuel ignition increased to 50 % when the cigarette butts were inserted inside the fuel.

The differences in results dealing with ignition of fuels by cigarette butts can be explained by the components affecting the burning of cigarettes, which have changed compared to the past. At present, it is not possible to switch from cigarette smouldering to flame combustion, what makes it impossible to ignite the surrounding fuel, even the totally dry hays.

Considering the different tree species composition of the Central European forests producing varying fuel loads, there is need to provide more studies focusing on impact of climate change on forest floor fuel moisture content and its ignition potential, which is directly connected with actual fire danger rate. This necessity has already been pointed out in Baidoc and Cornwell [97]. The floor fuel moisture is strongly dependent on relative air humidity and soil drought. With soil and vegetation (fuel) drought is the hydroclimate directly linked. It is a non-stationary variable, varying as at local and regional as at global scale. Hydroclimate is dependent on five principal components: evaporation, transpiration, condensation, precipitation, and runoff. All of them describes the water cycle in the forest and has very strong impact on vegetation moisture content. According to scenarios of climate change for the future. Some authors [98,99] doubt on the precipitation effect on increasing moisture content of forest litter when there are long periods characterized with high temperatures and drought. This effect shows high level of uncertainty to the future. It is a dangerous situation for forests and forest management. Considering the scenario, that the precipitation will not be capable of increase the moisture content of forest fuel, especially fine forest fuel, high enough above the critical moisture content value (moisture of extinction), then there is extreme high danger of intensive and severe forest fires even crown fires in the Central European region.

Conclusion

The implementation of fire research related to studying litter or herbal fuel needs more experiments to be provided and database of fuel parameters to be built to allow wildfire modelling in the practice of fire investigation, namely in the Slovak Republic.

Investigation of surface forest fire behaviour in laboratory conditions

This study deals with an investigation of surface forest fire behaviour in laboratory conditions and using the beech forest litter as a testing material.

The main objective of study was the identification and verification of opportunities of digital image analysis application in fire engineering and development of a methodology for automated image processing and derivation of selected parameters necessary for describing fire dynamics from images produced by thermal imaging (infrared band) and optical cameras. There were totally five fire tests provided, while three of them were carried out in a laboratory chamber with the simultaneous use of an optical (video) camera used to record the development of flame burning in time. The other two fire tests were carried out in a laboratory fume hood with simultaneous recording of the fire propagation with the Fluke RSE600 thermal imaging camera from above and with an optical camera from the front. For images pre-processing and processing several software were used. Methodologies were developed to derive selected parameters of fire dynamics, which enable wider and more complex use of knowledge obtained from records from a thermal imaging camera, as well as from classic video camera. The results of the study have their application in science and in practice. From the point of view of application in science, they point to the possibilities and suitability of the application in the work of applied digital technologies for the study of fire behaviour and the automated derivation of its selected parameters. The study provides guidance for conducting similar experiments using digital technologies aimed at studying fire behaviour, too.

The material that was investigated was the forest litter collected in the beech forest (stand no. 551, located on the territory of the University Forestry Enterprise of the Technical University in Zvolen) on August 17, 2021. This stand was characterized by the following woody vegetation: European beech 95 %, Silver fir 2 %, European larch 2 % and Sessile oak 1 %. The age of the stand was of 60 years.

The sampled beech litter was dried to a dry state in the MEMMERT air dryer before the fire tests were carried out, and in this state, it was also used in individual experiments, in the amount of 100 g for each test. The duration of each experiment was set to 10 min. While the following data were also recorded during the test: end of flame burning, end of glowing and smouldering.

Laboratory fire tests (5 tests totally) were carried out using the available research infrastructure of the Combustion Laboratory, which is managed by the Department of Fire Protection. The fire tests were carried out in two phases. In the first phase, three fire tests were carried out in the laboratory chamber, together with providing video recordings of the flames.

In the second phase, two fire tests were carried out using not only a video camera, but also a thermal imaging camera. These were carried out in the MERCI G laboratory hood. Here we consider it necessary to emphasize that the implementation of the fire tests served exclusively the purpose of obtaining a basic set of data, i.e., images that were the basis for the processing of image analyses and the development of methodologies for automated image processing and the derivation of selected parameters of fire dynamics.

The experiments were performed using a circular test dish with a diameter of 50 cm and a height of 3 cm. During the experiments, the mass loss of the fuel was recorded at intervals of 10 s. RADWAG WLC R2 precision scales were used for this purpose. Thermocouples (T1 – T5) connected to an autonomous measuring station ALMEMO®710 by AHLBORN and a Fluke RSE600 thermal imaging camera providing a sequence of images with a temporal resolution of 8.6 frames per 1 s and a spatial resolution of 640 x 480 pixels were used to record the course of temperatures during the fire.

The GoPro4 video camera was used to create videos of the fire tests. These records were used in a later phase to derive selected flame parameters applying digital image analysis tools.

From the provided laboratory fire tests, data on the course of temperatures recorded by individual thermocouples (T1-T5) were obtained and further analysed.

Using the RADWAG precision scales, the mass loss of the samples was recorded during the

10 min lasting fire tests. These were processed into graphs. From these data, we also calculated the relative mass loss (2) and the relative mass burning rate (3) in time:

$$\delta_m(\tau) = \frac{m(\tau_0) - m(\tau)}{m(\tau_0)} \cdot 100 \quad (\%) \quad (2)$$

$$v_r = \frac{\delta_m(\tau) - \delta_m(\tau + \Delta\tau)}{\Delta\tau} \cdot 100 \quad (\% \cdot s^{-1}) \quad (3)$$

Where:

$\delta_m(\tau)$ – relative mass loss over time (%)
v_r – relative rate of burning ($\% \cdot s^{-1}$)
$\Delta\tau$ – time interval in which the weights are recorded (s)
$\delta_m(\tau + \Delta\tau)$ – relative mass loss in time (%)

Data on the surface temperature of the fuel at the positions of the thermocouples, which recorded the temperature inside the fuel, were processed from the records obtained by the thermal imaging camera. Subsequently, these temperatures were compared with each other, and the results were analysed and discussed.

The course of temperatures on the surface of the fuel was also recorded and analysed on other profiles, both within the entire surface of the test dish and on specified profiles across the test dish.

From the thermal imaging records, video records and observations, the duration of the flame burning and the time of the glowing (smouldering) of the fuel were obtained. These times were compared to each other. Conclusions were drawn from the results of the comparison.

Data on the mean, average and maximum height of the flame during the fire tests were derived from the data acquired by the video camera. These were derived from images for each 5 s interval.

To calculate the flame height, it was first necessary to define the mean flame height (m). This is best to determine by averaging the visible height of the flame as a function of time. This is the height at which the flame appears in half of the time (equation 4).

Equation (4) considers the height of continuous and pulsating flame in a half of the flame burning time.

$$L_f = \frac{L_{fk} + L_{fp}}{2} \quad (m) \quad (4)$$

Where:

L_{fp} – flame height (m)
L_{fk} – height of continuous flame (m)
L_{fp} – height of pulsating flame (m)

We calculated the average flame height as the average of all flame heights recorded at 5 s intervals during flame burning.

The maximum flame height we determined based on the highest flame height value from the flame height values recorded at 5 s intervals during the flame burning.

Using the data from the fire tests carried out in laboratory fume hood, we calculated the density of the radiated heat flux (mm) according to the equation (5) for each pixel of the image (Wien's displacement law):

$$\lambda_{max} = \frac{b}{T} \tag{5}$$

Where:

λ_{max} – wavelength at which, at temperature (T), the radiation intensity is maximum
b – universal constant 2.898 (mm·K^{-1})
T – thermodynamic temperature on surface of the material (°C)

In the Idrisi TerrSet environment, input images were processed applying image analysis tools (Idrisi Image Processing), i.e., images obtained every 5 s from video recordings and representing the course of fire tests in a specific time. Those further underwent thresholding and reclassification. As a result, we got 2D flame shapes outlines, which were further used for flame heights calculation.

The rate of burning was calculated based on the mass loss of the sample recorded during the experiments at 10 s intervals.

Further, there are presented the results of fire tests, the results of image analysis processing aimed at deriving selected parameters important for understanding the fire dynamics.

Temperature course in a fire

In this subsection, we present the results of the fire tests namely, temperature curves obtained from data from individual thermocouples (T1 – middle of the bowl, T2 – western edge of the bowl, T3 – northern edge of the bowl, T4 – eastern edge of the bowl, T5 – southern edge of the bowl) located inside the layer of beech litter and also the course of temperatures measured on the surface of the test sample using a Fluke RSE600 thermal imaging camera. The results presented here were obtained during the laboratory fire tests and from processing of the thermal imaging images (in the SmartView R&D software) and of video recordings.

Temperature course – data from the thermocouples

Thermocouples T1-T5 were in the middle of the fuel complex placed on a circular test dish with a height of 3 cm and a diameter of 50 cm. Thermocouple T1 was situated in the centre of the test dish and the other thermocouples was located 2 cm far from the dish edge.

Figures 16-18 show the results for the fire tests carried out in the laboratory chamber.

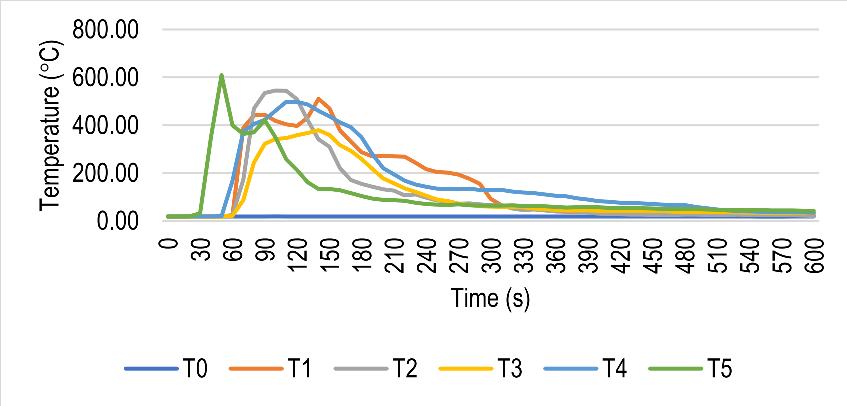

Figure 16 Temperature course during fire test 1 (chamber) recorded by thermocouples T1-T5

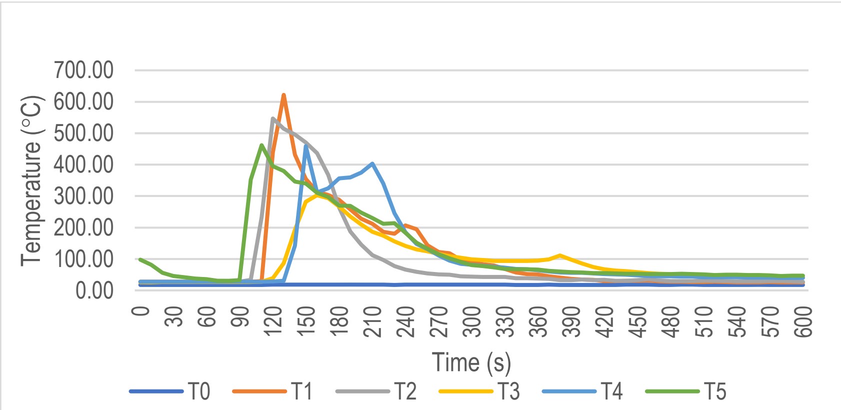

Figure 17 Temperature course during fire test 2 (chamber) recorded by thermocouples T1-T5

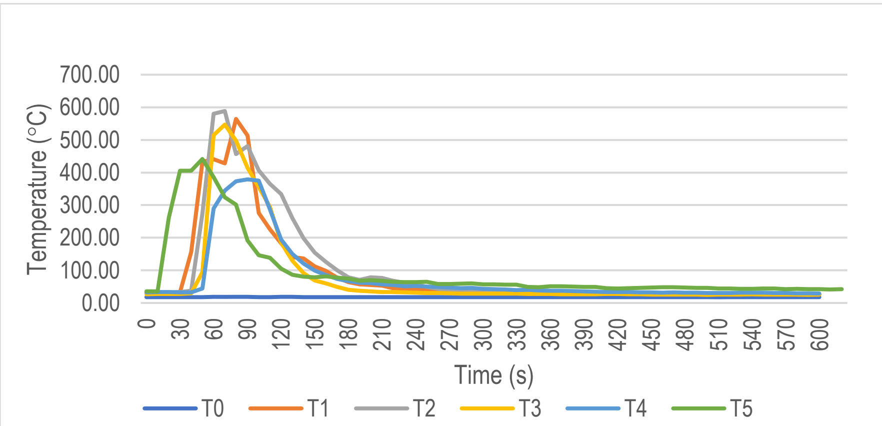

Figure 18 Temperature course during fire test 2 (chamber) recorded by thermocouples T1-T5

From the course of the provided fire tests, it is obvious that the different course of temperatures in the individual experiments. Combustion was initiated by igniting the fuel in the centre of the test dish (thermocouple T1). Thermocouple T0 recorded the temperature of the surrounding environment. In Table 3, there are presented the maximum temperature values reached on thermocouples T1-T5 during all three tests carried out in the laboratory chamber.

Table 3 Maximum temperature values reached by thermocouples – fire tests in the chamber

Fire test /Thermocouple	1		2		3	
	T MAX (°C)	Time (s)	T MAX (°C)	Time (s)	T MAX (°C)	Time (s)
T1 (C)	510.0	140	622.0	130	564.3	80
T2 (W)	549.6	100	546.8	120	588.7	70
T3 (N)	378.7	140	302.7	160	547.0	70
T4 (E)	497.6	110	402.9	210	379.0	90
T5 (S)	420.2	90	461.9	110	441.5	50

*Note: W – west direction; N – north direction; E – east direction; S – south direction; C – centre.

From the results shown in Table 3, it is possible to deduce that the heating of the fuel occurred gradually, depending on the direction in which the fire front progressed and where the fire controlled by the available fuel later occurred (maximum temperatures reached during further burning of the fuel). Since the ignition of the fuel always occurred in the centre of the test dish, it is obvious, for example in fire test 1, that the fire front moved from the centre of the test dish first towards the West (T2) and towards the East (T4), i.e., especially in the horizontal direction, slower in the vertical direction. In the case of fire test 2, the front of the fire moved faster especially towards the West (T2) and South (T5). In the case of fire test 3, fire spread the fastest both, in the Western (T2) and Northern (T3) directions.

Next, there are presented the results for the fire tests carried out in the laboratory fume hood (Figures 19 and 20). The obtained results were validated based on knowledge obtained from the study of thermal (infrared) imaging records.

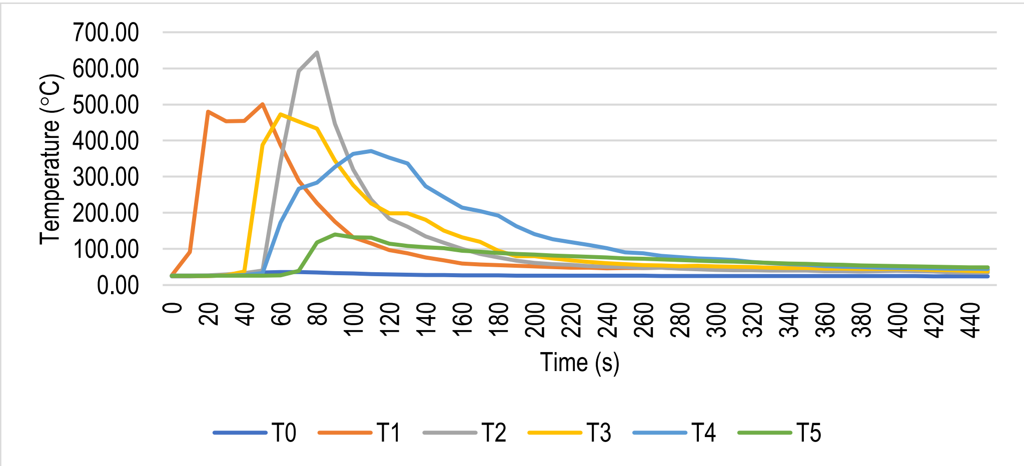

Figure 19 Temperature course during fire test 1 (fume hood) recorded by thermocouples T1-T5

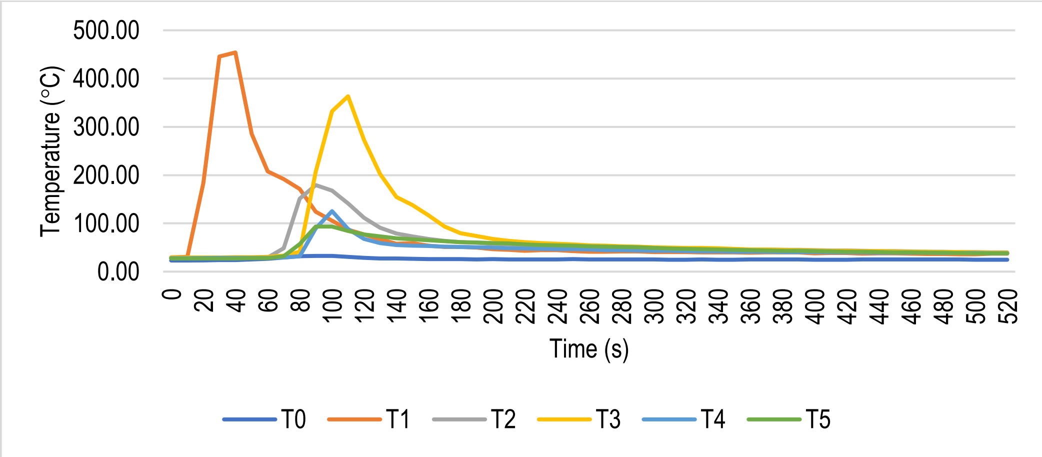

Figure 20 Temperature course during fire test 2 (fume hood) recorded by thermocouples T1-T5

As in the case of the fire tests carried out in the laboratory chamber, significant differences during both experiments were also seen in the case of the tests carried out in the laboratory fume hood. In Table 4 we present the maximum temperature values reached on thermocouples T1-T5 during both tests.

Table 4 Maximum temperature values reached by thermocouples – fire tests in the fume hood

Fire test	1		2	
/Thermocouple	T MAX (°C)	Time (s)	T MAX (°C)	Time (s)
T1 (C)	500.7	50	454.1	40
T2 (W)	644.0	80	179.3	90
T3 (N)	472.7	60	363.3	110
T4 (E)	371.1	110	125.3	100
T5 (S)	140.1	90	93.4	90

Results presented in Table 4 point out the fact that due to the above-mentioned principle of evaluating the results, in the case of fire test 1, the fire front moved first towards the western and northern edges of the dish. In the case of fire test 2, the fire front moved first towards the northern (upper) edge.

Images from a thermal imaging camera were used to validate the findings presented here. The results of the analysis of thermal imaging images pointed to the following facts. In fire test 1, the fire front moved fastest to the North, or Northwest, where it reached the northern edge of the test dish (T3) already in time of 43 s (Figure 21).

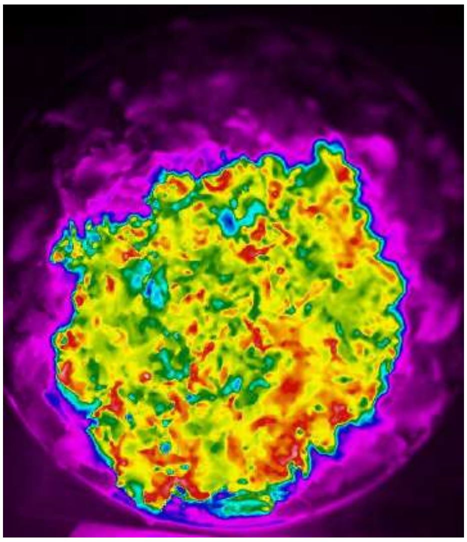

Figure 21 Fire front reached edge of the test dish – fire test 1

Subsequently, the fire front reached the western edge of the test dish at 56 s, the eastern edge at 65 s, and the southern edge of the dish at 67 s from the start of the fire test. Also, for this reason, considering the amount and structure of available fuel storage, the highest combustion temperatures were later reached at those positions.

In the case of fire test 2, the assumption about the spread of the fire front was not confirmed. Based on the results of the digital image analysis of the infrared images, the fire front moved significantly towards the Northern edge of the test dish at the beginning (Figure 22), but later it spread mainly towards the southern edge, which reached at time of 61 s. The western edge of the test dish was reached at time of 64 s from the beginning of the fire test.

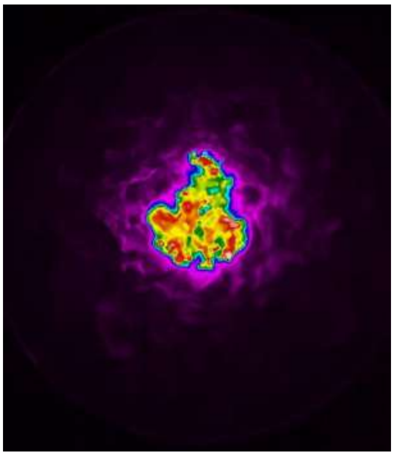

Figure 22 Fire front movement at the beginning of fire test 2 (time 20 s)

The fire front reached the eastern edge of the test dish in 73 s and the northern edge in up to 146 s, while on the surface of the test dish there was also an area of unburned fuel (Figure 23).

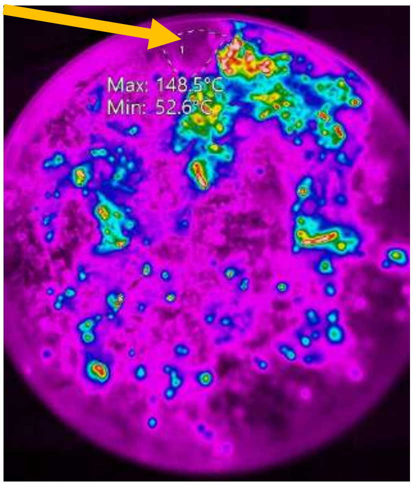

Figure 23 Position of unburned area in fire test 2

Temperature course – data from the thermal imaging camera

The temperature course on the surface of the test sample was recorded for the position of the individual thermocouples, the entire test dish and subsequently on the individual profile lines. To determine the temperature of the surface of the test sample, recordings from a Fluke RSE600 thermal imaging camera were used, which were processed in the SmartView R&D software. Therefore, the temperatures were determined only within the framework of 2 fire tests carried out in the fume hood.

The thermal imaging camera records individual images at an interval of 0.1 s. In Figure 24 and Figure 25, there are presented the values in this interval, therefore the time units are expressed in the format h:min:s, instead of seconds (s).

First, there are presented the results of the temperature course measured on the surface of the test sample detected at the positions of thermocouples T1-T5.

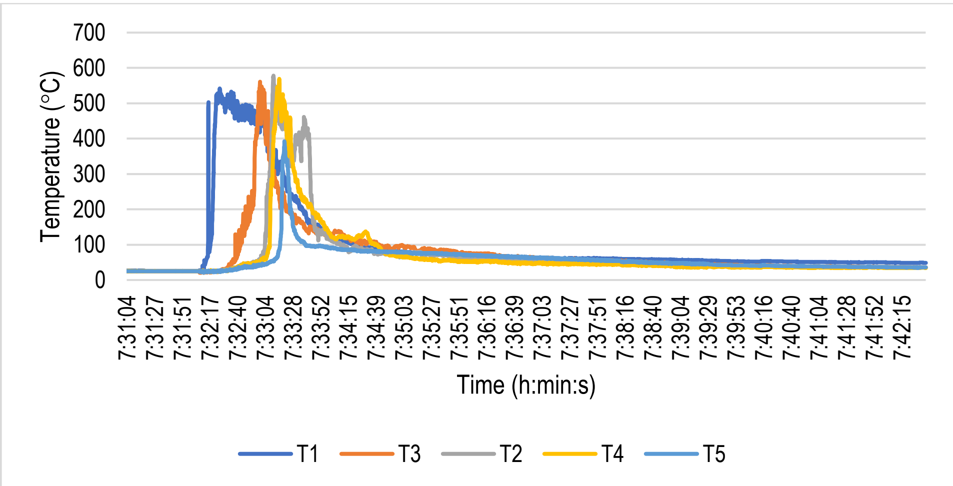

Figure 24 Temperature course during fire test 1 recorded by thermocouples T1-T5

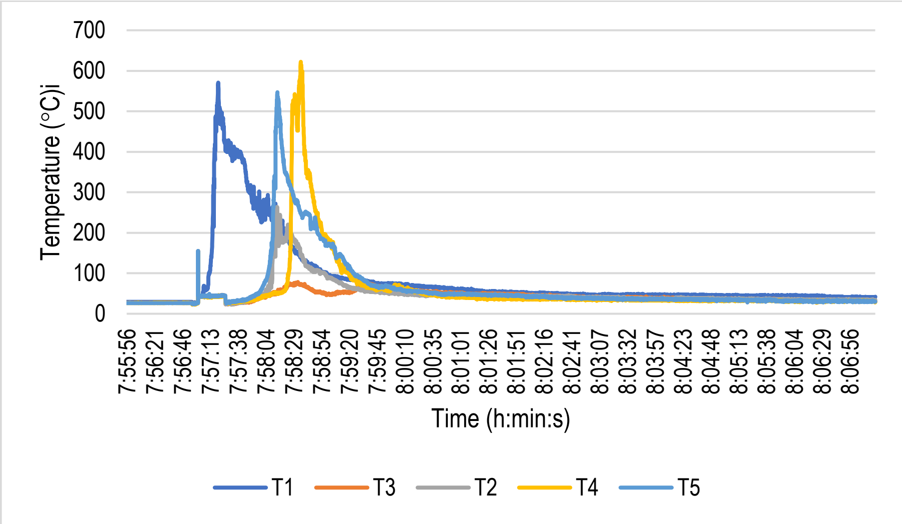

Figure 25 Temperature course during fire test 2 recorded by thermocouples T1-T5

During the fire test, the maximum and average temperatures reached during the burning of beech litter were recorded on individual thermocouples. In Table 5, there is an overview of these data, which are supplemented with the time in which this value was reached. At the same time, there also presented outputs from the SmartView R&D program, i.e., images from the thermal imaging camera, capturing the surface of the test dish and the course of the temperature of the sample during the fire at the pre-defined times, calculated from the start of the fire test.

Table 5 Maximum and average temperatures recorded by thermocouples during the fire test carried out in the fume hood

Fire Test	1		2	
/Thermocouple	T MAX (°C)	Time (s)	T MAX (°C)	Time (s)
T1 (C)	541.7	13	571.0	7
T2 (W)	578.0	59	264.2	58
T3 (N)	560.9	48	78.4	80
T4 (E)	568.6	64	622.5	82
T5 (S)	392.3	69	547.4	61

Next, there are presented thermal images recorded at time of 13 s (Figure 26), 48 s (Figure 27), 59 s (Figure 28), 64 s (Figure 29) and 69 s (Figure 30) from the start of the fire test. These show the propagation of the fire during the fire test 1.

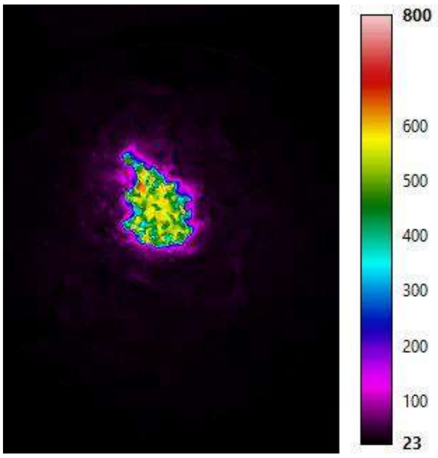

Figure 26 Fire propagation during the fire test 1 – time of 13 s

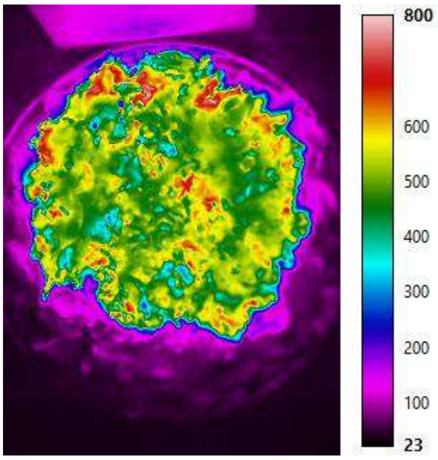

Figure 27 Fire propagation during the fire test 1 – time of 48 s

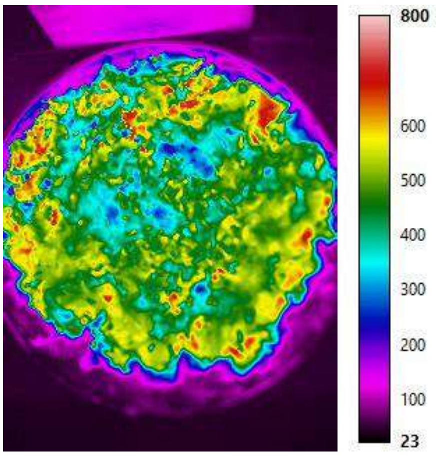

Figure 28 Fire propagation during the fire test 1 – time of 59 s

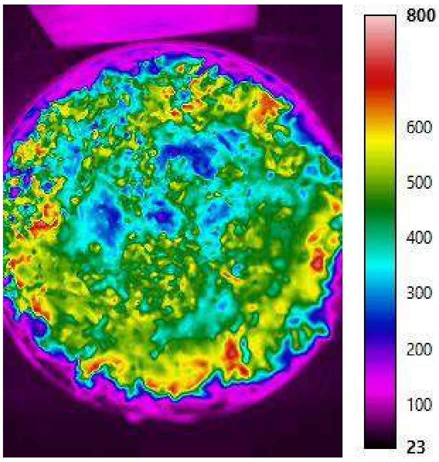

Figure 29 Fire propagation during the fire test 1 – time of 64 s

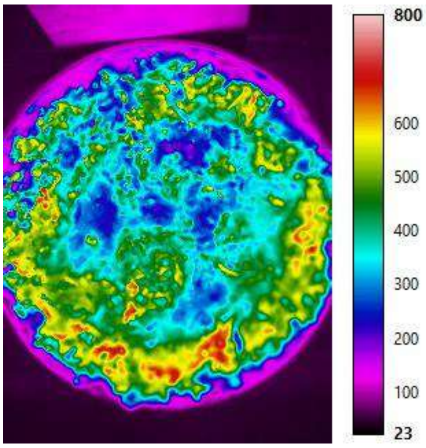

Figure 30 Fire propagation during the fire test 1 – time of 69 s

The course of temperatures during fire test 1 calculated for the area of the entire test dish is presented in Figure 31.

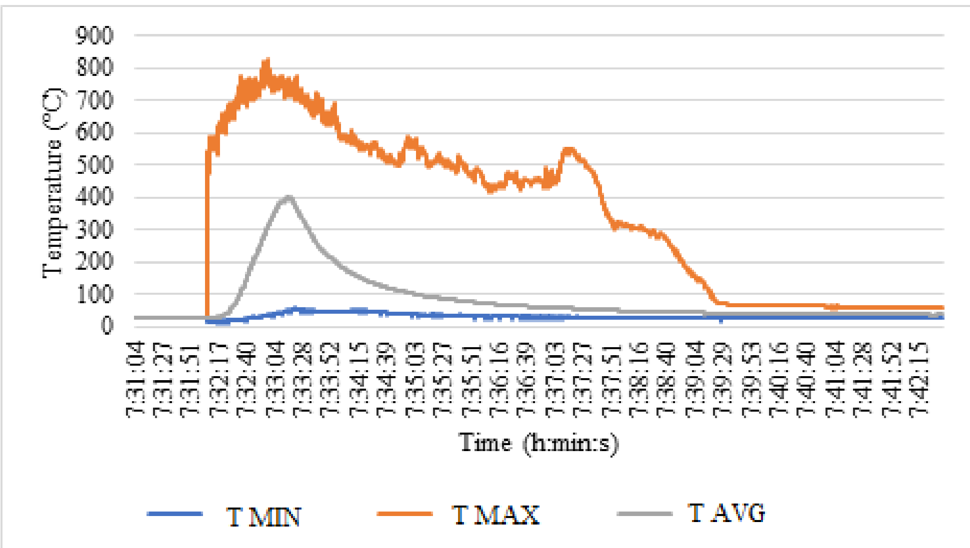

Figure 31 Temperature course within the area of the test dish during fire test 1

During the fire test 1, the maximum temperature value of 770.6 °C was recorded at 21 s from the start of the fire test. At this time, the highest average temperature during the test was also recorded, namely 179.7 °C. At the time of the end of the test, there were no more spots on the surface of the test dish leading to re-ignition of the fire in case of a sudden supply of air.

The temperature during burning was automatically detected on profiles (4 profiles - eight cardinal points) created in the SmartView R&D software based on temperature information stored in infrared images acquired by the FLUKE thermal imaging camera.

Comparison of temperature course inside and on the surface of the fuel sample

The comparison of the temperature course on the surface and inside the fuel during the fire test was possible when providing the fire tests in the laboratory fume hood, together with using the FLUKE RSE600 thermal imaging camera.

We consider it necessary to draw attention to the fact that the performed study present ways of using progressive recording techniques and digital image analysis of images to derive important fire parameters that serve to understand fire dynamics. The objective of the study was not the analysis of the behaviour of forest litter during a fire itself. This would require the implementation of a sufficient number of fire tests, e.g., for the purpose of deriving dependencies between parameters. The results presented here also correspond to this fact.

Figures 32-37 show the results of the fire test 1 and data recorded by the thermocouples T1-T5.

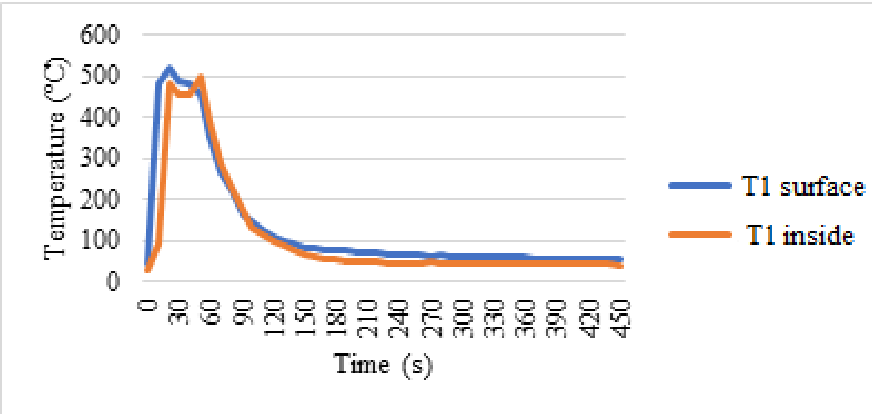

Figure 32 Temperatures course comparison on the surface and inside the fuel - fire test 1 (fume hood), T2

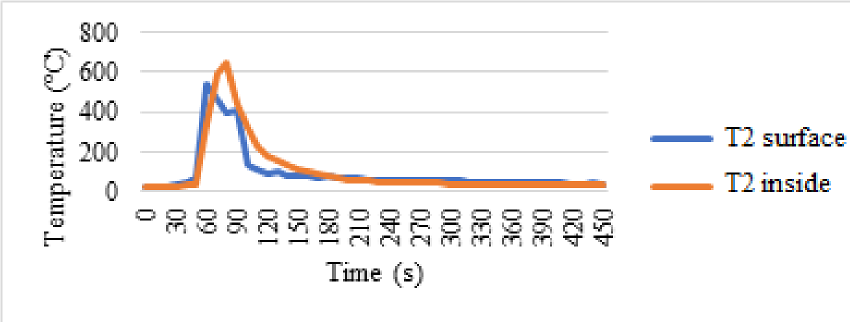

Figure 33 Temperatures course comparison on the surface and inside the fuel - fire test 1 (fume hood), T2

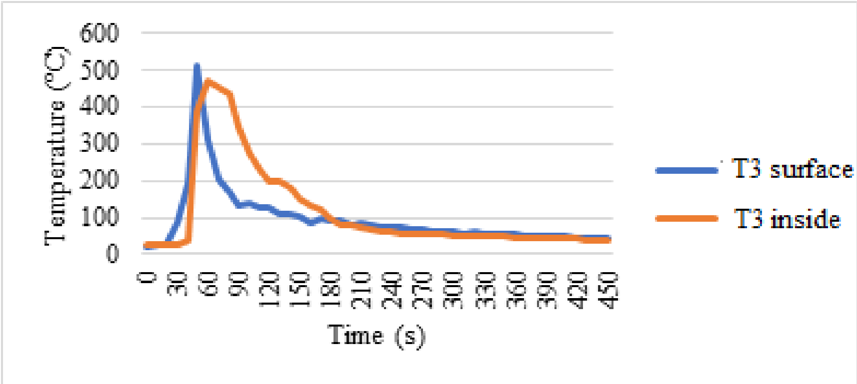

Figure 34 Temperatures course comparison on the surface and inside the fuel – fire test 1 (fume hood), T3

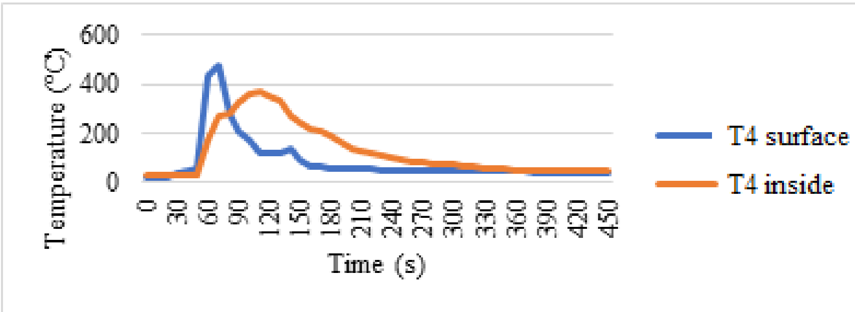

Figure 35 Temperatures course comparison on the surface and inside the fuel – fire test 1 (fume hood), T4

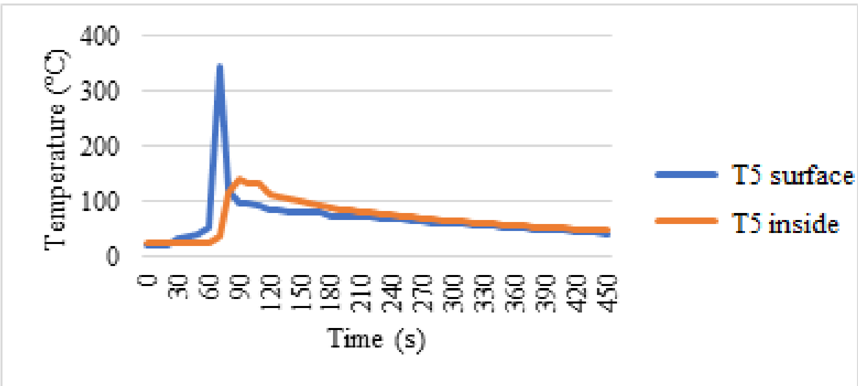

Figure 36 Temperatures course comparison on the surface and inside the fuel – fire test 1 (fume hood), T5

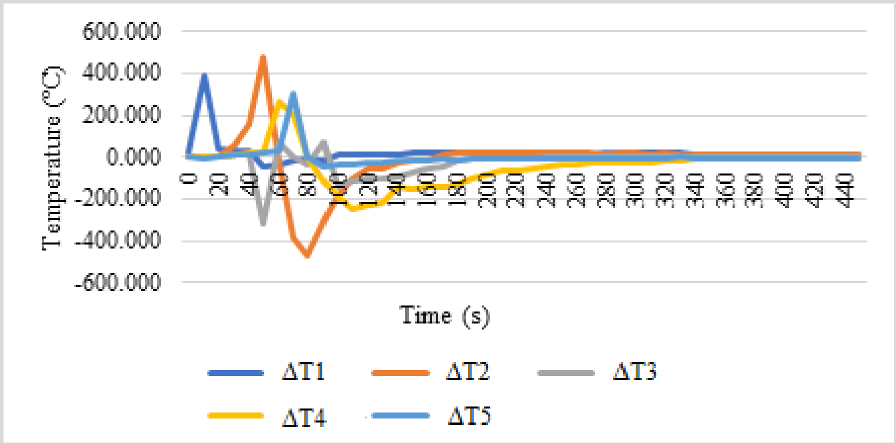

Figure 37 Temperatures course comparison on the surface and inside the fuel – fire test 1 (fume hood), T1-T5

The significant differences between the temperatures recorded by the thermocouples and the temperatures recorded by the thermal imaging camera occurred in the flame burning phase. The minimum (*T MIN*), maximum (*T MAX*) and average (*T AVG*) values of temperature differences at the position of individual thermocouples during the fire tests are provided in Table 6.

Table 6 Values of temperature differences at the position of individual thermocouples during fire test 1

Fire test /Thermocouple	1			2		
	ΔT MAX (°C)	*ΔT MIN* (°C)	*ΔT AVG* (°C)	*ΔT MAX* (°C)	*ΔT MIN* (°C)	*ΔT AVG* (°C)
T1 (C)	389.7	-45.0	24.7	452.7	-184.2	19.9
T2 (W)	473.8	-473.1	-11.3	157.0	-67.1	-2.4
T3 (N)	72.1	-319.7	-22.6	34.8	-316.4	-29.7
T4 (E)	258.4	-250.0	-42.2	437.9	-8.9	20.6
T5 (S)	305.3	-43.7	1.7	402.8	-8.4	27.1

Duration of flame burning and glowing/smouldering

The study of combustion during fire tests was divided into flame and flameless combustion phases. From the measured values and calculations, we determined 3 phases of combustion. While the flame burning phase itself took place in two sub-phases, i.e., phases of fire development and steady burning. Flameless combustion took place in the last phase called decay. While the highest mass loss, relative burning rate, highest temperatures and flame height were observed right during the flame burning. The rate of the flame burning allowed the fire to spread around the entire perimeter of the test dish. During flameless combustion, the values were stabilized and without significant changes until the end of the experiment. The transition from flameless combustion to flameless combustion was accompanied by smoke, which could be observed visually.

The duration of flame burning was detected from video images analysis. In Table 7 and 8, we present data on the duration of flame and flameless (smouldering/incandescence) burning (also as a percentage of the entire duration of the fire test, i.e., 600 s) for fire tests carried out in the laboratory chamber and for fire tests carried out in the laboratory fume hood. The burning was initiated by the flame of a match.

Table 7 Flame burning duration

Fire test	Flame burning duration (s)	Flame burning duration (%)
Chamber1	132	22
Chamber2	169	28
Chamber3	154	26
Hood1	176	29
Hood2	217	36
Average Chamber	152	25
Average Hood	166	28

Table 8 Glowing/smouldering duration

Fire test	Glowing/smouldering duration (s)	Glowing/smouldering duration (%)
Chamber1	328	55
Chamber2	271	45
Chamber3	296	49
Hood1	265	44
Hood2	min. 383	min. 64
Average Chamber	298	50

As seen from the results shown in Table 7 and Table 8, there are obvious differences in fire behaviour between the individual tests. The reason for this is mainly the fact that forest litter is not a homogeneous material in its structure, like e. g. wood. The behaviour of the fire in this case is mostly influenced by its distribution on the surface and the overall structure of the fuel. Even with the greatest effort to create test samples that will be similar. This will create a problem because such samples cannot be prepared with this type of material. However, this does not mean that it is not necessary to investigate them, on the contrary, we need to create an extensive set of data based on several fire tests and then try to derive dependencies between the parameters affecting the behaviour (dynamics) of the fire.

Flame height

In terms of flame height, several parameters were monitored. The maximum, mean and average flame height values were derived from the video data extracted for 5 s intervals of flame burning. Results are presented in Table 9 and Table 10.

Table 9 Average and maximum flame height

Fire test	Average flame height (m)	Maximum flame height (m)
Chamber1	0.24	0.52
Chamber2	0.20	0.72
Chamber3	0.16	0.50
Hood1	0.16	0.45
Hood2	0.08	0.21

Further, there are introduced results for mean flame height (Table 10).

Table 10 Mean height of the flame according to equation (4)

Fire test	Mean height of the flame (m)	Time (s)
Chamber1	0.16	65
Chamber2	0.02	85
Chamber3	0.04	80
Hood1	0.01	90
Hood2	0.03	110

Using the results of fire tests carried out in the fume hood, there was developed an algorithm that enables the automated calculation of the density of the radiated heat flux (equation 9) for the entire area of the test dish.

There are only presented the results for the maximum temperature values recorded in both fire tests.

In the case of fire test 1, the highest temperature, 770.6 °C, was recorded by the thermal imaging camera at time of 21 s from the start of the fire test. After substituting this temperature into equation (9), we obtained the value of the wavelength of the maximum radiation intensity at the level of 0.0038 mm = 3.8 μm (mid-wave infrared radiation – MWIR).

A higher maximum temperature value was reached during the fire test 2 (797.6 °C), within 65 s from the start of the test. In this case, the wavelength value of the maximum radiation intensity was calculated to be 0.0036 mm = 3.6 μm (MWIR).

Next, the result of the automated determination of the wavelength of the maximum radiation intensity in the form of a time profile of the density of the radiated heat flux calculated for the centre of the test dish (position T1) are presented (Figure 38).

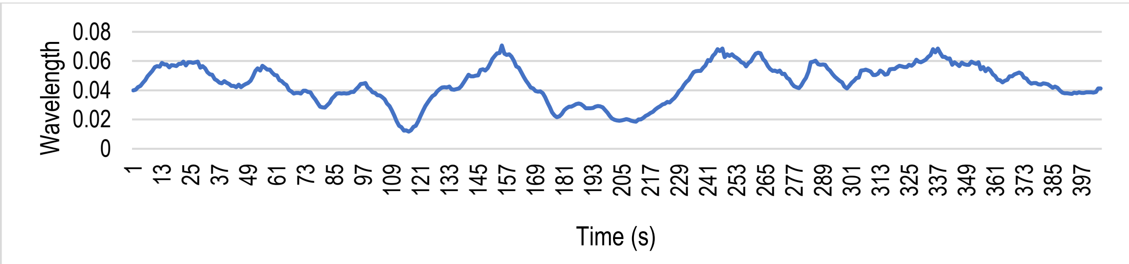

Figure 38 Density of radiated heat flux in time in the centre of the dish (position T1)

These values are extracted from the generated image, where each pixel contains a wavelength value calculated according to formula (5). After converting the values from mm to μm and classifying (reclassifying) the wavelength values into the appropriate category, we obtain information about the type of infrared radiation and its spatial distribution on the surface of the sample (material).

Burning rate

From the point of view of calculating the burning rate, we focused on determining the relative mass burning rate and surface burning rate of fuel recorded on surface of the test dish.

Relative mass burning rate

We mass burning rate is expressed based on the mass loss data, which was recorded during the tests with accurate scales from the RADWAG company. The fire test lasted a total of 600 s = 10 min.

In Figure 39, there are presented the results of mass loss for fire tests carried out in a laboratory chamber.

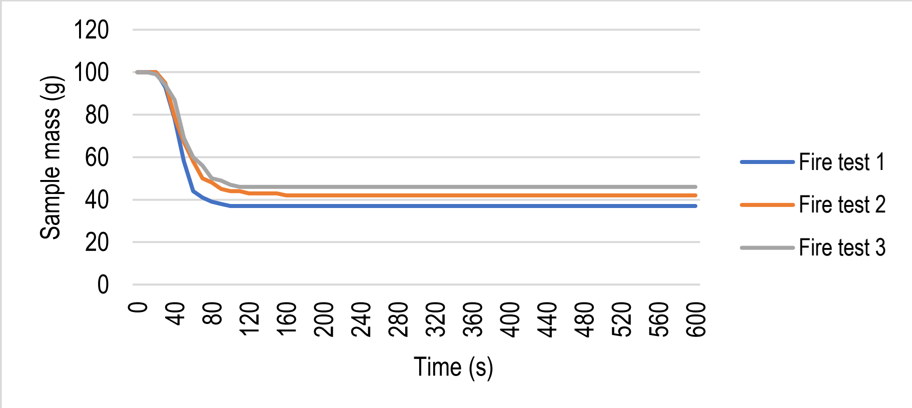

Figure 39 Mass loss of samples during fire tests carried out in the chamber

Figure 40 gives a view of the relative mass rate of burning of the samples during the implementation of fire tests in the laboratory chamber.

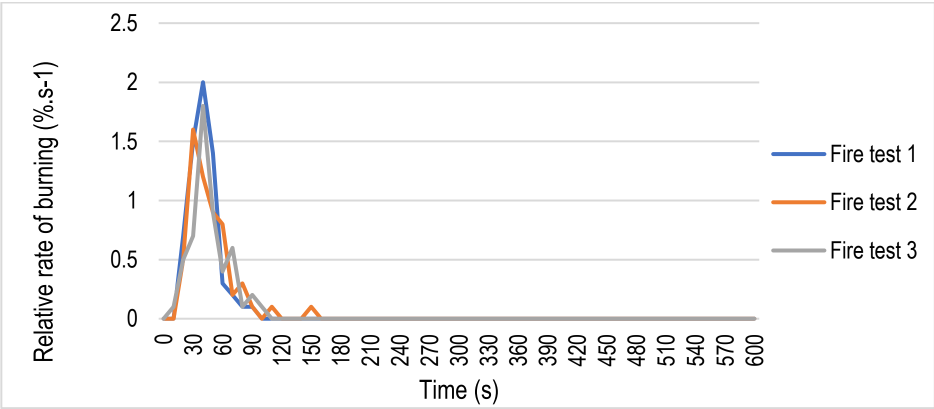

Figure 40 Relative mass burning rate of samples during fire tests in the chamber

In Figure 41, there is introduced the results according to the mass loss of samples during fire tests provided in laboratory fume hood.

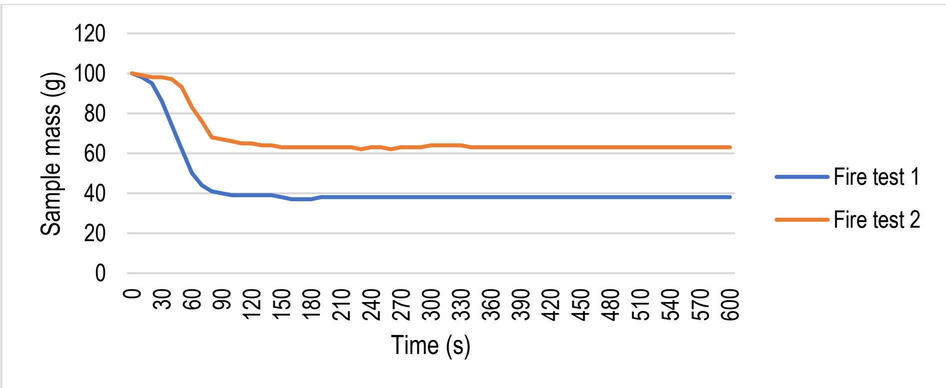

Figure 41 Mass loss of samples during fire tests carried out in the fume hood

Figure 42 provides an overview of the relative mass rate of burning of samples during fire tests in a laboratory fume hood.

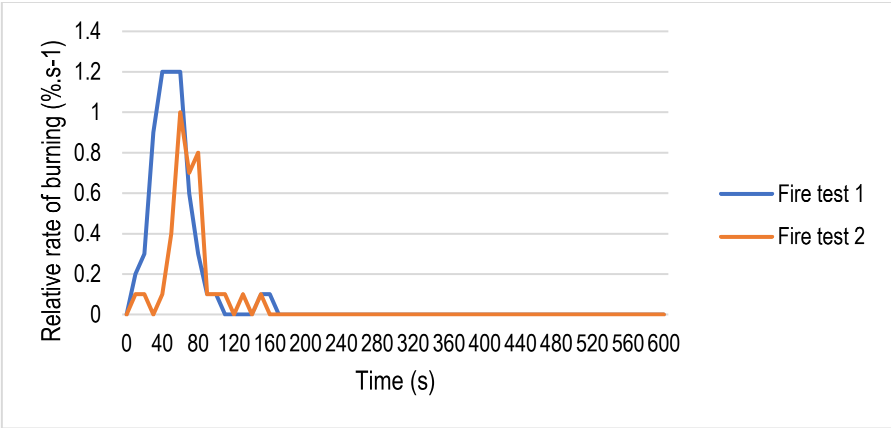

Figure 42 Relative mass burning rate of samples during fire tests in the fume hood

Surface burning rate

The calculation of the surface burning rate was preceded by analyses aimed at determining the increase in the burning area (burning area with a temperature above 400 °C) within the test dish over time (time interval of 1 s). Here are presented the results for fire test 1 (Figure 43). At the same time, there are also presented the result regarding the extent of the fire area on which the temperature above 400°C was reached during the fire (Figure 44).

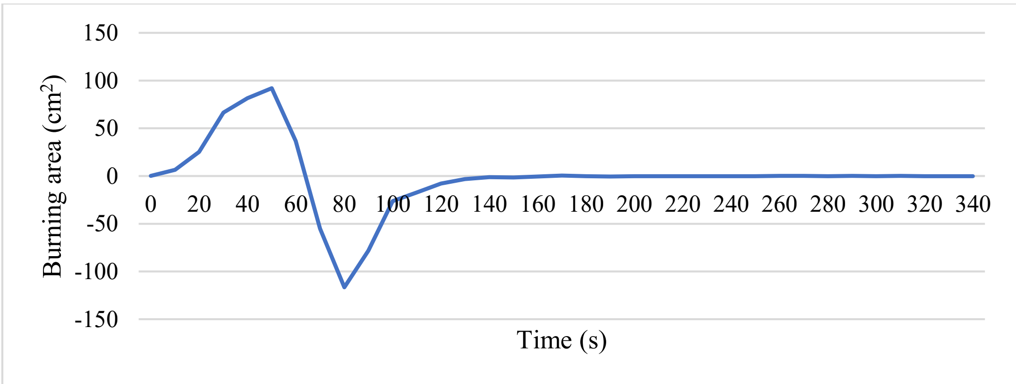

Figure 43 Fire test 1 – Increase in burning area over time

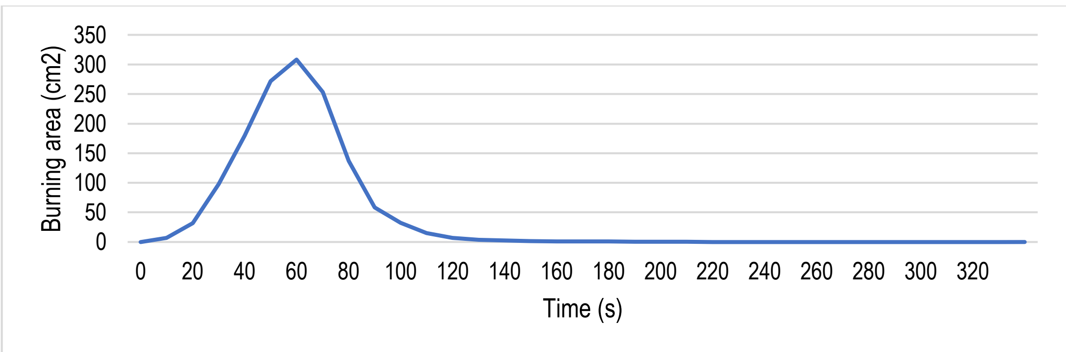

Figure 44 Fire test 1 – Total burned area over time

From Figure 43 and 44, it is obvious that the highest increase in the burning area is precisely in the phase of flame (steady) burning. While the maximum increase in the burning area was recorded in 50 s after the start of the fire test and represented a value of 92 cm^2. In the time 60 s after the start of the test, the largest burning area was reached, namely 308 cm^2.

The surface burning rate was calculated based on the algorithm developed in the Python programming language. In this subsection, we present the results of the image analysis for fire test 1, the images of which were also used for the development of an algorithm for the automated calculation of the area burning rate of the sample in 600 s.

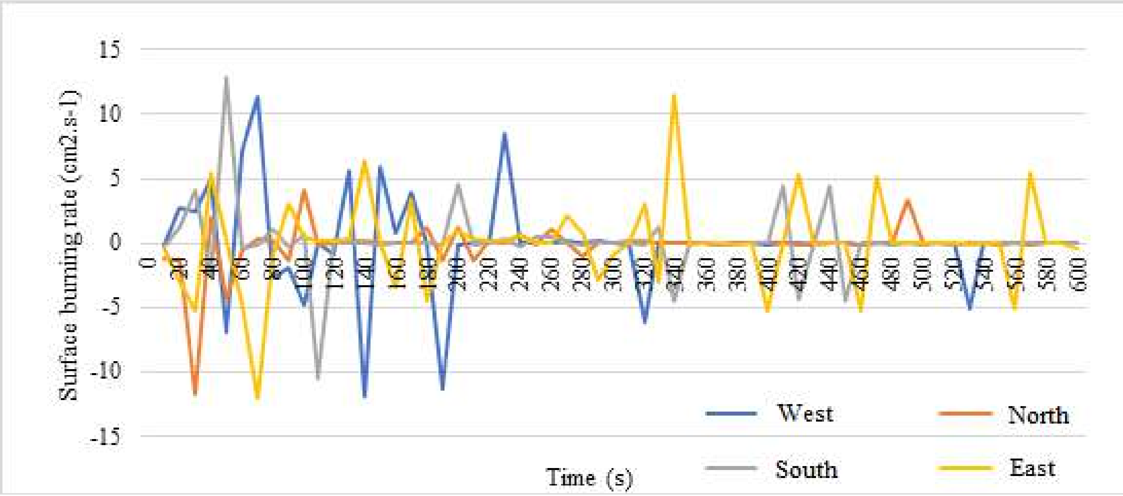

Figure 45 Course of the surface burning rate in four directions in 10 s intervals

In Figure 45, it is possible to detect phases in which the burning took place faster (flame burning phase) and phases where the burning rate values reached lower values (smouldering phase). In the direction to the south (to T5) from the centre of the bowl, the maximum value of the surface burning rate of 12.8 $cm^2 \cdot s^{-1}$ was reached in 50 s from the start of the fire test. In the direction to the west (to T2) from the centre of the bowl, the maximum value of the surface burning rate of 11.3 $cm^2 \cdot s^{-1}$ was reached in 70 s from the start of the fire test. In the direction to the east (to T4) from the centre of the bowl, the maximum value of the surface burning rate of 11.5 $cm^2 \cdot s^{-1}$ was reached in 340 s from the start of the fire test. In the direction to the north (to T3) from the centre of the bowl, the maximum value of the surface burning rate of 4.1 $cm^2 \cdot s^{-1}$ was reached in 100 s from the start of the fire test.

The values of the surface burning rate reached not only positive but also negative values. The reason is mainly heterogeneity of fuel. In the case of a homogeneous fuel, the propagation would be constant, but the heterogeneity of the fuel caused differences in the time required for preheating the fuel and its subsequent ignition. At the same time, after burning off the fuel in the parts near the place of initiation, it subsequently cooled down, which caused the reduction of the total area with a temperature above 400 °C.

In Figure 46, there is presented the course of surface burning rate in 1 s intervals.

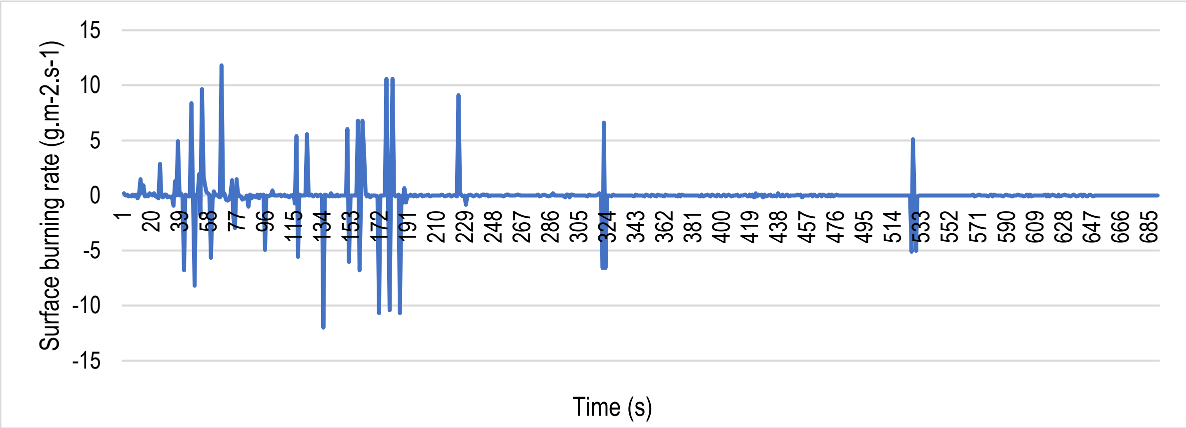

Figure 46 Course of the surface burning rate in 1 s intervals

Automated delineation of flame outlines

For the completeness, we also present the image processing methodology/algorithm applicable in the Idrisi Terrset environment, as well as an example sample of the outputs from the image analyses aimed at identifying the flame outlines (2D visualization of the flame) from the sequence of frames obtained from the video recordings.

File/Import/Desktop Publishing Formats/JPGIDRIS (Output Reference Information/Plane)

File/Display/SEPARATE	Creates separated images (raster) from 24-bit colour or any other binary image in RGB channels. For further analyses select raster *Band 2.*
Digitize/Polygon	Serves for creation of polygon vector layer (test dish outline) based on raster file (image). Specify the name of the file and digitize the outline of the test dish by continual clicking on the left mouse button.
RASTERVECTOR	Converts the vector file with test dish outline to raster file. The spatial parameters of creating raster file should be copied from raster *Band 2* (select it from the list).
Idrisi GIS Analysis/Image Calculator	(*Raster file with outline of the test dish*raster Band2)* Creation of a raster reducing the image extent to area with test dish and flame.
Idrisi GIS Analysis/Database Query/Reclass	Reclassification of raster values into two classes based on thresholding the flame spectral values. (In study, the reclassification of raster values with threshold of 190 was applied for flame detection).
Composer/Add Layer/Vector	Visualization of the 2D surface of the flame within the test dish. Using this procedure, we overlay the raster image of the

2D flame with a vector one representing the outline of the dish (Figure 47).

Figure 47 Flame area during the fire test 1 in time of 20 s

Outputs (raster files) of image analysis from the Idrisi TerrSet environment can be further processed (calculation of flame height) in this environment these outputs can be used after exporting them to ASCII text format as input data to other program environments such as MATLAB to process further calculations.

Conclusions

In terms of contributions for science, the study presents the possibilities and suitability of applying digital technologies for the study of fire behaviour and automated extraction of selected fire parameters (e.g., the development of fire temperatures over time on the surface of the sample, the calculation of the surface burning rate over time, the detection of the flame shape and height, etc.).

It also provides guidance for carrying out similar experiments using digital technologies to study the behaviour of fire, also in other types of materials, as well as to study the fire dynamics in enclosed spaces, but also in the process of fire investigation.

The course of the fire tests carried out, recorded by the thermal imaging camera and by the video (optical) camera, and the digital outputs themselves are a key input to the image analyses and the creation of algorithms enabling the automated derivation of selected fire parameters from them.

The contribution of the study to research in the field of fire dynamics and fire investigation are mainly the developed algorithms, which are not presented here, but which allow a broader and more comprehensive use of the knowledge obtained from thermal imaging camera recordings as well as from classical video recordings. The algorithms are written in Python and are easily extensible, i.e., additional analytical functions can be added to the algorithms. They are the basis for their further and broader application in research, specifically in the field of machine learning and the application of artificial intelligence tools.

In terms of practical application, the developed algorithms for automated derivation of fire parameters are immediately applicable, especially in the practice of fire investigation.

3.3 Wildland fires history

3.3.1 Wildland fires history in Europe

The number of forest fires worldwide has been steadily increasing in recent decades. It is now estimated that on average up to 600 000 ha of forest are damaged or even destroyed by forest fires each year [100].

In Europe, but also worldwide, the situation regarding the frequency of fires is steadily worsening and the consequences can be severe. But in the current situation, several factors create favourable conditions for fire. Natural and especially climatic factors usually predetermine the probability of wildfires. Management measures in forests are additional factors influencing fuel accumulation in forests, mainly due to fire suppression and gradually expanding transit zones between urban areas and the natural environment [101,102]. Consequently, the distribution of forest fires in space is determined not only by climatic conditions but also by socio-economic factors [103,104].

Socio-economic factors could be simplistically described by concepts such as gross domestic product, population, or livestock density. Explicit linkages and interactions between these factors have been studied particularly in the Mediterranean region, where, over the last decades, changes in fire occurrence are also closely related to socio-economic changes [105-107].

Urbanization due to the departure of young populations from rural areas and agricultural mechanization leads to another problem, namely fuel accumulation [108-110].

In many cases, the limited availability of volunteers and firefighters in rural areas leads to an increase in uncontrolled fires caused by grassland burning [110]. These problems are strongly influenced by national policies.

Grassland burning on agricultural land is a common practice throughout Eastern Europe in spring and early summer [111].

In general, there is now also a preference in forestry management practice for a shift in forest management from achieving a purely productive forest function to nature conservation and its use for recreational purposes. On the other hand, the recreational use of the forest also means the gradual construction of cottage settlements, which will cause an increase in transit zones between the built-up area and the natural environment, which increases the risk of fire occurrence, as man and his intentional or unintentional activity is still the most common cause of fire in the natural environment.

All these factors and processes influence the risk of fire occurrence on a general European scale, but it should also be stressed that, compared to the Mediterranean countries, the conditions in Central and Eastern Europe often lack consistent and long-term records of fire occurrence, based on which data can be used to calculate the risk of fire occurrence using statistical and geostatistical methods [112-113]. 2011).

Due to the lack of the Annual Report on Forest Fires in Europe, the Middle East and North Africa in 2022, there is introduced the statistics of fires, which occurred in 2021. They have been even more destructive than the ones in 2021, confirming the worrying destructive trend of recent years. In fact, an area covering 8,600 km² already burnt in 2022. [114]

In 2021, wildland fires were mapped in 22 of the EU 27 Member States, burning 500,566 ha in total, more than the approximate 340,000 ha of 2020 but far from 1 million ha of 2017. [84]

The 2021 report on forest fires shows that Italy was the most affected country in terms of burnt area, followed by Turkey, Portugal, and Greece, especially in August, as highlighted by national reporting.

Wildfires severely affected Europe's Natura 2000 protected sites. The total area burned in 2021 was 102,598 ha (about 20% of the total area of all Natura 2000 sites), less than the last two years and slightly below the average of the last 10 years.

In southern EU countries with longer recording periods, burnt areas doubled compared to 2020 and it was the second worst year since 1986 in terms of average fires size. The total number of fires was the lowest recorded, meaning that there were far fewer but larger fires. [84]

3.3.2 Wildland fires history in Central European countries

Slovakia

The wildfires are caused mostly by human activities in Slovakia. Most often, it is a deliberate human activity associated with the burning of agricultural and grassland areas close to the forest. This activity is typical throughout the territory, particularly in the spring and autumn seasons. It is most pronounced in the period of the survey of meadows and pastures in the territory of the Slovak Republic, which is carried out by the Ministry of Agriculture of the Slovak Republic and the outputs of which are used for redistribution of subsidies for haying of meadows and pastures to their owners or users. This is carried out at 10-yearly intervals. The last survey was carried out in 2022. The fire statistics for 2022 confirmed this fact. [84]

The fire season 2021 was not critical from the point of view of fire danger (Figure 48).

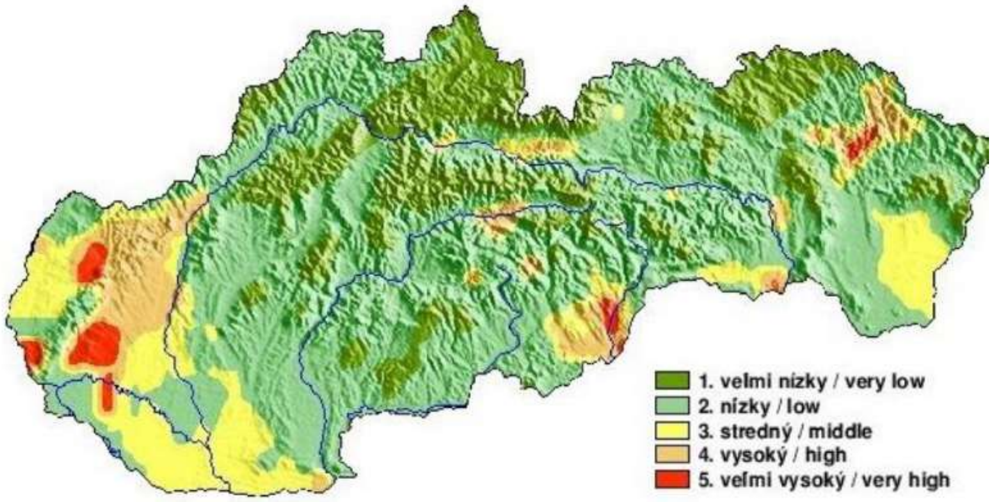

Figure 48 Forest fire danger map (Source: [84])

The number of wildfires and the average size was like previous years. The number of fires was influenced substantially by the weather, the number of days with rain and the human factor (negligence particularly) in spring and summer.

A total number of 101 forest fires was reported in Slovakia in 2021, corresponding to a total burnt area of 158.94 ha. The average burned forest area per fire was of 1.6 ha. The most extensive fire occurred in March 2021 around the village Mužla, district Nové Zámky, and damaged 40 ha of mixed forest. The cause of the fire was negligence of adults.

The fire causes in 2021 were represented by logging and forest operations (28%), human negligence (campers, visitors, children), unknown (24%), agricultural operations (8%), arson (8%), natural causes (6%), other (2%).

In Table 11, there is introduced fire history for period 2007-2021

Table 11 Number of fires, burnt area in Slovakia since 2007 (Source: [84])

Year	Total number of wildland fires	Forest fires		Wildland fires in other land
		Number	Burned area (ha)	Number
2007	4,355	463	679	3892
2008	2,012	182	118	1830
2009	3,174	347	510	2827
2010	3,433	123	192	3310
2011	6,338	303	403	6035
2012	7,380	517	1683	6863
2013	3,669	233	270	3436
2014	3,419	153	192	3266
2015	4,770	242	353	4528

Year	Total number of wildland fires	Forest fires		Wildland fires in other land
		Number	Burned area (ha)	Number
2016	2671	136	175	2535
2017	4456	162	295	4294
2018	3150	262	248	2888
2019	3933	210	462	3723
2020	5883	221	477	5662
2021	3823	101	159	3722
Average	4,164.4	243.7	414.4	3,920.7
Total	62,466	3,655	6,216	58,811

Czech Republic

Forest fires fighting and prevention is covered by the Fire and Rescue Service of the Czech Republic. In 2021 a total number of 1,517 forest fires were recorded and ca. 411 ha of forest areas were burned. The total number of fires was around average compared to the 10 years average (2011-2020) of 1,410. The burned area was also almost the 10 years average of 375 ha. The 2021 fire season was not as severe as 2020, but considering total numbers, it was one of the worst fire seasons in the last 20 years. In general, the fires were very often corresponding to the usual fire risk degree over the country (Figure 49)

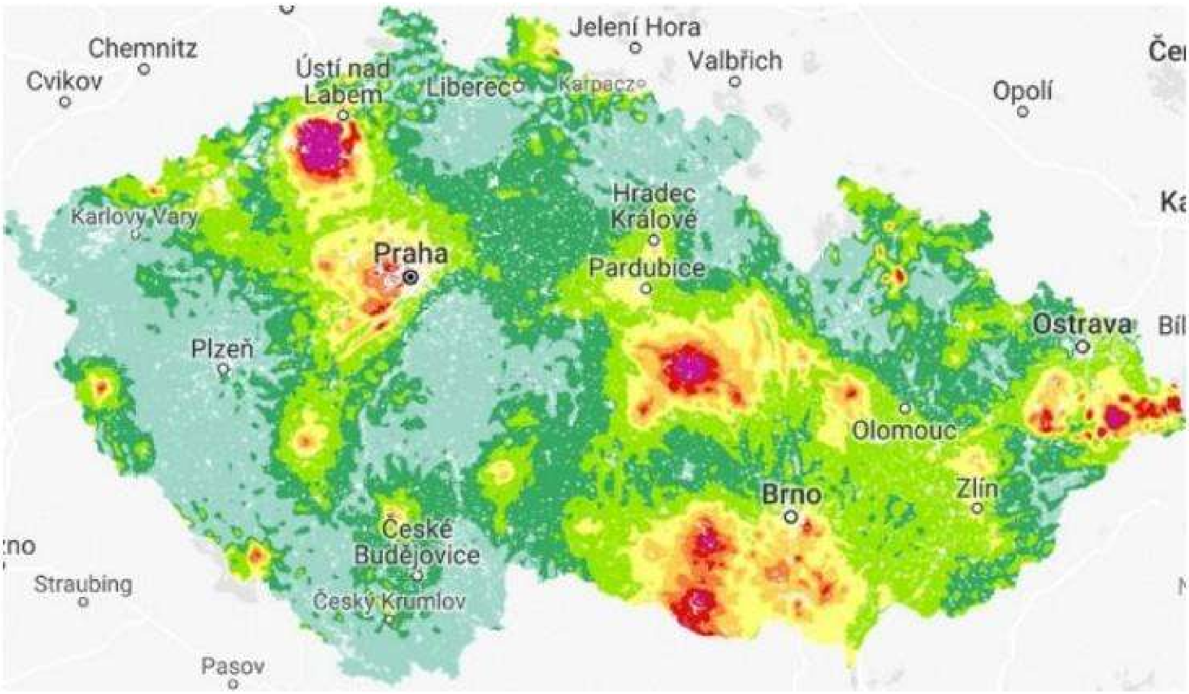

Figure 49 Figure Forests with high risk level, common situation
(Source: Czech Academy of Sciences, 2022)

In Table 12, there is provided information of wildfires history since 2005.

Table 12 Number of fires, burnt area, economic losses, and casualties in Czech Republic since 2005 (Source: [84])

Year	Number of fires	Burnt area (ha)	Dama136ge caused162 (m EUR)262	Saved values (m EUR)	175People killed	Pe2535ople injure4294d
2007	805	316	0.7	13.3	0	202888
2008	470	86	0.1	4.5	3	10
2009	514	178	0.3	6.2	0	20
2010	732	205	0.2	5.0	1	12
2011	1,337	337	0.3	6.5	1	27
2012	1,549	634	1.8	26.2	2	30
2013	666	92	0.2	3.0	0	7
2014	865	536	0.3	3.3	2	10
2015	1,748	344	0.7	24.7	1	33
2016	892	141	0.2	7.8	0	6
2017	966	170	0.3	3.4	2	9
2018	2,033	492	0.6	10.5	0	35
2019	1,963	520	0.7	12	0	31
2020	2,081	484	0.7	10	2	21
2021	1,517	411	0.3	7.1	0	15
Average	1,209.2	329.7	0.5	9.6	0.9	19.1
Total	18,138	4,946	7.4	143.5	14	286

Hungary

Data on Forest fires are collected in close cooperation with the disaster management authority. Data are collected on the spot by fire fighters, who have been uploading the database day by day. Forest fires data are produced and analysed with a GIS method and checked on the spot by the forest authority. The gathered fire data are processed and evaluated by size, date, cause, and duration of fires. Data from 2011-2021 are shown in Table 13.

Table 13 Number of fires, burnt area in Hungary since 2007 (Source: [84,88])

Year	Total number of wildland fires	Forest fires		Wildland fires in other land
		Number	Burned area (ha)	Number
2007	6,691	603	4,636	6,088
2008	6,639	502	2,404	6,137
2009	8,658	608	6,463	8,050
2010	3,120	109	878	3,011
2011	8,436	2,021	8,056	6,415
2012	15,794	2,657	14,115	13,137
2013	4,424	761	1,955	3,663
2014	5,535	1,042	4,454	4,493
2015	5,057	1,069	4,730	3,988
2016	2,531	452	974	2,079
2017	6,782	1,454	4,934	5,328
2018	2,981	530	906	2,451
2019	7,296	2,088	6,541	5,208
2020	4,339	1,239	2,895	3,100
2021	4,350	1,154	2,413	3,196
Average	6,138.6	1,315.2	4,724.8	4,823.5
Total	67,525	14,467	51,973	53,058

A total of 1,154 forest fires were registered in 2021. This value is not extreme; it is considered average in this decade. The average burned area per fire was of 21 ha. Fire totally or partially consumed forests and caused serious damages. Based on the yearly data set, there were more wildland fires than the average of the previous 10 years during summer 2021.

There are two most dangerous forest fire periods during every year. Traditional use of grassland includes burning methods in early spring, which can accidentally spread to nearby forest. These fires usually burn in March and April. Spring forest fires usually burn with low or medium intensity in broadleaf forests, juvenile growth, shrubs, and grasslands. Summer fires were registered in the Great Plain, where crown fires can also occur in pine forests.

In 2021, a total of 618 forest fires occurred in spring, which is 53% of all forest fires in 2021. Most of the spring fires (49%) burn in northern areas (Borsod-AbaújZemplén County, Heves County, Nógrád County and Pest County), see Figure 50. It indicates these areas as high forest fire danger zones. In these areas not only traditional grassland management methods, but other social-economic factors add to forest fire danger. A total of 463 forest fires occurred in the summer period but there were no large fires last summer.

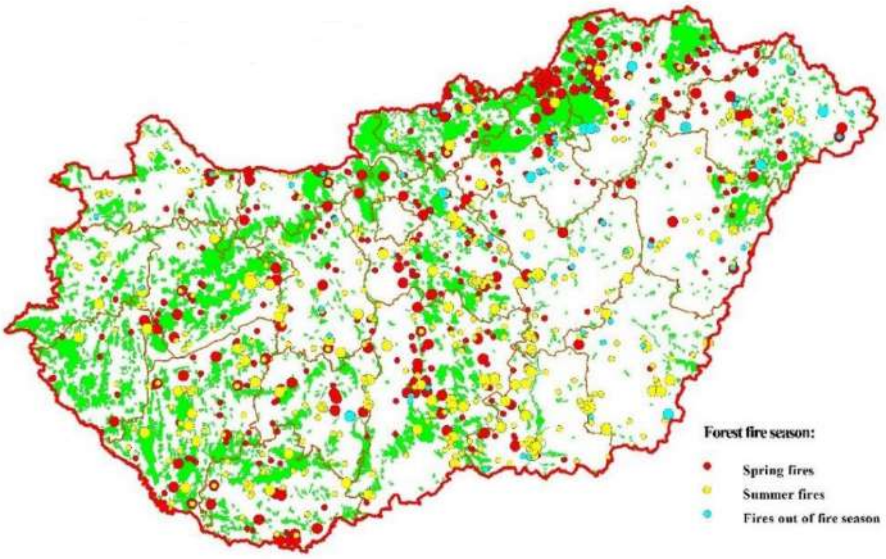

Figure 50 Locations of forest fires in Hungary in 2021

Up to 95% of wildland fires are surface fires in Hungary. Surface fires, when surface litter and other dead vegetal parts and smaller shrub burn have been common in Hungarian wildland. They can develop in whole fire season. Crown fires are mostly occurring in coniferous forests, mainly in the Great Hungarian Plain during summer. Ground fire is not significant in Hungary, though – due to partial, relatively thick peat – it is not unknown either. (http://erdotuz.hu/forest-fires-in-hungary/)

Most forest fires do not ignite inside the forest, but in the agricultural area adjacent to it. Approximately 58% of the wildland fires in 2021 occurred in a 500 m buffer zone around residential areas. Up to 88% of all wildland fires were no further than 2 km from residential areas in 2021. Up to 98% of forest fires were surface fires in fire season 2021, when surface litter and other dead vegetal parts and smaller shrubs burnt down. The average rate of fires smaller than 1 ha is almost 77%. There was no large forest fire in 2021. There were only 2 fires where more than 50 ha were burnt. Statistical analysis showed that the number of forest fires under 0.5 ha has been increasing in the last decade. In particular, the increase in the number of spot fires under 1,000 m^2 is significant.

Considering the fire causes, up to 99 % of forest fires were human induced (negligence or arson). Most fires are induced by negligence (adults and infants) and only a small proportion of fires are caused by arsonists. Typical forest fire causes are the incorrectly extinguished fires of hikers, illicit agricultural fires, discarded cigarette butts and sometimes slash burning.

Poland

The meteorological conditions determined the fire danger risk trend in the year 2021 and favoured the occurrence of wildland fires, especially at the beginning of the fire season.

In 2021 in Poland, a total of 3 295 fires broke out (2 243 in forest and 1 052 in other non-wooded natural land), over 3 332 less than in 2020 (6 627 fires), with a surface area of 893.74 ha (575.42 forest and 318.32 ha other non-wooded natural land), over 7 522.90 ha less than in the last year (8 416.64 ha). The greatest proportion of fires occurred in June 2021 (31.23%; i.e., 1,029) – Figure 83. This was followed by May (14.39%) and April (14.02%). The lowest number of fires in the fire season (April-September) occurred in September (4.43%) and August (6.34%). 82.06% of fires occurred in the fire season. According to Figure 51, the largest number of fires in 2021 occurred in Mazowieckie Province (689 - 20.91%). The lowest number of forest fires occurred in Opolskie Province (51) and Warmińsko-mazurskie Province (67).

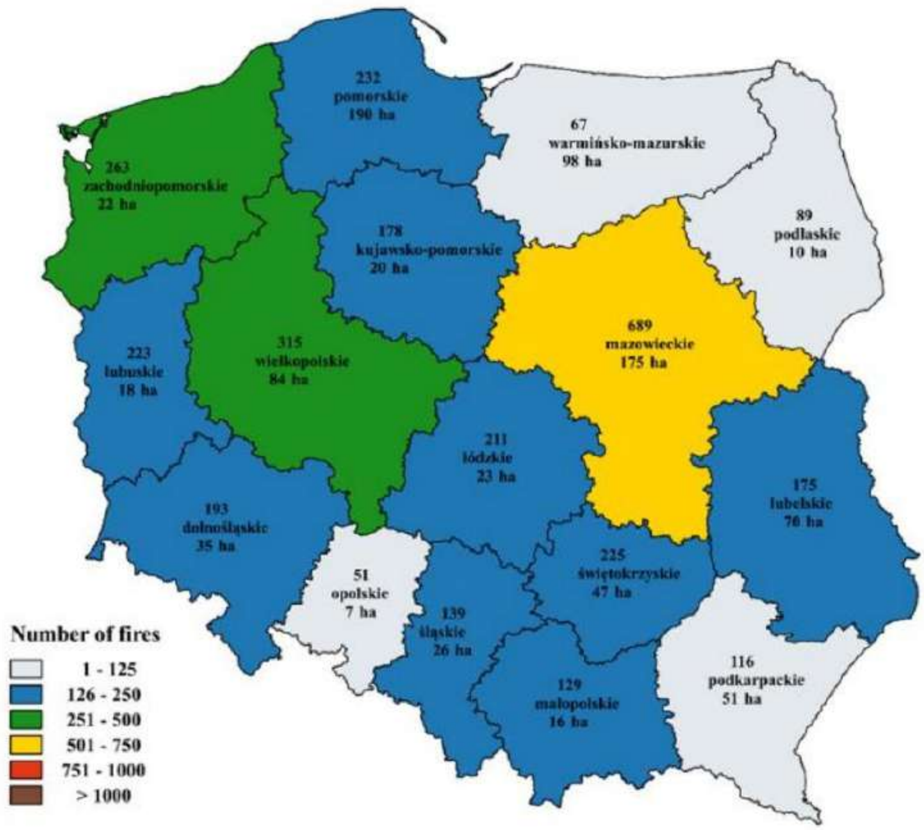

Figure 51 Number of forest fires and burned areas by provinces in 2021

Data on wildland fire for period 2007-2021 are shown in Table 14.

Table 14 Number of fires, burnt area in Poland since 2007 (Source: [28,84])

Year	Total number of wildland fires	Total burned area (ha)	Forest fires		Non-wooded fires	
			Number	Burned area (ha)	Number	Burned area (ha)
2007	8,302	2,840.9	5,086	1,642.7	3,216	1,198.2
2008	9,090	3,027.1	5,568	1,810.7	3,522	1,216.4
2009	9,162	4,400.5	5,633	2,524.6	3,529	1,875.9
2010	4,680	2,126.2	2,975	1,358.3	1,705	767.9
2011	8,172	2,677.8	5,126	1,526.1	3,046	1,151.7
2012	9,265	7,235.3	5,752	4,781.7	3,513	2,453.6
2013	4,883	1,288.5	3,168	810.4	1,715	478.1
2014	5,245	2,690.5	3,603	1956.9	1,642	733.6
2015	12,257	5,509.9	8,292	3765.9	3,965	1,744.0
2016	5,286	1451.1	3,545	862.4	1,741	588.7
2017	3,592	1,022.5	2,334	692.7	1,258	329.8
2018	8,867	2,696.1	5,947	2,047.3	2,920	648.8
2019	9,635	3,572.5	6,532	2,340.7	3,103	1,231.8
2020	6,627	8,416.6	4,458	1,842.3	2,169	6,574.3
2021	3,295	893.7	2,243	575.4	1,052	318.3
Average	7,223.9	3,323.3	4,684.1	1,902.5	2,539.7	1,420.7
Total	108,358	49,849.2	70,262	28,538.1	38,096	21,311.1

Human activity was the main cause of the wildland fires. Specifically, arson represented almost half of the fires (41.67%), followed by negligence (26.19%) and accident (6.10%), whereas unknown causes accounted for 25.28%.

Further, there are provided results concerning the comparison of fires number and burnt area in selected Central European countries.

Figure 52 provides results of comparison of fires number in selected Central European countries.

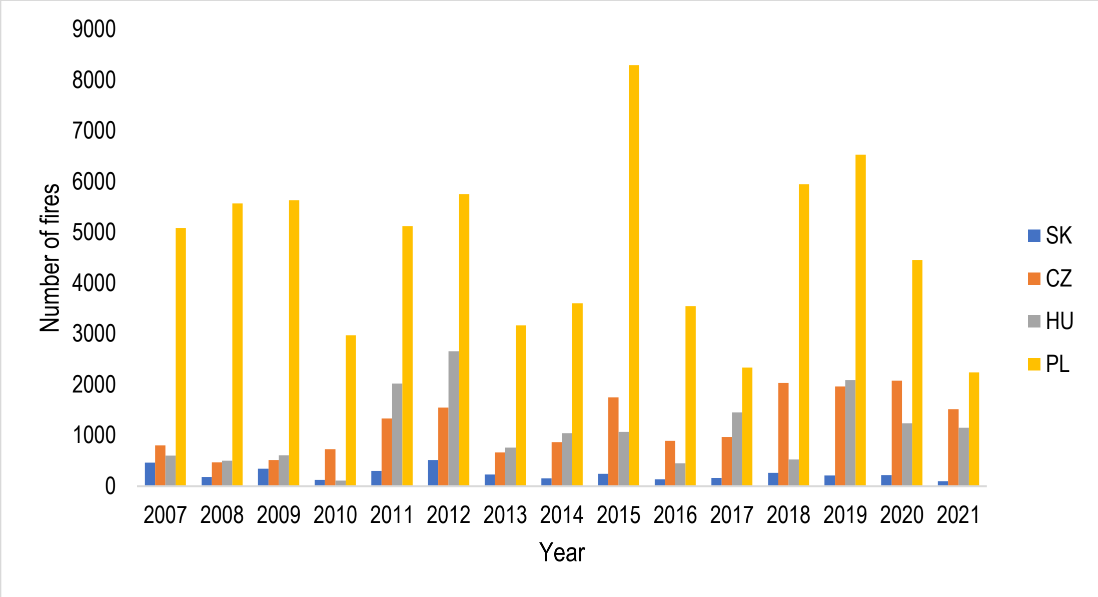

Figure 52 Comparison of fires number in selected Central European countries

Figure 53 provides results of comparison of burnt area in selected Central European countries.

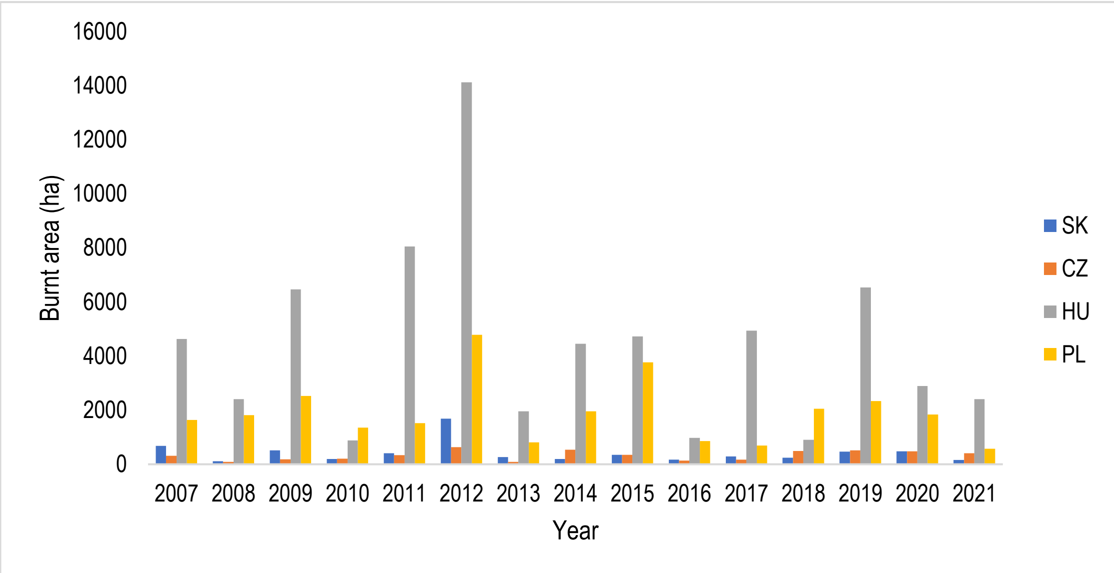

Figure 53 Comparison of burnt area in selected Central European countries

The fire number is highest in Poland, followed by Hungary. The higher number of fires is caused mostly by higher extent of country and population. The number of fires was higher during year with hot spring and summer season (e.g., 2012, 2019). A higher number of fires does not automatically imply a large area of fire-affected land. This is also evident from Figure 53. The largest burnt area reached Hungary in 2012, when had the highest number of fires, too. In 2015, Poland recorded highest number of fires, however the burnt area was like in previous year. There occurred more fires with smaller extent. In Slovakia the highest number of fires was recorded in 2012. This year also the highest extent of burnt area was recorded. In the Czech Republic, the highest number of fires was recorded in 2020.

4. WILDLAND FIRES CONSEQUENCES

The risk of wildland fires increases in extremely dry conditions, such as drought, and during high winds. Wildland fires can disrupt transportation, communications, power and gas services, and water supply. They also lead to a deterioration of the air quality, and loss of property, crops, resources, animals, and people.

Wildland fires also simultaneously impact weather and the climate by releasing large quantities of carbon dioxide, carbon monoxide and fine particulate matter into the atmosphere. Resulting air pollution can cause a range of health issues, including respiratory and cardiovascular problems. Another significant health effect of wildland fires is on mental health and psychosocial well-being.

The use of chemicals in firefighting also adds an additional problem to the already dramatic consequences of forest fires. Chemicals contained in “flame retardants” used to extinguish fires accumulate in the soil for years. The findings of the study highlight the presence of ammonium polyphosphate, known to alter soil fertility, biodiversity and affect the composition of vegetation.

The increasing frequency and severity of wildland fires observed in Europe in recent years has several potential causes, including ongoing climate change and the phenomena and processes that are occurring under altered conditions, not only natural ones, as a result.

Therefore, before the description of wildland fire`s consequences, there are introduced the basic fact on the climate change and its impacts as at European as at country level.

4.1 Climate change consequences in Europe and Central Europe

It is safe to state that climate change is one of the biggest challenges of mankind. The effects of climate change are already being felt, with the resulting damage having a worldwide impact. Global impacts vary due to multiple factors, with a country’s economic power playing one of the biggest roles in preparedness, resulting in vulnerable nations. Decisions must be made to mitigate climate change consequences by increasing preparedness in vulnerable areas against the presumed impacts. Climate change will undoubtedly affect the entire planet and calls for international collective actions.

Most human activities, in particular the combustion of fossil fuels, have accelerated the rise in carbon dioxide emissions and thus the increase in global warming, with tangible impacts on humans, animals, and the ecological balance around the world. The immediate environmental consequence of global warming is the increase in natural hazards that result in disasters, e.g., melting glaciers, more extreme and more frequent floods, wildland fires, storms, droughts, and heatwaves. The indirect consequences include threats to human health, and the reduction of biodiversity and habitable areas, leading to migration and deterioration of community, public health, and socioeconomic conditions in most countries of the world. The impacts of climate change will lead to socioeconomic and political instability, which will change the living conditions of many communities.

Measurements provide information on the past and recent climate. To estimate possible changes of climate parameters, perspective climate models can be applied. These models can be divided into two main approaches- dynamical and statistical climate models. Dynamical climate models can be grouped into Global Climate Models or Global Circulation Models (GCMs), Regional Climate Models (RCMs), Earth System Models (ESMs), Coupled Atmosphere Ocean Global Climate Models (AOGCMs), and others. GCMs and AOGCMs are strongly simplified but contain the most important physical processes describing our climate system. They are limited to the representation of large-scale effects on the global climate due to changes in greenhouse gas concentration, eruptive volcanoes etc. Their spatial resolution for the whole globe is from 3° down to 1.2°. RCMs use model output from GCMs as forcing to simulate the climate at smaller scales for certain regions. They contain complex model physics and due to their high spatial resolution from 50 km down to 3 km (0.5°–0.025°) it is possible to reproduce regional and local effects through the integration of orography and land use. The second group of climate models follows a statistical approach. Statistical relationships between large scale processes and local measurements are extended to estimate future climate and possible changes can be derived very locally. Typical statistical models are a weather generator, Markov chains, linear regression, or principal component analysis. Dynamical and statistical models both have their advantages and disadvantages and the decision of what kind of climate model to use depends on the application and the specific question to be answered in relation to future climate change. [115]

Changes in several climatic-impact drivers have already emerged in all regions of Europe increases in mean temperature and extreme heat and decreases in cold spells. With increasing warming, confidence in projections is increasing for more drivers. Mean and maximum temperatures, frequencies of warm days and nights, and heatwaves have increased since 1950, while the corresponding cold indices have decreased [116]. Average warming will be larger than the global mean in all of Europe, with largest winter warming in Northern European countries and Eastern European countries and largest summer warming in Mediterranean region [116]. An increase in hot days and a decrease in cold days are very likely. Projections suggest a substantial reduction in European ice glacier volumes and in snow cover below elevations of 1,500–2,000 m, as well as further permafrost thawing and degradation, during the 21st century [116]. During recent decades mean precipitation has increased over Northern European countries and Eastern European, while magnitude and sign of observed trends depend substantially on period and study region in Mediterranean region [116]. Precipitation extremes have increased in Northern European countries and Eastern European countries, vary spatially in Western and Central Europe and have not been changed in Mediterranean countries. A widespread increase of precipitation extremes is projected for >2°C for all sub-regions, except for Mediterranean countries where no change or decrease is projected in some areas [116]. Mediterranean countries are projected to be most affected within Europe with all types of droughts increasing for 1.5°C. At 4°C, hydrological droughts in Northern, Western, Central and Eastern European countries will increase. Projections for the 21st century show increases in storms across all of Europe for >2°C with a decrease in their frequency in the Mediterranean countries [116].

European land and freshwater ecosystems are already strongly impacted by a range of anthropogenic drivers (very high confidence), particularly habitats at the southern and northern margins, along the coasts, up mountains and in freshwater systems. Interacting with climate change are non-climatic hazards, such as habitat loss and fragmentation, overexploitation, water abstraction, nutrient enrichment, and pollution, all of which reduce resilience of biotas and ecosystems. Peatlands in Eastern Europe and other historically important cultural landscapes in Europe are overexploited for forestry, agriculture, and peat mining [117]. Forests in Western and Central Europe were impacted by the extreme heat and drought event of 2018, with effects lasting into 2019.

Local losses of species have been observed in response to climate change in Europe. Strong climate-induced declines have been detected in thermosensitive taxa, including many freshwater groups, insects, amphibians, reptiles, birds, and fishes.

The climate of the twentieth century in Central and Eastern Europe is marked by an overall temperature increase, although more pronounced in the Alps and their surroundings than elsewhere in this region. Other climate elements, like precipitation have developed diversely with regional increases and decreases of smaller distances. For the Greater Alpine Region area covering the southern part of Central Europe (4–19° E, 43–49° N, 0–3500 m asl) temperature increased significantly by about 1.2 °C during the twentieth century. This increase was similar in all the subregions. Warming at the high mountain observatories in the Alps did not differentiate significantly from that in the lowlands. The respective numbers for the seasons are 1.1 °C for spring, 1.3 °C for summer, 1.2 °C for autumn and 1.3 °C for winter. The strongest warming occurred in the 1980s and 1990s.Thus, focusing on a shorter period of the last 30 years, a much more severe warming can be found in the series. Together with the higher mean temperature level, several extremes derived from daily maximum and minimum temperature are expected to have increased as well. [118]

3.1.1 Climate change consequences in Slovakia

Slovakia is located between latitudes 47° and 50° N, and longitudes 16° and 23° E. The Slovak landscape is noted primarily for its mountainous nature, with the Carpathian Mountains extending across most of the northern half of the country. Among these mountain ranges are the high peaks of the Fatra-Tatra Area (including Tatra Mountains, Greater Fatra and Lesser Fatra), Slovak Ore Mountains, Slovak Central Mountains, or Beskids. The largest lowland is the fertile Danubian Lowland in the southwest, followed by the Eastern Slovak Lowland in the southeast.

The climate change will affect the urban areas and rural areas as well. In urban areas, climate change is expected to increase risks to humans, the economy, and ecosystems, including risks from heat stress, storms and extreme rainfall, floods, landslides, air pollution, drought, water scarcity, etc. Rural areas are expected to have a significant impact on water availability and supply, food security, infrastructure, and agricultural incomes, including shifts in food and non-food crop production areas around the world. The effects of climate change are expected to slow economic growth, make poverty reduction more difficult, prolong existing ones and create new poverty traps, especially in urban areas.

The following environmental, economic, and social pressures are likely to be significantly affected by climate change in Slovakia.

From the environmental perspective, it is the lack of water, deterioration of water quality, drought, deterioration of soil properties, reduction of organic carbon in the soil, salinization of soil, increased water, and wind erosion, change in ecosystem functioning and provision of ecosystem services, degradation to forest ecosystems, habitat fragmentation, spread of non-native and invasive species, loss of biodiversity, change of landscape image, floods, windstorms, wildland fires, landslides.

Among the expected economic pressures belong reduction of soil fertility and agricultural production, shift of agricultural production areas to more northern areas, changes in agroclimatic production potential, changes in crop composition, reduction of forest production, changes in forest species composition, occurrence of pests, diseases and weeds, endangerment of sources of drinking water and drinking water and drinking water supply, irrigation problems, increasing the vulnerability of residential and rural environments, the need to reduce the energy intensity of buildings, deteriorating safety and traffic flow, increased energy consumption, endangering the flow of industrial operations, major industrial accidents, unstable supplies of stock, raw materials and electricity, increased risk of failures and material damage in the energy and industrial sector, the need to deal with emergencies and natural disasters, threats to human safety and health, threats to food security, changes in the prices, increased requirements for innovation and renewables, changes in the length and quality of the tourist season, threats to tourism potential, threats to competitiveness.

The social pressures are represented by threat to the health of the population (change in the distribution of infectious diseases, presence of new pathogens, worsening of allergic conditions), deterioration of quality of life, unemployment, migration.

Since 1993, national climate change scenarios have been prepared for the Slovak Republic as modified outputs from several Global General Circulation Models (GCMs) and Regional Circulation Models (RCMs). The statistical and dynamic downscaling method used with data from Slovak meteorological network from the period 1951 – 2010. All the GCMs and RCMs offer outputs of several variables with daily frequency for the period from 1951 to 2100. These models were used to obtain climate change scenarios for the Slovak Republic. Based on the outputs and the measured meteorological data for reference periods 1961-1990 and 1981-2010 daily scenarios were designed for about 60 meteorological and about 150 precipitation stations in the Slovak Republic. Scenarios were prepared for the following variables: the daily means, maxima and minima of air temperature, daily means of relative air humidity, precipitation totals, means of wind speed and sums of global radiation. Based on these baseline scenarios, several other scenarios for snow cover, evapotranspiration, heatwaves, soil moisture, runoff, etc., were designed. In this approach correlation/regression and simple modelling methods to obtain scenarios for other climatic/hydrological elements were used.

In general, models suppose a comparable increase of temperature in whole area of our territory in accordance with similar assessments for Central Europe region. Scenarios of precipitation totals expected small growth in the north and decrease in southern part. Result of the future temperature and precipitation conditions would have impact on higher potential evapotranspiration and enhanced drought occurrence.

New and more detailed climate change scenarios based on GCMs and regional (RCMs) models, enabled the calculation of a series of statistical characteristics such as complex environmental and socio-economic scenarios depending on the changing climate: number of summer days, tropical days, super-tropical days, heat waves, icy days, frosty days, days with heavy rain, days with low or no precipitation, days with snowfall, days suitable for specific tourist activities (skiing, swimming, summer and winter hiking, etc.).

An analysis of current and future climate change scenarios confirm the existence of extremes and risks, their interdependence and possible consequences in the whole range from ecosystems, natural resources to the economy and the social sphere. Bonds and interactions between the effects of climate change and its possible consequences forms very complex and dynamic system.

The management of this system requires a large amount of information and is largely limited by the uncertainties of the future development of the scenarios. Climate change projections and modelling results confirm that the magnitude of climate change impacts on human and natural systems calls for adaptation measures that both reduce the vulnerability of these systems and further strengthen their resilience through technological and ecosystem-based solutions and managerial abilities. [118]

3.1.2 Climate change consequences in the Czech Republic

Today at global warming of about 1.1°C above pre-industrial levels, the Czech Republic has increasingly experienced the impacts of climate change. In 2020, the Czech Republic hit a new record high of average annual air temperature: 2°C higher than that of 1960s. In recent years, the Czech Republic has seen an increase in heat waves, which will likely continue with increasing global warming. The frequency and duration of droughts are also expected to increase and so are the damages. In previous years, droughts alone costed the Czech Republic damages estimated at 500 million EUR. The combination of droughts and heat waves also result in extreme wildfires in the Czech Republic, and they are projected to worsen over time with climate change. Heavy precipitation is also projected to occur more frequently in the Czech Republic, with up to a 35% increase in winter precipitation projected for the period 2071-2100. The resulting more severe and frequent floods can pose a great threat to the country, particularly because they are expected in vulnerable areas around the Morava River (part of the Danube River Basin), where around 2.8 million people live. Moreover, the Czech Republic has a historically high death rate from flooding compared to other European countries. Climate change affects the timing, intensity, rate and frequency of disturbances and its impact on forest ecosystems. The incidence of pests and diseases, such as the infestation of bark beetles that put 50% of Czech forests at risk, which are at least partly linked to climate change, will likely intensify. There are also health-related climate change impacts. Between 1990-2016, up to 1000 fatalities in the Czech Republic were due to extremely high temperature. This will likely increase drastically and at 4°C global warming, extreme heat is projected to claim 3.6% of total deaths. And the repercussions will be more severe in urban areas with denser populations. [118]

3.1.3 Climate change consequences in Hungary

In Hungary the general annual twentieth century warming of about 0.8 °C (most expressed in summer by increase of about 1 °C) initiated an extended calculation of extreme temperature and precipitation indices for the whole country using grids of the basic variable's daily temperature and precipitation (Lakatos et al. 2011). Countrywide the grid point average of hot days (Tmax >¼ 30° C) and warm nights (Tmin >¼ 20 °C) showed a remarkable increase beginning in the 1980s. Maps allow for a better identification of the most sensitive regions of the country. These maps coincide with the Austrian studies (Nemec et al. 2012) which state that warming does not necessarily cause more heavy precipitation. Changes of the annually greatest 1-day total rainfall between 1961 and 2009 vary from -15 to+10 mm. This increase could be detected mainly in the regions east of the Danube. Precipitation in general has decreased by 11 % in Hungary since 1901, especially since the 1970s. This decrease in precipitation is especially pronounced in spring. Although summer precipitation does not display a special negative trend drought event with dry and warm months are immanent in the climate of Hungary. The Hungarian plains are most affected, with drying occurring in late spring/early summer and during late autumn. [118]

3.1.4 Climate change consequences in Poland

Measurements of 51 stations evenly distributed, homogenised, and averaged over the territory of Poland confirmed the rising of annual temperature for the second half of the twentieth century. It is obvious that not all months contributed to the annual temperature increase of approximately 1 °C; however, the most pronounced warming was found in spring. Poland belongs to the group of countries in which a stronger increase of minimum temperature than maximum temperature caused a decrease of the daily temperature range at most stations. This effect correlated with increasing cloudiness. With rising minimum temperature, Poland experienced a prolongation of the frost-free season. The prolongation of the growing season of approximately 1 month is documented as well as the reduction of frost days by about 45 days during the past 60 years. There was recorded a strong relationship between hot weather and lack of precipitation. Over the year no significant changes have been observed in the annual amounts of precipitation, but more interestingly, decreasing summer precipitation trend has been found. March is the only month where significant precipitation increase was detected. [118]

4.2 Wildland fires consequences

Wildland fires affect ecosystem function, structure, and adaptation, while significantly contributing to emissions of greenhouse gases, soil erosion, water and air pollution, and land cover. Wildland fires also threaten human lives and properties and can cause important socio-economic impacts.

Polluted Water Resources

Forested water bodies account for freshwater recourses and public drinking-water systems derive from watersheds within forests. With each wildfire, watersheds grow more vulnerable to stormwater runoff and erosion.

Following a wildland fire, the soil's capacity to absorb water is significantly compromised – a concerning outcome in the event of post-fire flooding. Watersheds may retain higher levels of nitrogen and dissolved carbon dioxide for 15 years after a wildfire, reducing drinking water quality within surrounding communities.

In addition, elevated nitrogen, and phosphorus from burned vegetation result in harmful algae blooms. Eating shellfish contaminated with toxic algae could result in paralysis or even death, while other people may experience severe vomiting, seizures, or diarrhoea.

There needs to be increased effort in water pollution clean-up following a wildfire. Current research is focussing on finding ways to test and recover water systems.

Forested watersheds vulnerable to wildland fire serve as drinking water supplies for many urban and rural communities. The highly variable nature of wildland fire behaviour combined with spatially complex patterns in vegetation, landscape, and hydrologic factors create uncertainty surrounding the postfire effects on water supplies. Wildland fires often cause dramatic changes in forest vegetation structure and soil conditions, and alter the watershed processes that control streamflow, soil erosion, nutrient export, and downstream water chemistry. The authors' work centres on field and laboratory studies to advance knowledge of postfire changes in soil and water chemical composition that influence drinking water treatment. High intensity postfire rainstorms typically increase runoff that erodes ash and soil from burned landscapes and dramatically elevates turbidity, nutrient, and dissolved organic carbon (DOC) levels in surface waters, which can cause short-term challenges for water providers. There is also growing evidence that water quality impacts can persist after high severity fires due to slow vegetative recovery, and nitrogen and DOC have remained elevated for 15 years following high severity fire. Low-moderate temperatures during wildland fire may also influence water quality.

Research showed that the solubility of organic matter, and C and N released from soils increased following soil heating at temperatures ≤ 350 °C. Further, the water extracted organic matter from soils heated at 225–350 °C included higher proportions of condensed aromatic structures, such as black carbon and black nitrogen. Short-term postfire water quality degradation following high intensity rainstorms can force water treatment plants to shut down or can significantly challenge treatment process performance. Extreme turbidity and high DOC in post storm water, coupled with compositional organic matter changes, reduced the coagulation efficiency of postfire water supplies. Field and lab-based studies documented the formation of small, aromatic soluble compounds during wildland fire that contribute to inefficient DOC removal from postfire stormwater. Due to increased postfire DOC concentrations, and poor treatability of post storm runoff, toxic disinfection by-product (DBP) formation increased during water treatment. Exceedance of drinking water standards for the carbonaceous DBPs, trihalomethanes and halo acetic acids, may present a critical management concern for water providers following wildland fires. Further, postfire formation of nitrogen compounds and increased nitrogenous DBP precursors for haloacetonitriles and chloropicrin were discovered. N-DBPs pose a public health concern due to their toxicity, and water providers should be aware of potential increases in N-DBP formation following fire. Evidence from the authors' studies demonstrates that even partially burned watersheds and wildland fires burning at moderate temperature can have significant, lasting effects on C and N exports, source water quality, drinking water treatability, and DBP formation. Both short- and long-term postfire water quality impacts can create challenges for drinking water providers as they confront variability in supply and treatability. Communities, forest managers, and potable water providers will need to adapt to more frequent, destructive wildland fires and anticipate greater variability in water quality. [119]

Vegetation

Fire is considered an important ecological factor, sustaining biodiversity, and deterring the invasion of exotic species [120]. Fire regimes, which comprises fire frequency, intensity, and severity, are key determinants of ecosystem functioning of many ecosystems. However, burning of vegetation, especially fires out of season and megafires, may induce severe changes in the functioning of ecosystems, even in those adapted to frequent burning. These changes may result in the fragmentation of the landscape, changes in soil properties, facilitating soil erosion and decreasing fertility [121] and made many native species more vulnerable to fire occurrence [122]. These negative effects may affect ecosystem services and bring sizeable economic losses.

The loss of vegetation can significantly alter an ecosystem by increasing erosion, reducing nutrient availability in the soil, and posing a heightened risk for disease and pest infestations. In turn, these may prolong regrowth or impact what grows in the area affected by the fire. Additionally, vegetation that once served as a habitat may threaten wildlife survivability.

Forest vegetation can absorb 7.6 billion metric tons of carbon dioxide annually, making it vital to protect one of the world's largest carbon sinks from further destruction.

Clean-up efforts for vegetation mainly focus on the areas less likely to recover from a wildfire. Rehabilitation often takes a year but can often last longer, especially in areas that are frequently subject to wildfires.

Endangered Wildlife

The characteristics and environmental context of fires, together with life-history differences between species, determine the degree of harm to animals [123]. Recently, a review of existing knowledge on fire management concluded that further investigation about species responses, including examination of occupancy, life history, dispersal, demographics, and behavioural responses is needed. Fires have been found to affect the distribution, abundance, and genetic diversity of populations, as they are life-threatening [124].

From the point of view of forest wildlife and birds, fire has a negative impact mainly on their habitats, destroys their shelters, significantly reduces their food supply and, not least because of fire, the loss of their lives.

Scientific evidence has established that some animal species can experience negative psychological stress, suffering, or even chronic stress, due to their cognitive development [125]. For this reason, it is expected that some taxa perceive fires as stressful events, and consequently trigger physiological and behavioural responses as an evolutionary adaptation to survival. While a state of stress can allow glucocorticoids to mobilize energy to positively modify behaviour [126], excessive amounts of perceived stress can lead to negative physiological and psychological consequences for the individual [127], such as fear, anxiety, despair and disorientation, and increased risk of death. The most immediate effects of fire on individual animals include risk of injury and death during flight to unburned areas, and second order effects include starvation, dehydration, predation and migration . Numerous studies have evaluated post-disturbance population recovery patterns and processes [128]. However, there is a lack of studies on the immediate experienced damage and short-term responses of wild animals during fires [128], including physiological and behavioural adaptations [129]. Naturally, impaired water and land have dire effects on wildlife. The subsequent consequences are critical to natural selection.

Wildfire effects on herbivores such as grazing mammals and insects are particularly troubling, especially since the latter drive essential ecosystem functions such as nutrient cycling and pollination.

Studies suggest wildfire pollutants in water bodies also suppress wildlife immunity, making animals more susceptible to disease, declining health, and higher mortality.

In 2020, scientists discovered a link between the 7.8 million acres burned and a mass migratory bird die-off in Colorado around the same time. The study found toxic air particles from wildfires were a contributing factor.

While some wildlife species benefit from controlled burns, many lose their homes and food in a wildfire. Clean-up efforts may entail relocating animals to shelters or zoos before releasing them into a healthy habitat — especially if the fire injured them.

Air Quality

Wildland fires are an important type of natural disturbance in forests, grasslands, and deserts around the world, and many wildlife species benefit from resources available in post-fire landscapes. However, just as people now grapple with health risks posed by routine smoke events, even in airsheds where smoke pollution was previously uncommon, wildlife must also contend with greater—perhaps even novel—exposure to wildland fire smoke with more intense wildland fire activity. The magnitude of smoke events in the 21st century further underscores the urgent need to study the impacts of wildland fire smoke on wildlife.

Wildfires release carbon dioxide and their emissions can prove to be significantly high. For perspective, wildfires emitted 91 million metric tons of carbon dioxide in California in 2020 – 30 million more than the state's power production emits on an annual basis.

Particles from smoke and the burning of hazardous chemicals can also travel long distances, further reducing air quality and bearing multiple respiratory and cardiovascular ailments for humans and wildlife.

In terms of air quality, fire poses a threat, particularly in terms of the emissions that are generated by fire and have an impact on the greenhouse effect. In the case of fire, the emissions that are produced by fire consist of 90 % carbon dioxide and water vapour. Carbon dioxide is also considered to be the largest contributor to the greenhouse effect, although it is not technically considered to be a pollutant. Whereas other combustion products (carbon monoxide and bicarbonates) are pollutants. The production of emissions depends to a large extent on the type of fuel and the way it is burned, with flame burning producing far fewer emissions than flameless combustion associated with increased smoke production.

Increased wildland fire activity has been linked to declines in average regional air quality and greater incidence of extreme air pollution episodes. Wildland fire smoke directly contributes to adverse respiratory and cardiovascular health outcomes and mortality in humans; in fact, studies have shown that the chemical composition of PM2.5 in wildland fire smoke is more toxic than that of urban ambient PM2.5 [130].

Wildland fire smoke also sickens non-human animals, as illustrated by numerous case studies in veterinary medicine that document morbidity and mortality in domestic animals exposed to smoke, including pets and livestock. These case studies demonstrate that, like people, animals can suffer from carbon monoxide poisoning, thermal and chemical damage to lung tissue, and greater susceptibility to respiratory disease because of smoke inhalation. In fact, animal models, including mice, rats, rabbits, sheep, and monkeys, are often used to study the onset and progression of human disease following exposure to the toxic gases and aerosols found in smoke. Although many animals in fire-prone habitats can detect and avoid wildland fires, fires still pose direct threats to wildlife [131], including exposure to extreme heat and smoke. Yet, the impacts of wildland fire smoke on the health and behaviour of wildlife are largely unknown [132].

This paucity of research on how wildland fire smoke affects the health and behaviour of wild animals hinders full consideration of the direct and indirect effects of wildland fires when conducting risk assessments for wildlife and developing conservation plans. In addition, research on the impacts of wildland fire smoke on wildlife is published in disparate journals spanning numerous disciplines (e.g., ecology, physiology, animal behaviour, veterinary medicine, etc); as such, ecologists, wildlife managers, and other stakeholders may be challenged to identify relevant studies. To date, review papers have synthesized findings on first-order effects of fire on animals, including injury, morbidity, and mortality, considered behavioural responses of mammals to fire, and discussed fire as an evolutionary force driving animal behaviour and survival [131], but none have focused specifically on the effects of smoke from wildland fires on the health and behaviour of wildlife.

Wildland fire smoke persists in the atmosphere even after flames have subsided and can travel hundreds of miles, creating hazardous air quality conditions and degrading visibility across large geographic areas. As a result, smoke from a single wildland fire could impact the health and behaviour of wildlife at a much larger spatial scale than the area burned. Direct effects of wildland fire smoke on individuals could scale to influence the demography of wildlife populations, with cascading community- and ecosystem-level impacts.

Forest

Forest fires cause both direct and indirect damage to forestry. Direct damage is related to the deterioration of the timber raw material, i.e., charring or burning of trees, processed or stored timber in the forest, but also in warehouses. Damage to or destruction of planting material, nursery crops, technical and operational equipment, etc., is also considered direct damage. Indirect damages include losses to the yield and quality of the timber raw material. Indirect damage is mainly caused by the emergence of secondary pests that attack fire-damaged and physiologically weakened trees. Indirect damage also includes increased costs of fire recovery and difficulties in forest management or reforestation.

Forest fire is part of the evolution of the natural environment. Fire plays a key role in shaping ecosystems as a factor in their renewal and change. But it is also a damaging threat, destroying homes, wildlife habitat and timber, and polluting the air with emissions harmful to human health. Fire also releases carbon dioxide and major greenhouse gases into the atmosphere. The effects of fire on the landscape can be long-lasting. Its effects can be influenced by the state of the forest cover before the fire and by the measures taken or not taken shortly after the fire.

In terms of the positive effects of fire, mention may be made of its impact on the soil and forest natural resources. In some parts of the world, fire is a necessary condition for the growth and regeneration of many tree species, as the smoke and heat generated by fire induce seed germination.

Its cleansing effects are also significant. Fire serves to remove any dead or decaying wood, branches and twigs scattered throughout the forest, which in turn improves the conditions for faster growth of new plants.

Forest fires are also useful in terms of maintaining the balance within ecosystems by destroying any harmful insects and plant diseases. An advantage in terms of vegetation removal is the over-lighting of the stand, which helps the regeneration of plant seeds.

Forest fires within individual ecosystems help to increase plant and animal diversity. During a forest fire, extremely large amounts of nutrients are released into the soil. As already mentioned, some species of plants or trees even need forest fires to germinate their seeds and promote their growth. The most well-known such tree species is the Pinus ponderosa sp. (Pinus ponderosa sp.).

Regularly occurring fires (controlled fires), especially in countries such as the USA, Canada, etc., also help to eradicate invasive species of raspberries and thus improve conditions for the growth of native species. In these countries, if fire is not carried out on a regular basis, it can lead to the encroachment of dense scrub and tree undergrowth on forest land. When such stands are subsequently exposed to fire, they cause widespread and intense fires, and thus inhibit the growth of new plants more than they promote it.

Changes in soil and water regimes are most significant, particularly in places where fire has had a widespread impact on the vegetation and soil properties of a given ecosystem [133]. Where fires have reached low severity or have affected only a small portion of a large watershed, changes in the soil and water regime of the area are difficult to detect.

If the direct or indirect effects of fire on soils and vegetation are significant, it is to be expected that associated changes in hydrological and geomorphological processes will also occur [133]. Some of these changes are barely perceptible, such as the seasonal increase in soil water content that leads to a seasonal prolongation of the soil entrainment process. Some of the changes may be associated with increasing numbers of other types of damage, such as avalanches. Others, such as shifting land masses, mowing of stream banks or siltation of watercourses, may have a direct impact on the catchment area (water erosion). These changes are the result of storms that have occurred in the area in the years following the fire and, of course, the severity of the fire itself.

Following a fire, the flow of watercourses located in the area may also increase significantly over the course of the year. This is mainly due to a reduction in loss by interception and transpiring vegetation and with a generally lower increase in evapotranspiration. This effect is directly proportional to the size of the catchment area affected by the fire and the annual rainfall [133].

The seasonal distribution of water supply can also be affected by fire. Maximum flows may also increase. This situation can be a significant benefit of fire to the quality of wildlife habitat and water systems, particularly in arid areas.

Also, various erosion processes may be accelerated because of fire, depending on the severity of the fire. These erosion processes include surface erosion, landslide from slopes and water erosion, which is manifested in the form of trickles of washed away soil or wind erosion, rapid processes of soil mass transport and several different effects on the sediment layer located in the watercourse bed.

Soil

Soil is one of the basic natural resources and its continuous management is aimed at its productive capacity. The interaction between fire and soil is significant because most fires spread through the burning of organic material and soil or at least part of it. Fire causes physical, chemical, and biological changes in the soil that are either desirable or completely detrimental in terms of ensuring the long-term productivity of the soil.

One of the effects of fire on soil is overheating. During a fire, the temperature just above the soil surface can exceed 700 °C. Temperatures exceeding 800 °C have been recorded in the fallow layer during fire. Temperatures deep in the soil are typically lower than at the surface. In intense green dense brush fires, the maximum temperature does not exceed 200 °C at a depth of about 2.5 cm but reaches temperatures as high as 275 °C below the rake layer 1996. [133]

Wet soils generally experience lower temperature increases than dry soils, although they produce the same heat when burned. In the field, when the soil and fuel are moist, there is a realistic expectation that the fire will consume less fuel and less heat will be applied to the soil surface.

Soil temperature may change significantly in the years following a fire. These changes are caused by the loss of the fire that was created by the tree canopy, the removal of forest cover, and charred residual organic material. The loss of canopy cover and the removal of forest cover results in an increase in the exposure of the area to solar radiation, while the charred (charred) soil absorbs heat energy much more efficiently. Soil temperatures often increase during the day. The lack of fire cover and charred forest ground cover also results in increased loss of heat energy during the night, and therefore minimum night-time temperatures are significantly lower after a fire.

The physical properties of the soil are usually less affected by fire than its chemical properties, but often recover much more slowly. Intense and repeated fires reduce the porosity and infiltration capacity of the soil, often resulting in a reduction in soil retention capacity, which can result in the loss of the soil organic layer, particularly because of flash floods. The impact of fire can create a water-repellent layer on or just below the soil surface, which has a high potential for both repeated fires and flooding. In terms of soil structure, increased aggregation of soil particles is observed after a fire, which are often unstable after exposure to the heat of the fire.

The effect of fire on soil chemical properties is mainly related to the removal of nutrients from the soil. These are caused by the consumption of vegetation (nutrient source) by the fire itself, but also by the thermal effects of the fire on the release of individual nutrients from the soil. For example, carbon is released at temperatures above 100 °C in the form of hydrocarbon, which causes soil water repellence at temperatures above 175 °C. Nitrogen is readily released at temperatures between 175 °C and 200 °C. Sulphur is removed in significant quantities at temperatures above 375 °C (. Potassium is depleted to a significant extent at temperatures above 550 °C. Inorganic phosphorus is released at 770 °C [133]

Because fire temperatures rarely exceed 750 °C, calcium, magnesium, and sodium usually remain in the soil and are the major components of ash.

The impact of fires on soil quality indicators is largely dependent on their severity and frequency [134]. Moreover, temperatures of 850 °C and higher may be attained on soil surfaces with dry, heavy fuel loads, and may have destructive effects on soil properties. Certain nutrients are also more vulnerable to fire than others. For example, levels of potassium (K), calcium (Ca), and magnesium (Mg) may be increased or unaffected by fire, while sulphur (S) and nitrogen (N) usually decline. Temperature specifically regulates the volatilization of nutrients within the soil. In organic matter, N begins to volatilize at 200 °C, while Ca requires 1,484 °C to vaporize [135].

Another negative effect of fire in relation to soil is the destruction of soil microbiotic life. This is mainly because of heat in fire. Soil is one of the most valuable natural resources utilized across socio-ecological and natural systems, and plays acritical role in nutrient cycling, as a warehouse for minerals, in carbon sequestration, and support for plant growth [136]. It is considered a non-renewable natural resource on a human timescale because of its rapid deterioration and slow phase of formation. Therefore, degradation of the biological, chemical, and physical properties of forest soils reduces its capacity to function fully, with such effects either temporary or permanent. Key drivers of soil degradation in forest ecosystems are deforestation, fires, erosion, and soil contamination [137].

Fires are considered a destructive factor in most forest ecosystems [138] and are viewed as global phenomena affecting most land areas. Fire influences forest ecology and functioning by affecting nutrient turnovers, hydrophobicity, species composition and regeneration, and ecological biodiversity.

Forest fires affect the biological and physico-chemical quality of soils and diminish the nutrient pool through various mechanisms, including volatilization, oxidation, ash transfer, and erosion [139]. [140] reported a drastic decline in microbial biomass carbon on a short-term basis following forest fires. [141] observed that forest fires with temperatures greater than 300 °C resulted in the destruction of soil water repellence, with a significant impact on soil water cycle and erosion characteristics.

Fires of high intensity can also alter soil physical properties and make it more vulnerable to nutrient depletion by erosion. With current global warming, higher temperatures and extreme droughts significantly increase the risk of forest fires [142]. There have been several recent predictions on the possible increase in fire duration, intensity, and frequency in forested regions, especially in the tropics, because of higher temperatures [143].

Therefore, increased fire risk will not only affect forest fora, but also soil physical, chemical, and biological properties [144]. Fire influence forest soils in complex ways but have not been studied as comprehensively compared to the effects of vegetation. Fires on forest soils influence a wide range of processes, including organic matter loss, nutrient availability, and their dynamics.

Consequently, information on the changes to soil properties following fire is key to finding sustainable and adaptable management practices of soils and forests [145].

Every year, forest fires destroy acres of land around the world, biodiversity of flora and fauna and acting as a major source of aerosol and greenhouse gas emissions [146]. This is a very hot topic for scientists to observe the implications of forest fire emission, as its effects are increasing from time to time in the developing world due to different substantial expansions. Over the years, there has been cumulative evidence about the impact of CO_2 emissions from industrialized systems on global warming [147]. This has extended to other so-called greenhouse gases, particularly the chlorofluorocarbons (CFCs), methane, and nitrogen oxides (NOx) [148]. Few efforts have been made to measure the emissions of these gases. Due to the burning of large forest areas globally every year, the amount of greenhouse gases emitted into the atmosphere by forest fires increases significantly. The contribution of these emissions to global warming has been found to be a significant factor [149]. Conversely, climate change due to global warming are largely responsible for the increased incidence of forest fires.

It is predicted that a major fire soon could turn the forest from a carbon sink to a source of atmospheric carbon [150]. Since fire activities are rapid, while greenhouse gas emissions continue to rise, climate change mitigation approaches focus primarily on human-caused emissions, which will have a greater impact than those that underlie forest fires. For a more accurate memorandum, estimates of carbon impacts are in dire need to better understand the severity, the impact of non-tree responses, and the essence of below-ground processes [151]. Even though it appears that the whole thing is burning in a forest fire, it is not so. Trees do not disappear completely even during high-intensity fires, but their resilience capacity is significantly affected. The destruction of fires has resulted in a short-term decline in greenhouse gases, but fire will still be an integral and essential part of the forest ecosystem on a long-term basis. The researchers supposed that global warming could lead to complex levels of forest fires and associated global carbon emissions in the future, even though there are several doubts present about how climate change will affect forest ecosystems, and there is no such warning that the incidence of forest fires will increase.

The need to study the relationship between environmental factors and forest fires is important to reduce risk [152]. Forest fires can be accomplished by reducing the resilience of existing ecosystems, clearing forests, and protecting the diverse flora and fauna, human life, and property that constitute the biodiversity.

Fire is a key ecological disturbance affecting a large fraction of the world's terrestrial ecosystems, spanning a broad range of regions and biomes [153]. Fire can consume large amounts of biomass, alter soil properties, and substantially impact key ecosystem processes, influencing hydrological [154] and biochemical cycles [155]. The relevance of fire to global patterns of biodiversity and vegetation distribution is also widely acknowledged [156].

The specific effects of a given fire depend on both ecosystem properties (e.g., fire-adapted versus fire-sensitive ecosystems) and fire characteristics (e.g., intensity, size, or recurrence. Even during a single fire, impacts can differ both spatially and across different ecosystem components (soil, vegetation, and so forth [157]. Current fire regimes are being modified by global change drivers.

Given its often substantial effects on the environment, fire is widely recognized as a key force affecting multiple ecosystem services [158], defined as "conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life". Indeed, wildland fires are often highlighted as one of the major disturbances that negatively impact ecosystem services in a range of terrestrial ecosystems, including forests and woodlands [159].

These impacts can affect soil erosion, runoff, water quality, and soil fertility.

However, fire can also enhance some ecosystem services(both directly and indirectly), including food provision or biological control of disturbances, due to the key roles played by natural disturbances in ecological processes [160].

The magnitude and extent of the impacts of forest fires can vary depending on the physical features, weather conditions, and forest types. For instance, the impact of forest fires on vegetation differs by frequency, magnitude, extent, season, phenological state of the vegetation, combined effects with other disturbances such as storms, diseases, and pest attack [161].

More trees are burnt by forest fire than any other natural disaster such as insects, parasites, frost, etc. Increasing temperature, reduced precipitation, and drought in particular are responsible for increased frequency of forest fires. Such rapid loss of forest to fires can exacerbate the extent and magnitude of socio-ecological consequences including shortage of fuel wood, displacement of people, degraded ecosystem services [162], which are critical resources for wellbeing of humans and biodiversity alike.

No two wildland fires are alike, the effects of wildland fires on the people and land in agricultural areas are drastically variable. The impacts can be direct, such as destroying crops, or indirect, like emotional distress in a community. The impacts can also be immediate or take years to realize, from pollution to respiratory illnesses to soil composition changes.

Wildland fires can affect agriculture directly by:

– Destroying crops in the path of the fire
– Smoke and heat can destroy outer layers of crops not even seen by fire.
– Emotional distress caused by wildland fire.
– Certain crops can add fuel to the wildland fire.
– Smoke inhalation and chemicals in the air can affect a farmer’s health.

4. WILDLAND FIRES FIGHTING

The main types of suppression tactics that can be implemented during a wildland fire incident are:

- Direct attack
- Indirect attack
- Aerial attack
- A combination of some, or all, of the above

Direct attack

Direct attack is where personnel and resources work at, or very close to, the burning edge of the fire. During direct attack, firefighters attack the fire aggressively by using hand tools and beaters and/or by applying water and/or retardants.

Direct attack can be applied on different parts of the wildland fire:

- Flank attack - Attacking the fire along the flank or both flanks simultaneously, usually moving from the tail towards the head.
- Head attack - Attacking the head of the fire. This attack method is usually only successful on lower intensity fires and when the flanks of the fire have already been extinguished. This type of attack will be dangerous on moderate to high intensity fires. Crews should never be deployed in front of the fire and/or in unburnt fuel.
- Tail attack - Attacking the tail of the fire. A tail attack may sometimes be accompanied by a flank attack, with direct attack crews starting at the tail and moving along the flanks.

Direct attack (Figure 54) using hand tools, beaters and knapsack sprayers can be a very successful suppression tactic when deployed against fires of low or moderate intensities (flame lengths up to 1.5 m).

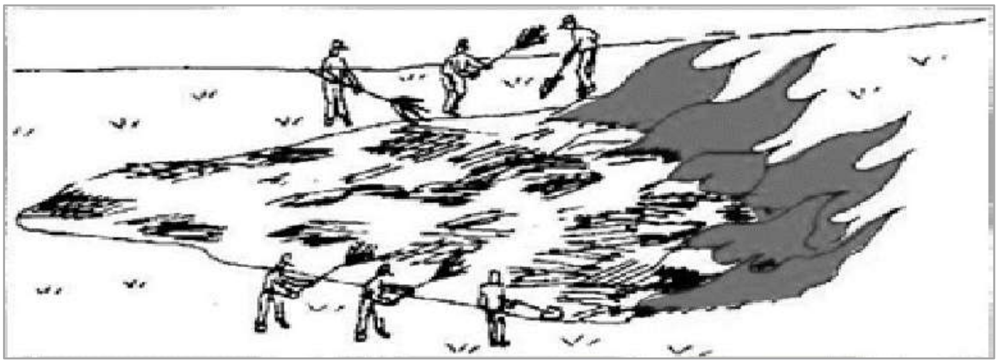

Figure 54 Direct attack (Source: [163])

Applying water and/or foam retardant using pressurised systems may still prove a successful suppression method for fires with flame lengths of 1.5 to 3.5 m. Personnel working with hand tools, such as beaters, should be withdrawn from the attack until flame lengths are reduced below 1.5 m.

When using direct attack, personnel and vehicles should always approach and attack the fire from the rear and, where possible, work from an area of fuel that has already been burned. This prevents personnel and vehicles from being deployed in unburnt fuel in front of an advancing fire, which presents a significant hazard. It also helps to reduce the likelihood of personnel or vehicles being outflanked by the wildland fire.

If personnel are tasked with using hand tools, particularly edged tools such as rake hoes, care should be taken to ensure that adequate space between personnel is maintained. The spacing required to maintain safety will depend on the type of tool in use and the task being undertaken. It is generally accepted that the safe working distance for swinging tools is twice the length of the tool plus the length of the arm, or approximately three metres; however, this should be risk assessed on an individual basis.

Indirect attack

Indirect attack (Figure 55) is where personnel and resources complete suppression activities some distance away from the fire front. This type of attack can be used on flames of any length, but it is often used for high and extreme intensity fires where it is not safe to implement direct attack methods.

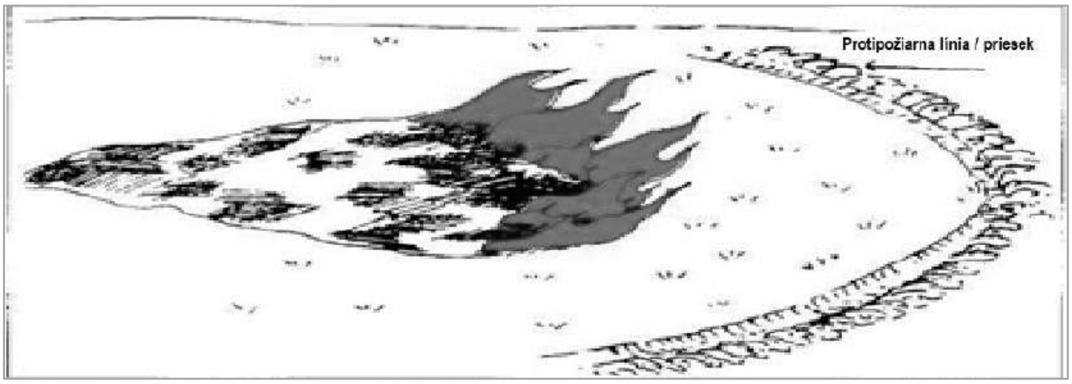

Figure 55 Indirect attack (Source: [163])

Indirect attack methods include creating or using existing firebreaks and fuel breaks as control lines, creating new control lines, or using fire as a suppression method.

There is an important distinction between firebreaks and fuel breaks:

Firebreaks are areas where there is a change or discontinuity in fuel that will reduce the likelihood of combustion, fire intensity and the rate of fire spread; they may be suitable control lines.

Fuel breaks are areas where vegetation and all other combustible materials have been removed to expose the mineral soil; they may be constructed and may be suitable control lines.

Firebreaks and fuel breaks are two examples of potential control lines. Control lines are constructed or natural barriers, including treated fire edges, which are used to control a fire. They can be constructed manually, mechanically or by applying water or retardants (which are called wet lines).

The minimum recommended width for a control line is 2.5 times the flame length, although it may be necessary or desirable in some circumstances to increase the width of a control line to ensure it is sufficient to contain fire spread.

When constructing control lines, it is vital that the rate of fire spread is considered so that there is sufficient time for personnel to construct the control line and leave the area before the fire arrives.

Burn-out is one of the activities in building a fire line. It consists of igniting the fire along the inside edge of the control line so that the fuel located in the area between the fire line and the edge of the fire is burned out.

Islands and terrain depressions located on the fire line should also be burned immediately after the fire line has been constructed, so that they are not a source of further fire spread later on. This burning creates a wider barrier to further fire spread in the main direction. Burning can be started by a torch or by pulling the burning material, e.g., with a rake. If burning is applied irregularly in an area and is not completed, it can be a source of further fire hazards when the fire intensifies again.

On a slope, burning should start at the top (ridge) and work downwards.

The burning procedure must be predetermined, considering:

– Fuel type, especially in relation to multi-layer fuel.
– The possibilities of achieving a perfect burn of combustible material.

Sources of danger in a perfect burn are uprooted trees, accumulations of heavy soil fuels, live trees with branches (limbs) reaching to the ground, and moss-covered trees. These must be removed.

Parallel attack is a specific type of indirect attack where control lines are created along the flanks of the fire towards and around the head of the fire. This suppression method is usually most effective when performed using appropriate vehicles, such as tractors pulling swipes or flails, or bulldozers.

Another indirect attack method is the use of controlled burning. Controlled burns can be lit in advance of the fire to: widen any existing control lines, create new control lines, burn out fuel ahead of the advancing fire, alter fire behaviour.

Controlled burning at wildland fires can be separated into two distinct methods:

– Defensive burning - lighting a controlled fire to remove fuel in front of an advancing fire, and extinguishing the controlled fire before the wildland fire arrives; this method is normally applied some distance from the fire front and should be planned in good time.
– Offensive burning - lighting a controlled fire and allowing it to burn into the approaching fire front; this is a higher risk strategy that requires careful assessment and planning.

Suitable control mechanisms are required to ensure that controlled burning is completed safely and appropriately at wildland fire incidents. Only those personnel that have received appropriate training, and have the relevant experience, should be allowed to use controlled burning as a suppression method.

In Central European countries, backfire is an unused method of fighting fires. The application of back-fire ensures that the fuel in the area between the control line and the front of the approaching fire is burned forward to extend the control line itself, to change the direction of fire spread, to slow down further fire development and to buy time to complete the control line.

The fire is usually ignited opposite the fire front. It is important that this fire can be controlled and that any localized outbreaks that arise because of this fire can be extinguished as quickly as possible. For this reason, it is not recommended to use firefighting techniques on small and routine fires.

The organization of the work involved in back-fire is of the utmost importance. Only one competent person must be responsible for the control, management and direction of all operations connected with the planning and execution of the backfire. In the case of the application of this technique to small fires, this responsibility falls to the intervention commander. For large fires, the controlling officer shall delegate responsibilities to the intervention commander or to the commander of the intervention section in which the fire is to be implemented. In doing so, it is essential to establish and keep open a direct channel of communication between the control staff, the intervention commander, the intervention section commanders, and the intervening firefighters. It is not recommended to deploy many forces when implementing back-fire, as this complicates their management.

Another important factor in the application of back-fire is its correct timing. Its correct timing depends on fuel, weather, available forces and resources, the rate of spread of the fire in the main direction, the topography of the terrain.

If the backfire is ignited too late, it may result in insufficient fuel burn-out. For large fires, it is necessary to obtain an overhead view to obtain an accurate estimate and location of the fire. Obtaining it requires the deployment of aerial equipment, i.e., aircraft, helicopter, or the currently advanced technology of unmanned aerial vehicles.

Indirect fire attack based on the application of back-fire is mainly used in the case of crown fire suppression and in the very rapid spread of intense fires.

In such cases, the only safe and effective firefighting technique will be the application of back-fire. If the fire is spreading very rapidly, there will be no time to deploy forces and resources close to the fire's edge. In such a case, the most appropriate solution is to build a fire line far in front of the fire front and ignite the backfire on that line.

The application of back-fire techniques requires the deployment of experienced firefighters, sufficient forces, and resources, but most importantly an experienced commander who, given his knowledge and experience, can determine the correct location for the backfire to be ignited.

The very principle of firefighting is based on the intake of air from the area, which triggers the main fire and which in turn produces a tailwind.

The following are the basic principles of backfire application.

In hilly or mountainous terrain, the best place to ignite a backfire is just beyond the top of the hill (slope), away from the slope on which the main fire is spreading.

The fire line must be wide enough to contain the main fire, or natural obstacles such as the crest of a slope or a pre-built firebreak/break can be used for this purpose.

The anchor points must be in place before burning commences. Anchor points are points where lines or obstructions on both flanks of the main fire join with lines laid across the fire face. Examples of anchor points are a road, lines or barriers found on the main fire line that are located at the front of the fire, examples being: a road, cliff, or manually created line. Lines along the flanks of the fire are to be constructed so that by the time the main fire and the backfire meet, the entire area of the fire can be brought under control.

If the backfire is ignited too late, the impact of the main fire on the control line is likely to be severe. The goal of early application of backfire is to have the backfire enter the main fire at a safe distance from the control line.

Fuel located within and adjacent to the control line must be dispersed or removed to prevent excessive heat production and/or the passage of flames across that line.

All trees adjacent to the control line shall also be burned prior to igniting the backfire. These should be sawn so that the trunks extend inside the control line or far enough away from it to prevent the surface fire from crossing beyond the control line.

Locations between the anchor points and the fire line should be burned first (these are the locations that are the most difficult to hold). Then the edge of the fire line is built up by burning away from the anchor points towards the centre of the control line. By burning from the anchor points towards the centre of the control line.

Next, it is necessary to burn the points starting from the anchor points along the wings of the fire in the downslope direction. Where there is a choice, the fire should be started at the top of the slope and ignited toward the base of the slope or downslope to prevent uncontrolled spread of the fire and to guide and contain its spread along the line.

Undesirable fire suppression phenomena include very slow fire spread, but also too intense a fire which can cause new localised fire outbreaks, fire skipping on surrounding combustible material and intensification of radiant heat production.

If the fire front approaches and spreads in the form of spurs, it is necessary to immediately ignite a backfire at the head of each of these spurs.

Fire protection can only be applied if no change in wind direction or wind speed is expected soon. Soil or water may be used to reduce the intensity of the fire. These should be applied along and close to the fire line until the fire intensity is reduced or the fire has merged with the main fire.

It is good practice to wet the area on the outside of and adjacent to the line to prevent new localized sparks caused by incandescent debris.

Aerial attack

Aircraft may be deployed at wildland fire incidents to use direct and indirect attack methods.

– Direct aerial attack involves aircraft dropping water or fire retardants onto the burning area.
– Indirect aerial attack involves aircraft dropping water or fire retardants in front of the burning area to form control lines or to strengthen existing control lines.

Aircraft and unmanned aircraft may also be used to support other tasks or activities at wildland fire incidents.

Mopping-up

Mopping-up is the process of catching up either the entire fire or catching up at multiple locations situated on the perimeter of the fireground to prevent localised outbreaks and the reignition and spread of the fire.

The size of the area to be extinguished depends on the fuel, the position of any smouldering fire in relation to the perimeter of the fire and any changes in the weather. The area burnt should be extinguished to a distance of at least 30 m from the edge of the fire, towards the centre of the fire. In some fuels and smaller scale fires, all fires within the fire line should be extinguished.

For fires in heavy fuels (trees), the cost of firefighting can be enormous. If it is not possible to burn completely all the fuel inside the fire line, or if the fire cannot be completely extinguished, a patrol must be started in the area until the fire danger of fire outside the fire line area has passed.

An extinguishing operation may mean success or failure for the entire fire management operation.

Firefighting should commence as soon as the fire line is completed. In many situations, firefighting may begin while the fire line is being established and during the phase of conducting the initial fire attack. Control of the fire will not be taken until it is ensured through the performance of firefighting operations that the spread of the fire in the area is permanently stopped.

The objective of fire suppression is to prevent smoke from forming, to cool all localised fire outbreaks and to extinguish all burning material. To prevent further fire ignition, which may originate from a hidden underground fire, it is necessary to patrol the fire area for a specified period.

In locations where there is no source of water for firefighting, but it is not abundant enough, hand tools are a very effective firefighting tool.

Although the most effective way is a combination of water extinguishing and simultaneous use of hand tools. Water extinguishing can be carried out either by using fire bags or by using remote water transport via hose lines. However, it should also be remembered that the success of firefighting does not depend on the amount of water delivered to the fireground, but on how efficiently it can be used.

Principles for the use of water extinguishing technology

When planning firefighting tactics, it is worth considering what type and amount of equipment will be deployed to pump and transport water to the fireground. Usually, the goal of the forest fire patrol at the fire site is to check for an available and sufficiently abundant water source in the vicinity. The water source may be a river, lake, dam, etc. The quantity and availability of water is another important factor to consider. If the water source is located at the bottom of a very deep ravine, it may not be reachable by the available technical equipment used to pump the water.

If the water source is located at a greater distance from the fireground, it is necessary to have enough hoses and several pumps needed to pump the water.

When water is pumped from a natural source, a portable water pump or floating pump is commonly used. When pumping water from greater depths, an ejector is also used. The second method of providing water to the fireground is to transport water to the fireground via tanker truck technology. However, this requires that the area be sufficiently accessible by a network of roads suitable for the deployment of this type of equipment.

Fire attack procedures and methods of use of the nozzle

In the case of a small-scale fire, only one or two nozzles are sufficient to suppress the fire, especially if it is a fine (light) type of fuel (grass). In the case of a heavy fuel type heavy and high and hot flame, several nozzles should be used, requiring that water streams be applied close together.

In a crown fire, several nozzles must be deployed simultaneously in a fire attack. As in the previous case, the water streams should be applied close together. The pressure on the nozzle must be high enough to create a long straight stream of water, as the nozzles should not be used near the edge of the fire.

The main objective of the men on the nozzle is to prevent the spread of the fire by knocking down the flames at the fire front. If this is not possible, then water streams should be directed to the flanks on either side of the fire or to the edge of the fire. If the fire is small and weather and meteorological conditions are moderate or low, a direct attack may be applied to the fire front. This should stop further spread of the fire. A flank attack is then continued, and extinguishing work is carried out from the rear, in a direction from the rear along the wings of the fire, around the fire front and then back to the point of origin.

The location from where firefighting operations will be conducted on the flank of the fire will depend on the extent of the fire and the amount and type of forces and resources available.

If a portion of the fire flank appears to be burned out, showing no further fire activity, the attack will be initiated at the point of intense fire burning. It is also important to control the edges of the fire to ensure the safety of the personnel.

If a fire appears to be rekindling behind the firefighter's back, he or she must leave the area as quickly as possible before being exhausted and trapped between two fires.

Next, firefighting work continues at the front of the fire to prevent the fire from spreading further. Subsequently, the fire is pinned down around its entire perimeter. Finally, it is necessary to check for localised outbreaks on the fireground, which need to be extinguished if necessary.

To penetrate the burning line, the men on the jet must strike it with a compact stream of water, aiming directly at the base of the outbreak. It is necessary to bounce the compact stream of water off the surface of the ground to break it up and cool the fuel. Once the edge of the fire has been extinguished, it is necessary to concentrate on it. Subsequently, the extinguishing work is carried out from that point and towards the fire front. The compact stream should be changed to a fragmented stream and only the burning fuel should be extinguished to extinguish it. The diffused water stream or the fog screen that can be applied in the case of combined streams can also be used as a protective shield for the intervening persons.

The burning, hot edges of the fire should be extinguished first, and only then is extinguishing applied to the entire perimeter of the fire. If, during the fire, it passes from one type of fuel to another or there are burnt-out or slow-burning parts on the fire area after it has taken control, it is necessary to extinguish the fire first on those parts where the fire intensity is the highest and only gradually to extinguish the remaining parts.

Information on the capacity of the available water sources for extinguishing and the capacity of the pumps used must always be known.

In the case of a ground (surface) crown fire, the cooling effect of the water is used in extinguishing the fire. Also, the properties of the fuel, particularly its moisture content, can be influenced by the delivery of water to the area.

Also, the overall arrangement of surface and underground fuels can be altered by the force of the water flow from the stream. In underground layers, this separation of burning and unburned fuel by water pressure is a key activity.

In general, the angle at which the water stream is directed to the edge of the fire determines the effectiveness of the separation of the burning and unburned fuel.

For fine fuels (grasses), the angle should be nearly parallel to the edge of the fire and the jet should strike the edge of the fire at about 5-8 m from the jet line (Figure 56).

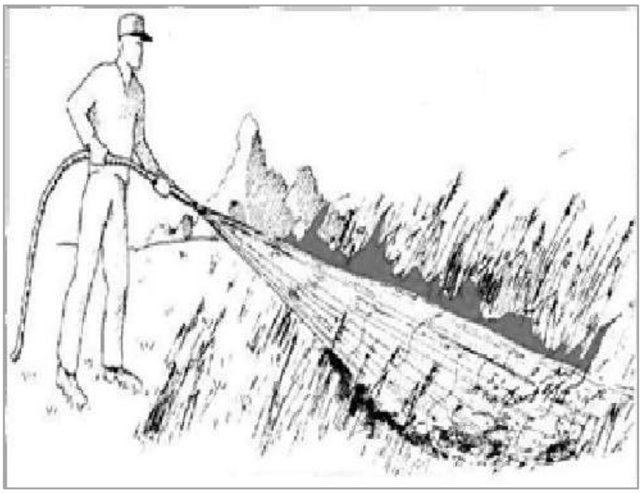

Figure 56 Directing the water stream to separate burning and not yet burning fine fuel (Source: [163])

As the underground fuel or flame front penetrates to greater and greater depths, the angle at which the water supply is directed should be increased accordingly and the stream should strike the edge of the fire at almost right angles, approximately 1.5 to 3 m in front of the man on the streamline (Figure 57). It is always the primary objective of the initial attack to keep the extinguishing line in an active state.

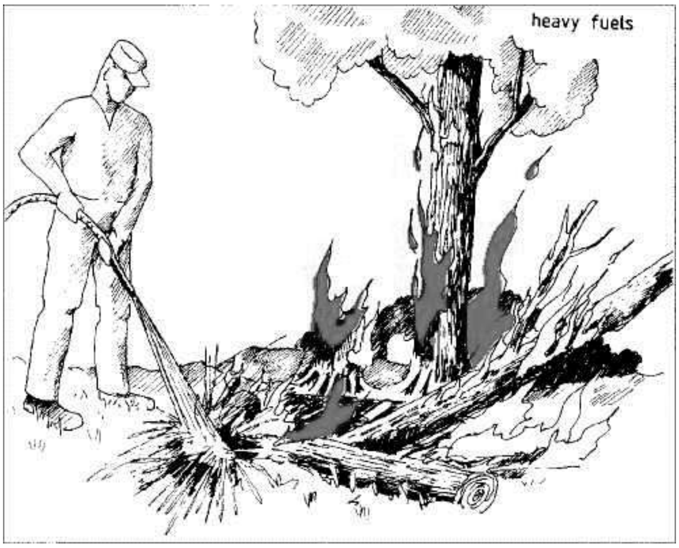

Figure 57 Directing the water stream to separate burning and not yet burning heavy fuel (Source: [163])

The following is some advice on the suitability of different types of nozzles and streams for use in different fire situations:

- Crown fire - a compact or fragmented stream with sufficient pressure and water flow depending on the intensity of the fire.
- Intense surface fire - fragmented or compact stream, pressure at the streamline and water flow is not as important.
- Low intensity surface fire - fragmented stream, not very high pressure, and water flow. Instead of extinguishing with jets, fire bags with pump can be used.

– Mopping up - a compact stream that is recommended for localised fire outbreaks.

Backpack Pumps

Backpack Pumps are not among the most useful and frequently used means of fighting a fire. However, they are the most effective and economical means of providing water to a fireground. They are particularly useful in the initial phase of a fire attack.

When using a pump, one hand must be placed near the front end and remain steady, to direct the pump to where the water is needed and as close to the base of the flame as possible. Pumping shall be done with the other hand. The hand in front adjusts the direction of the stream (Figure 58).

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Figure 58 Backpack Pump use (Source: [163])

The amount of water carried in the backpack is not very large and must therefore be used as efficiently as possible.

These backpack s are very useful in the initial attack phase. They help to prevent the spread of fire in light fuels. They are particularly effective if they are easy to fill.

The backpacks are almost indispensable in local fires, as a supplement to hand tools in the initial fire attack and especially in the phase of catching up local fires.

Some practice and training are required to use this equipment properly.

Water transport to the fireground

From more distant water sources, with the help of ground firefighting equipment, water is transported in the following possible ways [66]:

– by long-distance hose line transport using CAS or fire pumps,
– by shuttle transport using CAS, exceptionally also by other tankers,

– combined transport - a combination of the previous two modes of water transport,
– other transport - transport of water to the fire site in transport backpacks with the help of manpower.

With the help of remote water transport, it is possible to supply large quantities of water to the fireground as required. The most effective use of this transport is within about 600 m.

The most used hoses for long-distance transport are type B hoses with a diameter of 75 mm, which must be included in a CAS. Type C hoses with a diameter of 52 mm are most used for distribution streams and type D hoses with a diameter of 25 mm can be used for attack streams.

When using CAS to transport water by a system of series-connected pumps, it is possible to connect the discharge outlets of the previous machines to the tank filling pipe of the next machine. The CAS then draw the extinguishing agents from their own water tanks, this method of connection being more stable from an operational point of view, easy to operate and partially eliminating any fluctuations in the water flow. The disadvantage is the possible clogging of the pipe or tank by dirt when pumping dirty water or the possibility of water leaking through the overflow pipe, which is particularly unpleasant in winter [66].

The density of the pump deployment depends on the terrain elevation that the conveyed water must overcome. It also depends on the type of hoses used, the local losses, particularly at manifolds or check valves, as well as the required pressure at the inlet of the next pump and the required flow through one or two hose lines. However, it should also be noted in the calculations that the pump should be loaded to a maximum of 75 % of its capacity for long-term operation. Most often, long-distance water conveyance is carried out using "B" hoses and flow rates from 400 to 800 $l.min^{-1}$ are calculated [164].

Among the long-distance transport of water to the fireground we can also include certain special water transport systems, which are mainly used for extinguishing natural environment fires in Slovakia. These systems include, for example: the pond system, the high-capacity pumping system (HYTRANS).

In the case of the pond system, it is a system of water pumping bags (Figure 59) - freestanding ponds with high-pressure portable pumps. The pond system is used in difficult mountainous terrain that is inaccessible to mobile technical means, especially fire trucks, due to the lack of overland roads and the extreme gradients of the terrain. In these conditions, only aerial equipment, firefighting using backpacks (Genfo backpack and Canadian Sprinklers), or the pond system can step in. This method of extinguishing agent transport not only allows water to be transported to the fireground, but also its efficient use at the fireground [165].

The pond water transport system to the fireground is composed of [69]:

– ponds - bags with a volume of about 1,000 litres,
– transport hose line with "C" hoses,
– attack line consisting of "C/D" manifolds, "D" hoses and "D" compact stream nozzles.

– articulated shut-off valves that serve as a check valve against system drainage,
– suction hoses,
– high-pressure portable pumps.

Different methods are used to transport this system to the intervention site: by aerial drop using airborne equipment, by ground equipment, in difficult terrain with the help of a special SCOT-TRAC 2000R vehicle, or four-wheelers. Terrain conditions, mainly slope, terrain obstacles or forest density, often do not allow the use of technical means of transport, therefore the system must be carried out by the intervening officers themselves, piece by piece, in backpacks. The practical discharge height of the pumps is in the range of 35-40 m, the end pump about 20 m. The first pond can be fed from the CAS or from a natural water source, with the possibility of transporting water a greater distance for greater pump output increasing by a further approx. 80 m if the CAS is used.

On top of the pond system (Figure 59), a large-capacity FIREFLEX-type tank of 38,000 l capacity can be placed, which can be used to scoop water for aerial equipment, or as a holding tank to build up firefighting attack streams etc.

Figure 59 Pond water transport system (Source: GFFM, 2007)

Nowadays, this system of extinguishing agent transport is used more and more frequently in practice. It has proved its worth in several forest fires, its design is still being improved and it is gradually being introduced in some fire stations.

The priority use of the high-capacity water pumping system (HYTRANS) (Figure 60) is for flood response, but it is also equipped with a system for long-distance water transport, which can be used for fires in wildland areas. This system is composed of a propulsion and pumping unit, hoses, and a reeling unit for their collection. Pumping is carried out by portable floating pumps which are connected to the drive unit by 60 m long hydraulic hoses. The propulsion unit consists of a diesel engine which drives the hydraulic pump. The pumps, depending on the type, can deliver water from 1,000 $l \cdot min^{-1}$ at 10 bars to 30,000 $l \cdot min^{-1}$ at 2,5 bar. The capacity of the pumps currently in the Fire and Rescue Service equipment is 3,500 l·min^{-1} at a pressure of 10 bar. In flood pump configuration this system pumps 50,000 l·min^{-1}. The advantages of this system are pumping from a depth of 60 m, transport to large distances, fast start-up, no need for watering, the possibility of being located further away from the water source, but also pumping from shallow water. The system also allows pumping of salt water, polluted water, sludge, etc.

It makes it possible to construct a long-distance water transport system up to 2,000 m and exclusively in terrain accessible to automotive equipment.

It is expected to be deployed mainly in grassland and agricultural fires, less so in forest fires, due to the ruggedness and inaccessibility of the terrain.

Figure 60 High-capacity water pumping system (HYTRANS) (Source: Pyronova, 2016)

Water shuttle

This water transport is mainly used when the distance between the water source and the fire site exceeds several hundred metres to kilometres, with fewer forces and resources that were insufficient or required more time to transport the water by long-distance hose line. For an efficient water transport loop to the fire site, it is ideal to build the most powerful CAS at the water source, which pumps water to the other CASs, and they circulate along a designated route to the fire site and back. It is most advantageous to include as circulating CAS those that have the largest water tanks. If tankers with large tanks do not have sufficient throughput, tankers with smaller tanks but sufficient throughput can be used.

Another filling option is that only suction lines are placed at the water source to connect to the intake throats of the circulating CAS. This filling solution has several disadvantages over the previous option for several reasons. The filling time of the circulating CAS is increased as the time required to handle the suction lines is longer. Every firefighting equipment should have a suction line and a pump in good condition. This filling option also requires increased demands on the expertise of the engineer, so in practice this option is not used very much.

To determine the required number of circulating cars, the times required for filling and emptying each CAS and to determine the travel times of cars along a specified route, mathematical relationships are available for calculating the shuttle service.

Currently, the following fire trucks are most often available at the Fire and Rescue Service and the municipal volunteer fire brigades for water shuttle service:

- CAS 30 - IVECO TRAKKER (water tank capacity of 9,000 l).
- CAS 32 - T815-7 6x6 (water tank capacity of 9,000 l). CAS 32 - T815-7 6x6 (water tank capacity of 9,000 l).
- CAS 32 - T815 (water tank capacity of 8,200 l). CAS 32 - T815 (water tank capacity of 8,200 l).
- CAS 32 - T148 (water tank capacity of 6,000 l),
- CAS - K 25 Liaz 101.860 (water tank capacity of 2 500 l). CAS - K 25 Liaz 101.860 (water tank capacity of 2,500 l),
- CAS 24 - MB Atego (water tank capacity of 2,500 l)
- CAS 16 - Praga V3S (water tank capacity of 3,500 l),
- CAS 20 - MB Unimog (water tank capacity of 2,000 l).

Reconstruction and modernisation of the CAS 32 T148 and CAS 32 T815 large-capacity tankers for the needs of volunteer firefighters was carried out in previous years and they were transferred to the selected municipality fire brigades in Slovakia, as they have very good off-road driving characteristics due to their lower centre of gravity.

Combined transport of extinguishing agents

In some cases, a fire is in an area where the terrain between the fireground and the water source does not allow the use of only one method of water transport, either long-distance or shuttle transport. In such a case, a combination of the two methods of water transport may be used, and a shuttle service may be used for the portion of the terrain suitable for CAS crossings. For the other part of the terrain unsuitable for CAS, use long-distance water transport. This method of transport is the most used in practice, despite its greater difficulty to operate and the number of forces and resources required.

Slovakia

For firefighting in the wildland areas, mainly automobile pumping appliance (CAS) and forestry specials are used.

Pumping appliance

A pumping appliance is a firefighting vehicle equipped with a pump and usually a water tanker, hoses, nozzles, and other auxiliary equipment needed to extinguish a fire. Its design and equipment must enable it to be deployed primarily in the field, especially on:

- fighting forest, grassland, and stubble fires (at a standstill and when driving slowly),
- supplying the response section with extinguishing agent when fighting a fire using a lightweight portable fire extinguisher,
- creating firebreaks by cutting through vegetation, breaking up topsoil, etc.

Technical and rescue equipment of CAS for extinguishing fires in wildland, especially forest fires must include):

- water tank made of stainless material, thermally insulated, with a capacity of 2 500 - 3 000 l,
- pump capacity of at least 1 800 l.min-1 at 0,8 MPa and 250 l.min-1 at 4,0 MPa,
- two flow reels with high pressure hoses DN 25, hose length min. 60 m + pistol grip combination flow reels with flow control and shot cone shape,
- swivel hinged or swivel detachable lafette nozzle with a range of min. 30 m located on the roof of the superstructure.

In the equipment of the Fire and Rescue Service in the Slovak Republic there are currently 2 types of pumping appliances (tanker trucks): CAS 30 T815-7 6x6.1 and CAS 30 IVECO Trakker AT 260T 45W 6x6.

Reconstruction and modernisation of CAS 32 T148 and CAS 32 T815 bulk pumping appliances have been carried out in the recent past. After reconstruction, these were transferred from the armament of the Fire and Rescue Service to the armament of the voluntary fire brigades of the municipalities. They still have very good off-road driving characteristics thanks to their lower centre of gravity.

CAS 30 T815-7 6x6.1

The CAS 30 T815-7 6x6.1 (Figure 61) is a heavy pumping appliance for water and foam intervention. The truck is built on a three-axle Tatra T815-731R32 26.325.6×6.1/411 chassis. It is an off-road pumping appliance, designed for off-road operation, thanks to its small overall height (2,850 mm), and for all types of roads. The superstructure is equipped with a centrifugal combination pump THT TO 3000, a water tank with a capacity of 9 000 l and a foam tank with a capacity of 540 l. The vehicle is designed for transporting a crew of four. The performance parameters of the machine chassis, the large volumes of the extinguishing agent tank, and the appropriate pump performance create the optimum prerequisites for fast and effective firefighting intervention even in difficult terrain and climatic conditions [166].

Figure 61 CAS 30 T815-7 6x6.1 (Source: District Directorate of FRS in Banska Bystrica, 2016)

Possible uses: helping in cases where the life, health and property of persons are threatened; fighting class A and B fires; transporting the team (1 + 3 = 4 crew members), extinguishing agents and fire protection equipment, as well as personal protective equipment to the place of intervention; carrying out water and foam firefighting; carrying out water shuttle transport and water transport by long-distance hose line.

The Tatra T815-731R32 26.325.6×6.1/411 chassis is fitted with a low middle cab, compared to the military standard design, a fiberglass roof is fitted, into which beacons, and engine intake are built to keep the overall height of the car as low as possible, while the cab is the highest place on the car.

The vehicle is powered by an air-cooled Tatra T3D-928.30 mechanical fuel injection engine with a power of 325 kW and a maximum torque of 2,100 Nm, meeting the Euro 5 standard, supercharged by a single exhaust turbocharger. Engine displacement is 12,667 cm^3 . The transmission is a fourteen-speed synchromesh with automatic gear shifting. The vehicle is also fitted with an additional two-speed gearbox.

The chassis is of frame construction mounted on a support tube. The front axle is driven with swinging semi-axles, switchable drive, and axle differential. The rear axles are permanently driven, with swing axles and axle differentials. The suspension of the car is provided by air springs and telescopic stabilizers. The vehicle allows ground clearance adjustment directly from the cab.

The superstructure of the vehicle is aluminium, classic concept - the front part consists of two cabinets, the second part of the tank and in the third part we find two cabinets for technical means and pump. The pumping equipment is stored in the rear compartment of the superstructure. The centrifugal combination pump THT TO 3000, with watering device, is driven from the vehicle engine by a set of connecting shafts. The pump allows low or high-water pressure intervention or combined operation. The pump includes an automatic piston pump with manual shut-off.

The flow reel is electrically operated, if necessary, also manually. It is equipped with a high-pressure hose DN 25 with a length of 60 m and a capacity of 200 $l \cdot min^{-1}$ at a pressure of 4 Mpa. The lafette flow line is removable, located in the upper part of the superstructure, also usable as a portable monitor. On the upper platform of the superstructure three accessory boxes (ladder, rip hooks) and a lighting mast are located.

The water tank and the foaming tank form a single unit and are welded from stainless steel sheet. The tank is prismatic in shape. It is equipped with a device for controlling the quantity of water in the tank. An overflow pipe ensures the tank is vented when the pumping equipment is in operation and the water is drained from the tank under the vehicle when it is overfilled. Filling of the tank is made possible by its own pump with the possibility of filling also in firefighting operation and from an external pressure source.

The capacity of the tank is of 9,000 l. The foam tank is secured against overpressure and under pressure with overflow and quantity control device. Tank capacity of 800 l.

The vehicle is equipped with, among other things, dual clutch control, secondary engine speed control, fog lights, etc. as standard. The vehicle's climb ability at a total load of 26,000 kg is 99,9 %.

CAS 30 IVECO Trakker AT 260T 45W 6x6

The CAS 30 IVECO Trakker AT 260T 45W 6x6 (Figure 62) is a heavy pumping appliance for water and foam intervention. The vehicle is designed to extinguish fires of highly flammable substances. The vehicle is built on a three-axle chassis IVECO Trakker AT 260T45W 6x6 and is equipped with a centrifugal combination pump THT TO 3000, a water tank with a capacity of 9,000 l and a foam tank with a capacity of 800 l. The vehicle is designed for transporting a crew of three persons. The performance parameters of the machine chassis, the large volumes of the extinguishing agent tank, and the appropriate pump performance create the optimum conditions for fast and effective firefighting intervention even in difficult terrain and climatic conditions [167].

Possible uses: providing assistance in cases where the life, health and property of persons are endangered; fighting class A and B fires; transporting the team (1 + 2 = 3 crew members), extinguishing agents and fire protection equipment, as well as personal protective equipment to the scene of intervention in such a composition that allows independent operation; carrying out fire-fighting intervention with water and foam; carrying out water shuttle transport and water transport by long-distance hose line.

Figure 62 CAS 30 IVECO Trakker AT 260T 45W 6x6 (Source: THT Polička 2015)

The IVECO Trakker AT 260T 45W 6x6 is an all-weather, all-road vehicle with three driven axles. The frame is a ladder double-wrapped one-piece U-shaped beam with a parallel base frame section. Both the front axle and rear axle have a double-steer axle with a hub in the wheel and a pneumatically operated differential lock. The cab is trambus. The chassis is provided by an IVECO power unit with a maximum output of 332 kW at 1,900 rpm. This enables the vehicle to reach a maximum speed of 110 km·h^{-1}. The gears are taken care of by a manual 16-speed gearbox. The air brake system has two circuits including ABS.

The superstructure is made up of two tanks, pumping equipment, foaming equipment, piping, fittings, bodywork, and accessories. The pumping equipment is stored in the rear compartment of the body. The centrifugal combination pump THT TO 3000, with watering device, is driven from the vehicle engine by a set of connecting shafts. The pump allows low or high-water pressure intervention or combined operation. The pump includes an automatic piston pump with manual shut-off. The foaming device consists of a mixer, a control system, a pipeline, and a foaming pump.

The flow reel is electrically operated, if necessary, also manually. It is equipped with a high-pressure hose DN 25 with a length of 60 m and a capacity of 200 l·min^{-1} at a pressure of 4 MPa and with a removable foaming attachment. Lafette nozzle located in the upper part of the superstructure, manually operated, 360° rotatable, with a capacity of 2200 l·min^{-1} and a range of 65 m. The lighting mast is fixed, pneumatic, telescopic, extendable to a height of 5 m from the ground, 360° rotatable with a power of 2 x 70 W.

The water tank and the foaming tank form a single unit and are welded from stainless steel sheet. The tank is prismatic in shape. The water tank is equipped with a device for controlling the quantity of water in the tank. There is a hatch of Ø 510 mm at the top of the tank with a hinged lid. The overflow pipe provides for venting of the tank when the pumping equipment is operating and for draining the water from the tank under the vehicle when they are overfilled. Filling of the tank is made possible by its own pump with the possibility of filling also in firefighting operation. From an external pressure source via two B 75 filler necks with check valves. The tank capacity is 9,000 l. The foam tank is overpressure and under pressure protected with overflow and quantity control device. At the bottom of the tank there is a flange for connecting the foaming agent pipe to the mixing device. Tank capacity 800 l.

The piping is used to interconnect the individual systems for suction, discharge, and transport of foam. The suction pipe connects the suction side of the pump to the water tank and, via the inlet fittings, to the other water sources. The suction line is also used for filling the own tank with the pump itself or from other external pressurised water sources. The discharge pipe is connected to the pump discharge and is routed to the sides of the vehicle and to the lafette nozzle. It is used to enable the mixer to operate and to flush after the foam spraying operation is completed.

CAS 32 T815

The CAS 32 T-815 (Figure 63) pumping appliance truck sprayer after the reconstruction after 2009 is classified as a heavy water and foam pumping appliance by its concept. It can be used wherever there is a high risk of fire. The vehicle is built on a three-axle Tatra 815-2 6x6 wheeled chassis and has a centrifugal single-stage pump, a water tank with a capacity of 8,900 l and a foam tank with a capacity of 400 l. The vehicle is designed for transporting a crew of four. The performance parameters of the machine chassis, the large volumes of the extinguishing agent tank and the appropriate pump performance create the optimum prerequisites for fast and effective firefighting action even in difficult terrain and climatic conditions.

Possible uses: rendering assistance in cases where the life, health and property of persons are endangered; fighting class A and B fires; transporting the team (1 + 3 crew members), extinguishing agents and fire protection equipment, as well as personal protective working equipment to the scene of intervention in such a composition that allows independent operation; water and foam fire-fighting; water shuttle and long-distance hose line transport, especially for forest fires; floods, airport runways, chemical plants, refineries, warehouses of flammable substances, large fires (warehouses, fields, meadows, forests, buildings).

Figure 63 CAS 32 T 815 Source: District Directorate of FRS in Dunajska Streda, 2014)

The Tatra 815 PR 2 is a vehicle with increased off-road capability with three driven axles. It is based on a central carrier tube. On the cross beams of the tube is the frame. The tube carries the drive torque distribution to each axle, containing the inter-axle and axle differentials with locks. The front axle is suspended by torsion bars, supplemented by hydraulic telescopic shock absorbers. The axle is driven, fitted with a differential. The rear axles are semi-independently sprung. The auxiliary drive of the pump drive is connected to the front of the gearbox. The cab is trambus for a crew of 1 + 3. The vehicle is equipped with a diesel, four-stroke, air-cooled, 12-cylinder, direct-injection, 6 cylinders in two rows in a "V" arrangement with OHV timing. The engine displacement is 19,000 cc, which gives the vehicle a power output of 235 kW at 2,200 rpm·min^{-1}.

The superstructure is made up of tanks, pumping equipment, foaming equipment, piping, fittings, bodywork, and accessories.

The pumping device is housed in the rear compartment of the body, heated by the waste heat of the engine exhaust gases.

The pump is centrifugal, single stage, driven by a motor through an auxiliary drive and shafts connected by cross joints. A burnt gas vacuum pump is used to create a vacuum in the pump casing.

The water tank has a capacity of 8,900 l made of stainless-steel sheet. The tank is made of sheet steel with anticorrosive coating and has a device for remote control of the amount of water in the tank. On the top of the tank there is a 510 mm diameter opening with a hinged lid. The foaming tank is made of stainless-steel sheet and is incorporated into the water tank. It is equipped with a filling opening at the top of the tank with a protective rim for fast filling, a drainage opening with overflow and a remote quantity control device.

The frame of the front cabinet is made of aluminium profiles and sheathed with aluminium sheet using bonding technology. The internal shelves are made of profiled aluminium sheet. The side openings are covered by aluminium roller shutters with handles. The frame of the rear cabinet is made of aluminium profiles and clad with aluminium sheet using gluing technology. The internal shelves are made of profiled aluminium sheet. The side openings are covered by aluminium shutters with handles. From the rear side, hinged doors with gas dampers are mounted. A ladder is mounted on the rear wall on the right, which is metal and has plastic partitions.

CAS 32 T148

The pumping appliance CAS 32 T148 6x6 (Figure 64) is built on a tri-axle chassis TATRA 148 6x6 type 8114.14 and is equipped with a centrifugal single-stage pump, a water tank with a capacity of 6,600 l. The vehicle is designed for transporting a 3-member crew, it ranks among the heavy pumping appliances designed for water intervention in places with water shortage. Its use is mainly in more inaccessible roads, in inaccessible fires.

Possible uses: to render assistance in cases where the life, health and property of persons are threatened; transport of the team (1 + 2), extinguishing agents and material means; carrying out firefighting action with water; carrying out water shuttle transport and long-distance hose line transport.

Figure 64 CAS 32 T148 6x6 (Source: Regional Directorate of FRS in Zilina, 2015)

The CAS 32 T148 6x6 is an all-weather, three-axle, high clearance vehicle with three driven axles. The chassis is formed by a central support tube which carries the axle boxes and the additional gearbox housing. The frame with the driver's cab, engine and clutch is mounted on the cross members of the central tube.

The internal combustion engine is a diesel, four-stroke, air-cooled. The transmission has 10 forward gears and two reverse gears. The front axle is pendulum, suspended by torsion bars, supplemented by hydraulic telescopic shock absorbers. The axle is equipped with a driveline that can be engaged on the dashboard, and its front differential can be operated in the same way. The twin rear axles are pendulum axles with semi-axles independently sprung by means of leaf springs, supplemented by hydraulic telescopic shock absorbers. The differentials of both drive axles are fitted with electro-pneumatically operated locking differentials with push-button control on the dashboard.

The driver's cab is an all-metal, two-door, locking cab with covered running boards. There are seats for three persons in the cab. The passenger seats are equipped with breathing apparatus holders and head restraints.

The superstructure frame is made of steel profiles and clad with galvanized sheets using bonding technology. On the sides, there are storage cabinets for fire accessories, which are covered with aluminium shutters. A roller shutter is also fitted at the rear to cover the flow reel cabinet. The left and right accessory boxes are separated from the flow reel by aluminium dividers. The upper platform is covered with a non-slip steel plate.

The superstructure consists of one 6,600 l tank, pumping equipment, fittings, bodywork, and accessories. The piping is divided into suction, discharge, hydrant, and drainage. The control panel is located at the pumping equipment on both the left and right side, accessible by opening the roller shutter. The pump is centrifugal, two-stage and made of aluminium alloys and is housed under the front of the tank and is made up of a pump with drive, a gas pump, the corresponding piping, and a motor speed control.

In the rear part there is a quick-action device consisting of a flow reel, a DN 25 pressure hose with a hose length of 60 m and a TURBO PW-25 combined pistol nozzle.

The water tank forms the load-bearing part of the entire superstructure. It is located behind the driver's cab above the rear axles and is mounted on two brackets. The tank is prismatic in shape, welded from steel plates and equipped with a device for remote control of the quantity in the tank. On the top of the tank there is an opening of Ø 510 mm with a hinged lid. Next to the opening there is an overflow pipe which ensures that the tank is vented when the pump is running and a device for draining the water from the tank under the vehicle when the tank is overfilled. The water tank is protected against damage from careless filling with water by the closing mechanism of the hinged lid, which also acts as a pressure relief valve. A pump suction flap flange is located at the bottom of the tank, and 2 flanges of the tank filling pipes and 1 flange of the rotating lafette are located on the sides of the water tank. There is also a flange for the water skimmer pipe on the rear lower part. The capacity of the tank is 6,600 l.

Forest specials

Among the forest specials UNIMOG forest specials on Mercedes Benz U1550L, U4000, U5000, CAS 24 Renault Middlum, Praga V3S ARS, CAS 30 T 815-7 4x4.1.

In this subchapter we have focused on the presentation of the operational and tactical parameters of only one of them: the CAS 20 Mercedes - Benz UNIMOG U 1550 L 4x4 [167].

CAS 20 Mercedes - Benz UNIMOG U 1550 L 4x4

The pumping appliance on the chassis CAS 20 MB Unimog U 1550 L 4x4, (Figure 65) is designed for extinguishing forest fires in difficult terrain, for transporting the fire brigade with the accessories necessary to carry out the firefighting intervention in difficult terrain [167].

Possible uses: Transporting a firefighting squad (1 + 2) with accessories to fires; transporting water to a fire in difficult terrain; carrying out firefighting in difficult terrain; fighting forest, grassland and stubble fires (when stopped and when driving slowly); supplying the fire-fighting section with extinguishing agent when fighting a fire using a light portable extinguishing device; creating firebreaks by cutting through vegetation, breaking up the surface layer of soil, etc.; some technical activities in flood and landslide relief.

The MB Unimog U 1550 L is a car designed for driving in difficult terrain. The frame is a ladder frame, welded from two U-shaped beams with high torsional flexibility. The car has portal axles with differential locks and reducers. The driveshaft is housed in a tunnel and the differentials are located above the centreline of the wheels, providing high ground clearance and off-road driveability. Suspension is provided by coil springs with telescopic dampers and stabilisers. The brakes are double-circuit, pneumatically hydraulic. The chassis provides optimum thermal and mechanical protection when fighting forest fires.

The engine is a 6-litre turbocharged in-line six-cylinder with a maximum power output of 177 kW at 2,600 rpm, liquid-cooled. The transmission is fully synchromesh, 8 forward and 8 reverse.

Figure 65 CAS 20 MB Unimog 1550 L 4x4 (Source: District Directorate of FRS in Poprad, 2013)

The purpose-built superstructure consists of three parts. The first part consists of a cabinet for storing equipment accessible from both sides of the superstructure, the second part is a 2,500-litre tank, the rear part houses the pump. On the left and right side of the equipment storage cabinets. The roof of the superstructure is loading bearing, allowing the movement of persons, the positioning and safe attachment of larger equipment parts (e.g., tow bar, ripping hook). The vehicle is equipped with a combined centrifugal pump with a rated output of 2,000 $l \cdot min^{-1}$ at 1.0 MPa and 400 $l \cdot min^{-1}$ at 4 MPa, which is driven from the vehicle engine by articulated shafts. The equipment includes a 200 litre foam tank, two winches with DN 25 high pressure hoses 60 m long with a nozzle, a swivel detachable lafette nozzle, a floating pump with petrol engine, chain and hand saws, a brush cutter, air isolation breathing apparatus with spare cylinders, B 75 and C 52 pressure hoses, C 52 combination hoses with foam-forming attachments, screen hoses and other means of suction and attack accessories as well as means for manual extinguishing - Genfo backpacks, fire blankets, diggers, chokers, shovels, picks, axes, pitchforks.

Material resources

Material resources used in fighting forest fires are divided into the following groups:

- personal gear and equipment (firefighter's helmet, gloves, belt, etc.),
- material equipment - suction accessories, extrication accessories, other and auxiliary material means.

We are not going to pay attention to the personal equipment, we will focus on the material equipment in which the transport of extinguishing agents take place. The transport of extinguishing agents starts at the water source, where it is pumped into the transport line by means of pumps, passing through the entire transport line up to the place of the fire.

Attention is given to the following three types of material means:

- material equipment for taking water from the water source to extinguish fires (suction fittings). Material equipment for taking water from the water source to extinguish fires,
- material equipment for the transport of extinguishing agents (discharge accessories),
- other and auxiliary material equipment.

Drawing accessories

The material equipment for drawing water from a water source for firefighting (suction fittings) is that part of the fittings which conducts water from the water source to the pump for the purpose of filling the CAS tank (water shuttle) or for direct use by the pump and pressure extinguishing fittings:

water extraction from a water source up to 7.5 m: suction basket, suction hoses, catch line, valve line, ejector, transitions,

water extraction from depths greater than 7.5 m: standing ejector,

water abstraction from a pressurised water source: hydrant extension, B75 - short hoses, skimmer, transitions,

hot and dirty water withdrawal: horizontal ejector.

A suction basket is a means of attaching to the suction hose to prevent spontaneous leakage of liquid from the suction line and the entry of foreign objects into the suction line. It also allows the suction line to be drained. It consists of the basket body itself, a non-return flap with an opening mechanism operated by a valve cable, a filter grid and a throat coupling which enables it to be connected to the suction line. The suction return flap of the suction basket shall seal reliably. The suction basket shall be tight and leak-proof. It is manufactured in three versions, the difference being the diameter for screwing onto the suction hose (110, 125 and 150 mm). The suction basket includes a valve and a catching rope [168].

The suction hose (suction tube) is connected on one side to the suction basket and on the other side to the suction neck of the pump. They are used to transport water from the suction basket to the pump. Suction hoses are manufactured mainly in diameters of 150, 125, 110 mm, less so in diameters of 75, 52, 25 mm and in lengths of 1,5 to 2,5 m in increments of 0,5 m. They are made of hemp, linen or cotton fabrics interwoven with rubber and spirally reinforced on the outside and inside with steel wire. They must be leak tested at least once a year (overpressure, underpressure, tightness). A catching rope is used for handling [168].

The valve rope serves as an auxiliary accessory, especially for operating the check valve of the suction basket or ejector [168].

The arresting rope is used as an auxiliary accessory for motorised syringes, it is also used to lower the suction hoses into the water source, to secure and retrieve them [168].

An ejector is a jet pump designed for pumping water from depths greater than 7,5 m, heavily polluted water, or water with a temperature above 60 °C, or for pumping water from inaccessible water sources. The inlet and outlet throat are equipped with throat couplings. At the bottom, the ejector is equipped with a suction basket with a non-return valve, which is operated by means of a valve cable [168].

The collector allows the pooling of at least two conveyor line streams into one with a larger diameter. Inside the header, a control damper is placed [168].

The hose crossing is used to join suction pipes or fittings with different diameters or types. The hose barb shall meet the requirements of strength and tightness at the test pressure, with no water seepage [168].

Discharge accessories

Means in kind for the transport of extinguishing agents (discharge fittings) - used for the transport of extinguishing agents from the pump to the fireground [168]:

- through the lafette nozzle to the fireground,
- low-pressure accessories - conveying lines: pressure hoses B75, pressure relief valve, manifold, and attack lines: pressure hoses C52 and D25, combined flow lines up to the fireground,
- to other pumps - in series or in parallel,
- in tanks - shuttle service.

The means of transport of extinguishing agents primarily include pressure hoses.

Water is conveyed from the pump to the fireground by means of pressure hoses. Pressure hoses are flexible pressure pipes designed to transport water and aqueous solutions. Pressure hoses can be folded and twisted flat when unfilled. The hoses are woven from synthetic fibres (so-called insulated) with internal or double-sided impermeable insulation to prevent the passage of water.

The hoses must meet demanding requirements, which include [169]:

- elasticity and flexibility (for ease of handling and to take up as little storage space as possible) and must retain these properties even at sub-zero temperatures,
- impermeability and resistance to the required values of internal overpressure,
- resistance to abrasion of the walls when handling on rougher surfaces,
- as little weight as possible,
- smooth walls - both internal and external,
- the material is as little as possible subject to ageing and thus to changes in mechanical and physical properties,
- heat resistance,
- low maintenance and storage requirements,
- repairs should not be technologically demanding.

Pressure hoses are divided into 4 groups according to their diameter. The individual diameters are indicated in mm or by means of capital letters.

These diameters are as follows [168]:

- D 25 - are mostly used for forest fire fighting or long-distance lines, or to higher elevations. They are also used in the lake system of extinguishing agent transport. Their handling when filled is simple. They are available in lengths from 5 - 120 m (by agreement).
- C 52 - Most used to form the attack line from the manifold to the flow lines. They are manufactured in standardised lengths of 20 m.
- B 75 - used mostly to create a transport line from the water source to the distributor, for long-distance transport of water between pumps, when refilling tanks, etc. They are produced in standardized lengths of 20 m and 5 m.
- A 110 - used in hose wagons to create a conveying line allowing, in conjunction with powerful pumping units, the long-distance conveyance of large quantities of water. They are not used in forest fires. Because of their considerable weight, they are too cumbersome to handle manually. They are manufactured in lengths of 25 m.

With pressure hoses, their ability to withstand internal overpressure is very important. Usually three pressure values are quoted [168, [169]:

Guaranteed operating pressure - the so-called working pressure, this is the pressure value at which the hoses are normally able to operate without time limitation without overloading.

Test pressure - is the pressure value at which the hoses are tested. The value of the test pressure varies between manufacturers. It is usually between 2,0 and 2,5 MPa.

Bursting pressure - is the pressure value at which the hose will burst (break). The value of the bursting pressure depends mainly on the type of fibre from which it is woven and the diameter of the hose. This value ranges from 3,5 MPa to values around 5,5 MPa.

Material equipment for the transport of extinguishing agents also include pressure couplings, manifold, pressure relief valve and nozzle.

Pressure couplings are used to connect hoses to each other or to connect them to the pump outlet or other material means. Depending on the point of use, couplings are divided into hose and throat couplings for use in the vacuum section or the overpressure section. A pressure coupling consists of a neck, a casing, a rubber seal, and a fuse. The design of the coupling must guarantee strength and tightness under both test pressure and vacuum.

The manifold is used to divide the flow of the hose line into several hose lines, each of which can be individually closed with valves (ball, lever). The manifold consists of inlet and outlet throats. The manifold must not leak.

A pressure relief valve is a safety device that protects the hose line and pump from water pressure surges. When the set water pressure is exceeded, the valve opens. Water starts to flow out until the pressure is reduced. Then the valve closes again. It is mainly used for transporting water over long distances and heights (long-distance transport). The adjustment of the required pressure can also be carried out manually during operation.

The flowline forms the last part of the attack hose line and is used to direct the flow of water delivered to the fireground into the burn zone. It converts the pressure energy of the water into motion energy. The more movement energy the water has, the greater the pressure will be. We supply water of a certain pressure at the flow line, which is converted to the velocity of the flowing water. The amount of water that flows out of the stream is dependent on the velocity of the discharge and the discharge cross section. The nozzle consists of the following parts: a nozzle body, a removable nozzle, a pressure neck coupling, a device for changing the shape and flow rate of the extinguishing agent stream.

A special place is given to the means of securing the supply of extinguishing agent to the fireground by means of aerial technology. This includes the Bambi Bucket and FIREFLEX.

The Bumbi Bucket is an integrated fire-fighting system used to extinguish fires in the undercarriage. It is a bag that is suspended on a rope under the helicopter, which pumps water to extinguish fires. Its huge advantage is that it can be filled directly from the water surface (e.g., reservoirs, rivers, lakes, or ponds). Its capacity is 270-9 780 l. An example of a Bambi bag is shown in Figure 66.

Figure 66 Bambi Bucket (Source: [170])

FIREFLEX is a large-capacity tank with a capacity of 36,000 – 54,000 l (Figure 67). FIREFLEX can be used as a standby tank or as an immediately available water source during firefighting operations.

The FIREFLEX self-supporting tank can be easily filled from the nearest water source, lake, stream or possibly a water tanker. [170]

Figure 67 FIREFLEX ([170])

This type of reservoir filling is also professionally called "water transport" in difficult terrain. It is also possible to fill a Bambi Bucket from a water tank.

Other and auxiliary means

Other and auxiliary means - used to ensure smooth transport of extinguishing agents. These include a crossing bridge, hose clamp.

The crossing bridge is designed to guarantee the protection of the pressure hose routed across the road when vehicles are passing.

The hose clamp is used to quickly seal damaged hoses temporarily in service, preventing further damage to the hose from spreading. The hose clamp shall be capable of being clamped to a hose of the appropriate size at a hose pressure of up to 0,4MPa and withstand a permanent hose pressure of up to 1,2 MPa.

A special category of technical and material resources is the equipment and facilities which forest or agricultural landowners and users should have at their disposal at the time of a fire and which can be deployed immediately and efficiently if necessary.

In terms of equipment, wheeled tractors, whether forestry tractors or all-purpose tractors, may be mentioned. In terms of equipment used to extinguish fires in wildland areas, shovels, buffers, axes and, for example, GENFO backpack, which have a capacity of up to 15 litres (Figure 68).

Figure 68 Buffer, axe and GENFO backpack (Source: [170])

Prescribed burning is not practiced in Slovakia. The State Nature Conservancy institution and national fire protection legislation do not permit the use of this fire tactics.

Czech Republic

Legislation in the field of repression, i.e., also the extinguishing of fires in the wildland areas:

- Act No. 133/1985 Coll. on Fire Protection [171], as amended by later regulations - the primary legal regulation for the area of fire protection in the Czech Republic,
- Act No. 320/2015 Coll. on the Fire Rescue Service of the Czech Republic [172] and on Amendments to Certain Acts, as amended - basic document describing the role and duties of the Fire Rescue Service of the Czech Republic,
- Act No. 239/2000 Coll. on the Integrated Rescue System [173] and on Amendments to Certain Acts, as amended by later regulations - basic document describing the coordination and activities of the components of the IRS in the liquidation of emergencies,
- Decree of the Ministry of the Interior No. 247/2001 Coll. on the organisation and activities of fire protection units [174], as amended - operating regulation to Act No. 133/1985 Coll. on Fire Protection,
- for the activity of the fire-fighting units, a methodological regulation - Bojový řád jednotek PO (issued by the General Directorate of the Fire Fighting Service of the Czech Republic), which, among other things, addresses the issue of forest fires.

Firefighting means It is very common, for bigger fires, to use large scale helicopter support, for tactical exploration and for aerial firefighting as well, using water buckets with up to 2,500 l of water. If needed, it is possible to ask for army helicopters (Figure 69) or some private planes in case of emergency.

Figure 69 Army helicopters
(Source: Fire and Rescue Service, General Directorate, Czech Republic)

Because of a rapid growth of the number of forest fires and visible climate changes, some decisions were made, such as buying special fire tracks or a consideration of new aerial firefighting means. The newest fire truck suitable for forest fire fighting is the Tatra CV-40 with a total water capacity of 21,000 l of water, or special heavy armoured fire trucks with high fire and explosives resistance such as CZS 40 Titan or CZS 15 Triton.

The group of equipment within the Fire and Rescue Service of the Czech Republic, which, by its technical design, is most suitable for deployment in wildland areas, includes the following vehicles [82]:

CZS 15 2000/0 - S3 TATRA 815-7 4x4 A hardened vehicle (Figure 70) for firefighting in hazardous environments (with explosion risk, for natural fires) with ballistic protection and fire extinguishing equipment remotely controlled from the crew compartment.

Figure 70 CZS 15 2000/0 – S3 TATRA 815-7 4x4
(Source: Fire and Rescue Service, General Directorate, Czech Republic)

Extinguishing agent - water 2 000 l.

Engine power of 300 kW

Weight with fillings of 17 t

CZS 40 12000/0 – S3 TATRA 815-7

A hardened vehicle (Figure 71) enabling firefighting in hazardous environments (explosion hazard, wildfires) with ballistic protection of the cab and a fire extinguishing system remotely controlled from the crew compartment.

Figure 71 CZS 40 12000/0 – S3 TATRA 815-7
(Source: Fire and Rescue Service, General Directorate, Czech Republic)

Fire extinguishing agent - water 12 000 l

Engine power of 373 kW

Weight with charges of 36 t

CV 40/21000 – S3

Tanker vehicle (Figure 72) for high-volume firefighting, primarily intended as a reservoir for fire extinguishing at the scene, at wildland fires or as part of a water shuttle.

Figure 72 CV 40/21000 – S3
(Source: Fire and Rescue Service, General Directorate, Czech Republic)

Fire extinguishing agent - water 21,000 l

Engine power of 447 kW

Weight with charges of 42 t

CAS 30 4300/300 – S3LP TATRA 815-7

The vehicle (Figure 73) is suitable for more demanding natural terrain, with a relatively light weight, and has a sufficient supply of water and wetting agent for initial rapid intervention. This also makes it suitable for fighting wildland fires.

Figure 73 CAS 30 4300/300 – S3LP TATRA 815-7
(Source: Fire and Rescue Service, General Directorate, Czech Republic)

Extinguishing agent - water 4 300 l, foam 300 l

Engine power of 280 kW

Weight with charges of 17 t

CAS 30 9000/540 – S3VH TATRA 815-7

Vehicle (Figure 74) for high-volume extinguishing suitable for more demanding natural terrain with a larger supply of extinguishing water and foam. This also makes it suitable for fighting wildland fires.

Figure 74 CAS 30 9000/540 – S3VH TATRA 815-7
(Source: Fire and Rescue Service, General Directorate, Czech Republic)

Extinguishing agent - water 9 000 l, foam 540 l

Engine power of 325 kW

Weight with charges of 25 t

Fours wheeler Polaris Ranger XP 900

Four-wheelers, or six-wheelers or eight-wheelers, are designed for movement in terrain inaccessible to conventional firefighting equipment. They sometimes have a folding hull for transporting materials, hoses, and other items, and may also be equipped with a high-pressure fire extinguishing system.

Extinguishing agent – water, approx. 250 l (if installed)

Engine power of 51 kW

Weight with cartridges approx. 760 kg

Prescribed burning is not practiced in Czech Republic. The State Nature Conservancy institution and national fire protection legislation do not permit the use of this fire tactics.

Hungary

Firefighting is mainly the responsibility of the Fire Service. Fire Service staff is well trained and equipped for fighting structural fires and other disaster situations, including fires in hazardous materials. They are however not adequately trained and equipped for wildland fire suppression. This is not a question of will but of costs. The engines are for structural use and are difficult to operate in the field. They are not equipped for wildland fire operations. Even though the forest offices and the national park services have light vehicles (which could better be used in off-road conditions), they have no firefighting equipment, and the staff is not trained. Furthermore, light personal protection equipment for wildland fire fighting is missing. Heavy equipment such as tractors, dozers and ploughs usually belong to the Forest Service and to its contractors. As mentioned before, the heavy fire engines are not able to approach the fires on difficult terrain or access routes of lower quality and size, and they are not equipped to build a longer mobile waterline in the field. Because of missing training and special firing equipment, burnout and backfire techniques are not used in fire suppression. The cheapest solution to upgrade wildland fire equipment would be to supply the 4WD vehicles of forest offices and national parks with slip-on units and other special light equipment. In addition, a new training standard should be developed, which would make the work between the different agencies more efficient. Aerial firefighting capacity is available in a limited way. Some contractors have small agriculture airplanes. However, they are used only for larger fires and not for initial attack. Besides those airplanes helicopters of the army with Bambi buckets are used to fight bigger fires. Small airplanes and helicopters are used in some cases. Since they do not belong to the Forest Service or to the Fire Service hence the requisition needs a longer time. However, in my esteem it is unlikely that Hungary should large water bombers, therefore cooperation with neighbouring countries would play an important role in case of extreme fire situations.

Prescribed burning is not practiced in Hungary. The Nature Protection act does not permit the use of fire.

Poland

The “State Forests” National Forest Holding (State Forests NFH) had equipment at its disposal consisting of 31 fire suppression airplanes and 6 helicopters, 333 patrol and fire suppression vehicles, 4 medium and 3 heavy vehicles, 257 portable pumps, including 171 floating ones. These means were used to extinguish 6% of all the fires in the areas managed by the State Forests National Forest Holding, whereas the other fires were suppressed by units of the State Fire Service and voluntary fire brigades.

In forest areas managed by the State Forests NFH, works were carried out to prevent the conditions for fire outbreaks and to reduce their spread, by repairing 3,735 km of fuel breaks and building 39 km of new fuel breaks; in addition, forests were cleaned over a surface area of 14 920 ha, by reducing the quantity of inflammable biomass.

Fire engines used by fire departments in Poland (both state and voluntary) have special designations that are determined by their characteristics such as weight and equipment as well as the chassis on which they are based. These designations have the following pattern: First there are several capital and lower-case letters which can be followed by numbers separated with slashes. The first letter is dependent on whether the vehicle is a firefighting vehicle (marked with a capital letter G - "Gaśniczy") or a special vehicle (marked with a capital letter S - "Specjalny"), The next letter is different depending what weight class the vehicle falls into. Vehicles with weight of up to 7.5 tonnes are classified as light (marked with a capital letter L - "Lekki"). Vehicles with weight between and including 7.5 tonnes and 14 tonnes are classified as medium (these aren't marked with any letter). Vehicles with weight of over 14 tonnes are classified as heavy (marked with a capital letter C - "Ciężki"). If the vehicle in question is a special vehicle the next letter describes the exact purpose of the vehicle (DŁ - command and communication, Kn - container transporter, Kw - quartermaster vehicle, Op - "Operational" vehicle used for transporting firefighters and commanders, R - reconnaissance, Rch - Chemical rescue vehicle, Rt - technical rescue vehicle, Rw - water rescue vehicle, W - hose transporting vehicle). Any letters following that are dependent on the type of equipment carried by the vehicle in question. These letters can also require numbers to be added to the vehicle's designation. These numbers are placed after the letters and appear in the order that the corresponding letters appear in. If more than one number is present, they are separated from each other by slashes. Afterwards the designation includes the brand and model of the chassis on which the fire engine is based. If the company which carried out the conversion to a fire engine is known its name is placed after model of the chassis separated with a slash. If another company converted a vehicle that was already a fire engine converted by a different company the name of the original company is left after the chassis model and the new company name is placed after the old one separated by a slash. For firefighting, in Lodz, the GCBAPr 6/48/1000 Scania P124C/AutoSHL. In different towns, counties, the different trucks are used.

5. ICT AND GEONFORMATION TECHNOLOGY SUPPORTING WILDLAND FIRE FIGHTING

As a result, forest fire sizes and duration are increasing each year and possible impacts, negative outcomes and potential losses are becoming more serious. To keep pace with this situation, new developments are occurring in firefighting equipment, communication equipment, tactical responses, and support capabilities. But information management is an area that can often be overlooked when focusing on operational activities. This area is undergoing such rapid shifts in importance and emerging technology that it cannot be discounted. In fact, information management is quickly affording important and useful opportunities that can benefit and improve wildland fire management in the future.

Growth rate of information is doubling every 18 months, nearly two-thirds of all information users have multiple computing platforms, and most of the organization's data is inefficiently managed. [175] Electronic technology processing speed, viewing size portability and overall utility are improving almost daily. Situational variables such as these, in combination with the need by fire managers to obtain real-time information as fast as possible and make potentially impactful decisions very quickly, are driving a need to improve information management capability.

From a wildland fire management perspective, it must be understood that there is more readily available quality information regarding fire environments and fire situations; faster and more comprehensive computing speed and capability; and better predictive models than ever before. To improve wildland fire management, these capabilities must be capitalized on and incorporated into management activities.

In response to this need, numerous activities are under way to take advantage of new opportunities and technology for wildland fire management. Multiple sources of information exist, and multiple applications are being created to provide quick, efficient ways to obtain these data. Emerging applications are enabling the rapid sharing of information among a variety of systems, but a lack of data standards can affect how well these processes work. Nowadays, the attention should be paid to data standards, data sharing and data management, as well as responding to concerns over exposing data for other than the intended purpose on easily accessible sites. This includes:

Exploring opportunities to find ways for managers and fire line personnel to use the technology such as tablets and web-enabled smart phones.

Development of a web-based decision support system that represents a single system for all wildland fires using geospatial data and access to analytical tools that allow better characterize overall risk.

Creating new fire management information displays to more effectively take advantage of geospatial data that enable users to view multiple information layers during wildland fire incidents.

Developing virtual situation awareness tools to display situation information for decision-makers and planners.

All these tasks involve continuous information management, use of emerging technology, and development of applications facilitating all aspects of wildland fire management.

For some years ago, scientists have been looking into the possibilities that digital technology can bring to predicting and preventing wildland fires. The remote capabilities of digital technology solutions seem to be an asset in managing the forest fire risk, starting with fire prevention, preparedness of coping capacities, monitoring, and detection of forest fires and ending in forest fire fighting.

Among these belong:

- **Geographical Information systems and remote sensing technology** employs both satellite [176] and drone [177] technologies to monitor wildland fires at an early stage and before they grow out of control. Satellites and bespoke software are used to pinpoint potentially dangerous fires and drones equipped with special infrared cameras are mobilized to track the fire's progress. If it becomes a major threat, the system alerts and dispatches fire tankers and ground firefighters to the fire's location to control it before it spreads. Drones have additional uses in fighting forest fires. They can be fitted with both regular and thermal imaging cameras and can fly into areas that manned aircraft cannot, including at night when winds die down and fires become theoretically easier to control. Drones are primarily used for mapping and hotspot detection. Drones can be used to produce maps overnight which can be used by fire and evacuation crews first thing in the morning and free up aircraft to do other vital work, leading to a decrease in the time needed to have control over the wildland fire.
- Another technological development that keeps humans out of harm's way are **firefighting robots** [178,179]. Often wildland fires get so hot that firefighters are unable to get close enough to extinguish them. Instead, firefighting robot can approach very close to the fire and suppress the fire besides their capability of transporting firefighting equipment.
- **Virtual reality** (VR) [178] can be applied to train, in a safe environment, firefighters who are responsible for ground operation or parachuting ones into remote areas to fight forest fires. The VR simulators create 3D representations of the fire scenario, with trainers able to change physical characteristics like wind direction and speed, to prepare firefighters for real life engagements in dangerous conditions.
- Low-powered **Internet of Things** (IoT) [179,180] connected sensors are also being used to gather data from remote areas that are potential wildland fire hotspots. Sensors can be used to collect the local weather data as well as detect and measure the level of CO and CO_2 and check for unseasonably high temperatures, indicating the possible presence of fires in the area.

Early warning and fire detection systems (e.g., CCTV based smoke detection systems and early-stage alerting systems as ForestWatch® [181] or FireWatch® [182] remote technologies and digital connectivity are helping to make firefighting a more proactive way, and potentially help to drive down the costs for prevention. This technology has a positive impact in many ways on top of saving lives and protecting property and environment.

This chapter includes the results of three experiments, i.e., spatial analyses carried out to assess the susceptibility of the territory to fire in a GIS environment, modelling of fire behaviour in the FARSITE environment and analysis of the accessibility of the territory for the deployment of firefighting equipment.

Assessment of the susceptibility of the area to fire in a GIS environment

The experimental area for processing the analyses and testing the developed decision models for assessing the susceptibility of the district territory to the occurrence of fire in the natural environment and flooding is the territory of the Banská Bystrica district. For the purpose of assessing the vulnerability of the territory to the occurrence of fire in the natural environment and to verify the suitability of deployment of the FARSITE software tool in the practice of crisis management, but especially the management of rescue services at the site of intervention, the territory affected by a forest fire in 2011, located in the cadastral territory (cadastral area) of the municipality of Staré Hory, was selected as the experimental territory.

Territorially, the area affected by the forest fire in 2011 belongs to the administration of the Slovenská Ľupča branch plant (OZ), which belongs to the subprovince of the Inner Western Carpathians. Four geomorphological areas are represented on the territory of the branch plant. The boundaries in the western part are formed by the Slovak Central Highlands, the orographic unit Kremnické pohorie (Kremnické pohorie). In the north it is the area of Veľká Fatra and Low Tatras. The eastern part is closed by the Low Tatras - Vajskovská valley. The southern part of the border belongs to the Slovak Ore Mountains. The fire-affected part of the territory belongs to the Veľká Fatra unit and is in the Starohorská valley. It has a predominantly mountainous character with considerably rugged terrain (Figure 75).

Figure 75 View of the nature of the area affected by the forest fire (Source: Regional Directorate of FRS in Banska Bystrica)

Figure 76 shows the location of the forest stands along with a view of the elevation distribution of the area that was affected by the forest fire in April 2011.

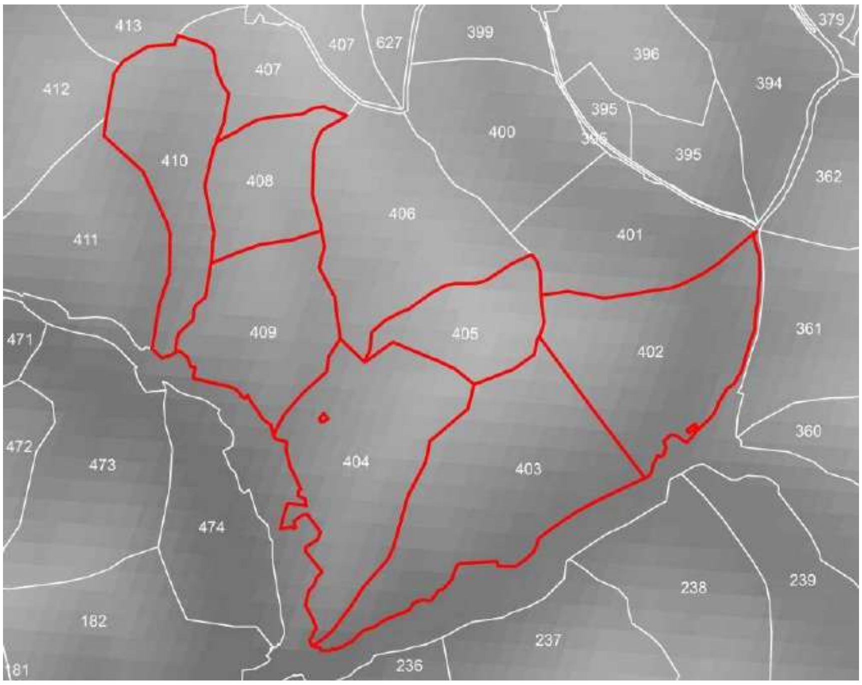

Figure 76 Forest stands affected by forest fire in 2011

From the basic forestry information about the area affected by the forest fire were selected:

– Area damaged by fire: 43,88 ha.

- Stand age: 15 - 175 years.
- Tree species composition of the stands damaged by the fire: coniferous 35% (spruce, fir), deciduous 65% (beech, mountain maple, sycamore).
- Extent of damage: from 20% - 100% on the indicated area.
- Duration of the fire: 3 days.

Creation of a geodatabase about the territory

The geodatabase of the territory data was initially processed in ArcGIS Desktop. For building the geodatabase already the existing geo-data were used, obtained from their providers or creators (Topographic Institute Col. Ján Lipský in Banská Bystrica, National Forest Centre in Zvolen, Forests of the Slovak Republic, S.E.

The following categories of geo-data were implemented within the built geodatabase:

- Topographic data: orthophotos, digital terrain model, contours.
- Thematic data:
    - Terrain parameters: derived in ArcGIS Desktop from a digital terrain model
        - slope of the terrain,
        - terrain exposure (orientation of slopes to cardinal directions),
        - terrain elevation.
    - Road network: road and street network from the CPD (Central Spatial Database) and forest road network from the National Forestry Centre.
    - Watercourses and water bodies: data from CPD and National Forestry Centre.
    - Forestry data: data from the National Forest Centre in Zvolen
        - pedological and phytocenological data,
        - forest spatial distribution units supplemented with attributes on the main tax parameters of the forest.
    - Fire-fighting equipment: data from Forests of the Slovak Republic, S.E.
        - suitable places to draw water from water sources,
        - field airport,
        - heliport,
        - storage of firefighting tools,
        - the headquarters of the forest administration,
        - ramp on the road.
    - product pipelines.
    - buildings.

The following thematic layers were created in the framework of the problem solving, processing of individual analyses:

– layer of fuel models for forest surface and canopy fuels in the Banská Bystrica district,
– layer representing the spatial distribution of fire risks in the form of a determination of the susceptibility of individual stands located in the territory of the district to the fire,

The susceptibility of the area to fire was assessed based on 2 groups of factors: natural and social.

The group of natural factors was represented by the relief shape factor, the terrain slope factor, the terrain exposure factor, and the tree species composition and stand age factor, the stand health or stand damage factor (wind or insect damage) and the fuel factor (fuel model representing the type of fuel and the volume of fuel occurring in the analysed area).

The group of social factors consisted of the following factors: distance from the nearest settlement, distance from the nearest road (state, forest, hiking trail, and bicycle trail), the factor of harvesting berries, the factor of harvesting and educational activities in the forest, and the factor of hiking and recreational areas.

Next, we present the intervals and fuzzy intervals of the values of the factors under consideration and their weights as they entered the evaluation.

The actual processing of these data in the NetWeaver or EMDS environment required their preprocessing in the ArcGIS environment according to the defined criteria (listed below). The results of the analysis were processed in the GIS environment into map outputs.

– Forest fuel factors (weight 1.0)

Fuel model (weight 1.0)

We considered a total of four classes of surface fuel:

- grass,
- mosses and lichens,
- grasses, herbs, and mosses,
- herbs,
- without herbaceous cover.

This fuel partitioning is mainly based on the assumption of different amount and moisture of surface forest fuels, with grassland being the most hazardous in terms of fuel moisture (fuzzy value 1).

Surface fuel height (weight 0.75)

In this case, three classes of fuel entered the evaluation in terms of defined intervals of their height:

- < 15 cm,
- 16 - 30 cm,

- 31 - 100 cm.

The height of the fuel poses a hazard, particularly from the passage of a surface fire to a crown fire or vice versa. This is often the reason for the spread of grassland fires, often caused by deliberate burning in the spring season, to woodland.

– Geographical factors (weight 0.75)

Landforms (weight 0.75)

Three basic terrain features were considered:

- Ridge,
- Valley,
- plane.

In general, the plains (fuzzy and valleys) are more at risk of forest fire, as this area is the most frequently settled, industrialized, and used for agricultural purposes.

Terrain slope (weight 0.5)

Only two intervals were considered in terms of terrain slope:

- 0 - 45°,
- > 45°.

Terrain exposure (weight 1.0)

Three intervals were considered in terms of terrain exposure (orientation of slopes to cardinal directions), with the interval between 135° and 225°, or southeast to southwest (fuzzy value of 1.0) being particularly dangerous from the point of view of fire occurrence.

- 0° - 135°,
- 136° - 225°,
- 226° - 360°.

– Growth factors (weight 0.75)

Tree species composition (weight 0.5)

We identified three categories in terms of stand species composition, with coniferous forest (fuzzy value 1.0) generally considered the most hazardous in terms of fire occurrence - resin, dead wood, twigging of spruce trees at the stand edge down to the ground (possibility of surface fire to crown fire.

- deciduous,
- coniferous,
- Mixed.

Stand age (weight 0.75)

In terms of stand age, three intervals were identified, stands up to 20 years of age (fuzzy value 1) considered the most dangerous in terms of fire occurrence, given the high stand density and the frequency of silvicultural activities in the forest (associated with human activities in the forest).

- 0 - 20 years,
- 21 - 80 years old,
- 80 years old.

Forest health (weight 1.0)

For the expression of the forest health status, we used (geo)information on the occurrence of harmful agents in the forest in the previous period, especially wind and bark beetles, the occurrence of which in the stand significantly weakens its resistance to the action of other harmful agents. The data on the occurrence of harmful agents were taken from the forest management records provided by the National Forest Centre in Zvolen. The highest fuzzy value of 1.0 was assigned to the identified stands where at least one of the mentioned harmful agents had occurred in the past.

– Social factors (weight 1.0)

Distance to nearest road (weight 1.0)

First, it was necessary to classify the roads in terms of their use - traffic, tourist trails and cycle paths. The sizes of the zones within which people are expected to move around these roads were also determined.

- 0 – 1,500 m (fuzzy value 1) for traffic roads, forest, and dirt roads,
- 0 - 50 m (fuzzy value 1) for hiking and cycling trails.

Distance to nearest settlement (weight 1.0)

Considering the results of previous analyses (Tuček and Majlingová 2007), the zone around settlements within which the movement of people is expected to occur was set at 3,000 m (the interval 0 – 3,000 m was defined as 1).

Harvesting (weight 1.0)

Forest types were identified and located, the name of which predisposes them to the collection of forest fruits such as blueberries, blackberries, raspberries, etc. Raspberries are also frequently found in clearcuts, for this reason we implemented in the analysis also data on harvests on larger areas in individual stands. We assigned a fuzzy value of 1.0 to these plots in the analysis.

Logging and educational activities in the forest (weight 1,0)

Data on the location of harvesting and growing (educational) activities in individual stands (fuzzy value 1.0) were obtained from the valid Forest Management Program or Forest Management Plan. These measures are set for the entire ten-year period of validity of the Forest Management Program. If necessary, more detailed plans of these activities for individual years can be obtained from the relevant branch plants of the Forests of the Slovak Republic, S.E., forest administrations, town planning offices, etc.

Tourism and recreation (weight 1.0)

A vector layer representing known tourist and recreational objects in the territory of the Banská Bystrica district was created, and a fuzzy value of 1.0 was assigned to these objects and to the zone created around these objects in a width of 500 m.

Consequently, the so-called pooled susceptibility of the Banská Bystrica district to forest fire occurrence was determined based on the combination of the above-mentioned groups of factors. The resulting values were classified into 5 categories - degrees of susceptibility to fire (Table 15).

Table 15 Categories of overall susceptibility of the territory to fire

Category	Name	Characteristics	Fuzzy interval
1	very low	unlikely occurrence of fire	0.00 - 0.20
2	low	low probability of fire	0.21 - 0.40
3	medium	probable occurrence of a fire	0.41 - 0.60
4	high	fire very likely to occur	0.61 - 0.80
5	very high	high probability of fire	0.81 - 1.00

For automated assessment of the risk of fire determined in the form of one of its components, namely susceptibility, a decision model was built in the NetWeaver environment.

By linking the decision model to the EMDS analytical environment, which is available as an extension for ArcGIS Desktop, we have obtained a tool for automated spatial analyses aimed at assessing individual risk factors and their groups, up to the determination of the combined susceptibility of an area to fire.

The results of the analyses are presented in graphical and tabular form. First, there are presented the results of the analysis concerning the associated susceptibility (Figure 77), calculated as the sum of the fuzzy values of the fuel, topography, vegetation, and social factor groups. The raster representing the spatial distribution of the values of this sum was subjected to another fuzzification process (the process of adjusting the values using fuzzy logic). Subsequently, these new fuzzy values were extracted for the centroids of each stand.

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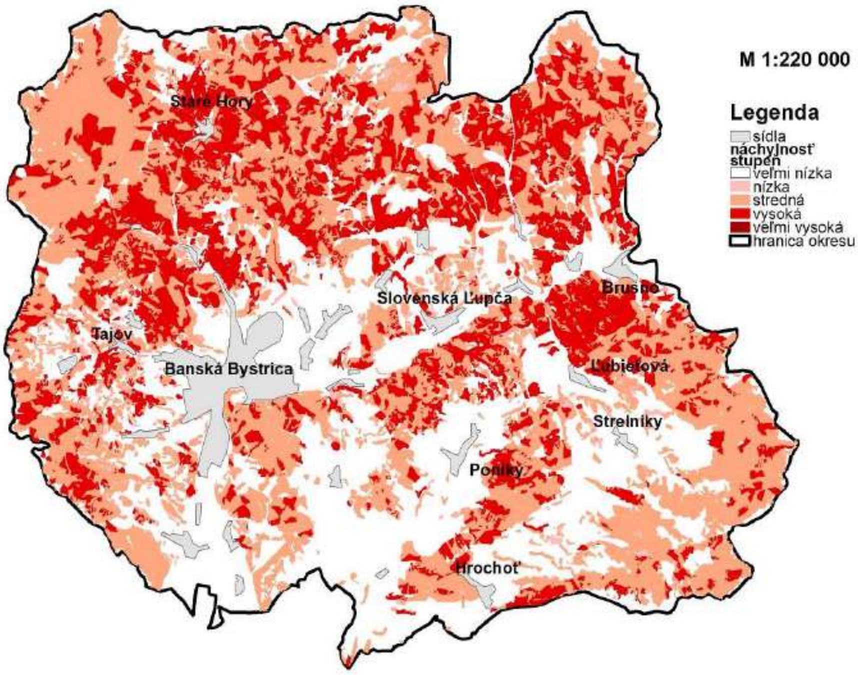

Figure 77 Results of the associated susceptibility in the Banská Bystrica district

A tabular summary of the results of the associated susceptibility is presented in Table 16.

Table 16 Results of the associated susceptibility for the Banská Bystrica district

Category	Degree	Characteristics	Area (ha)	Representation (%)
0	very low	unlikely occurrence of fire	54	0.122
1	low	low probability of fire	0.99	0.002
2	medium	probable occurrence of a fire	682.75	1.537
3	high	fire very likely to occur	26,991.76	60.762
4	very high	high probability of fire	16,793.81	37.805
5	very low	unlikely occurrence of fire	6.28	0.014
Total			44,421.79	100.00

The results of the associated fire susceptibility analysis show that up to 60% of the district falls into the medium fire susceptibility category and 38% of the district even falls into the high fire susceptibility category (Figure 77 and Table 16). The higher degree of susceptibility of the territory is mainly due to fuel and terrain factors.

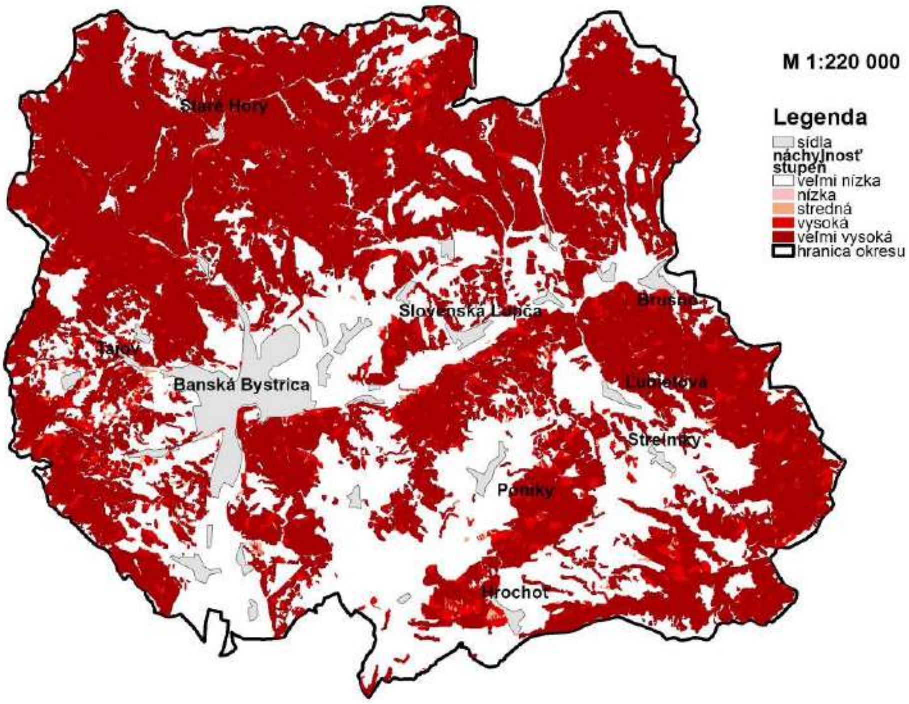

Figure 78 Results of the Banská Bystrica district susceptibility analysis in terms of terrain conditions

Table 17 presents the results of the susceptibility analysis of the Banská Bystrica district in terms of geographical factors or terrain conditions.

Table 17 Results of the susceptibility analysis of the territory of Banská Bystrica district - geographical factors

Category	Degree	Characteristics	Area (ha)	Representation (%)
0	very low	unlikely occurrence of fire	5.90	0.01
1	low	low probability of fire	27.49	0.06
2	medium	probable occurrence of a fire	273.52	0.62
3	high	fire very likely to occur	2,530.30	5.70
4	very high	high probability of fire	41,584.58	93.61
Total			44,421.79	100.00

From the results of the analysis presented in Figure 78 and Table 17, it is evident that there is more than 93 % of very high fire susceptibility in the area under consideration. This is mainly due to the increased susceptibility value of the area caused by the landform factor, its ruggedness.

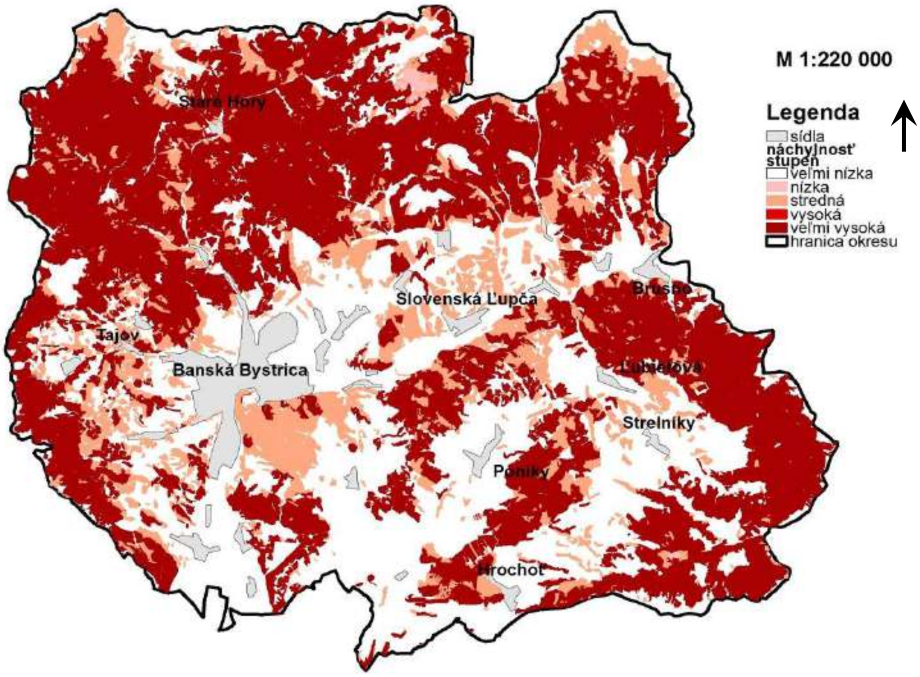

Figure 79 Results of susceptibility analysis of Banská Bystrica district in terms of forest fuel factors

In Table 18 we present the results of the analysis in tabular form.

Table 18 Results of susceptibility analysis of Banská Bystrica district - forest fuel factors

Category	Degree	Characteristics	Area (ha)	Representation (%)
0	very low	unlikely occurrence of fire	0.62	0.001
1	low	low probability of fire	162.72	0.366
2	medium	probable occurrence of a fire	9 348	21.044
3	high	fire very likely to occur	0.00	0.000
4	very high	high probability of fire	34,903.45	78.573
Total			44,421.79	100.00

As already mentioned, the factors of surface forest fuel also had a significant influence on the associated susceptibility of the Banská Bystrica district. As can be seen from the results (Figure 79 and Table 18), up to 78% of the Banská Bystrica district territory falls into a very high degree of susceptibility in terms of the composition of surface forest fuels and their height. These are mixed and species-diverse forest stands, which create a very suitable environment for the growth of many species of plants and herbs that constitute fuel for the surface type of forest fire. It should be noted here that these factors are also highly dependent on the relative moisture content of this fuel.

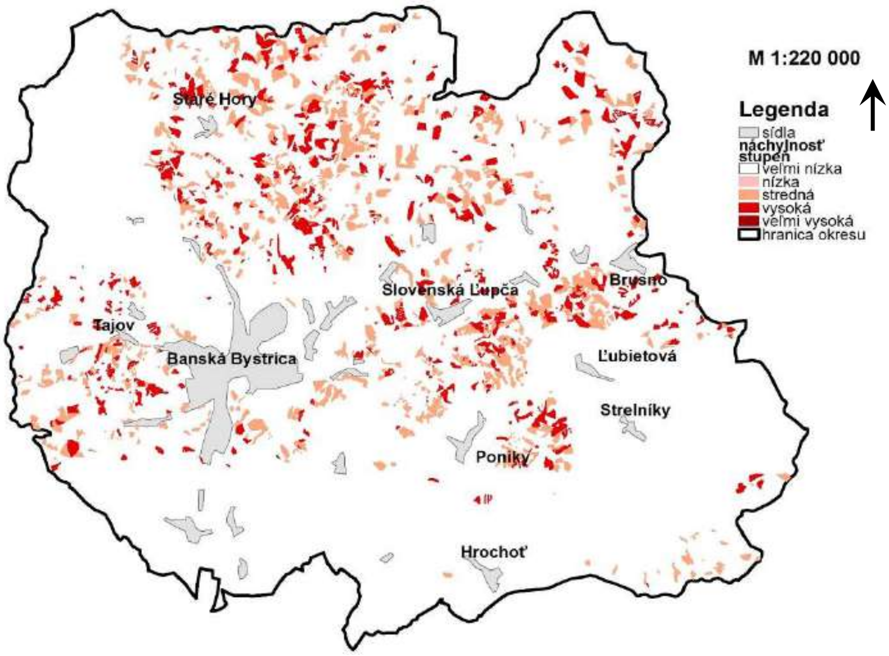

Figure 80 Results of susceptibility analysis of the Banská Bystrica district in terms of vegetation factors

The results of the analysis are tabulated in Table 19.

Table 19 Results of susceptibility analysis of the Banská Bystrica district - vegetation factors

Category	Degree	Characteristics	Area (ha)	Representation (%)
0	very low	unlikely occurrence of fire	38 341.87	86.31
1	low	low probability of fire	0.00	0.00
2	medium	probable occurrence of a fire	0.00	0.00
3	high	fire very likely to occur	3 682.02	8.29
4	very high	high probability of fire	2 397.90	5.40
5	very low	unlikely occurrence of fire	0.00	0.00
Total			44 421.79	100.00

In terms of vegetation cover, it is evident from the results shown in Figure 80 and Table 19 that almost the entire area is in the lowest fire susceptibility degree of the area, where fire is very unlikely to occur. This is mainly due to the tree species composition of the stands, which is predominantly mixed, and the age of the stands. Higher susceptibility is found in stands that have been affected by wind calamity and subsequent over-breeding of bark beetles over the last 10 years.

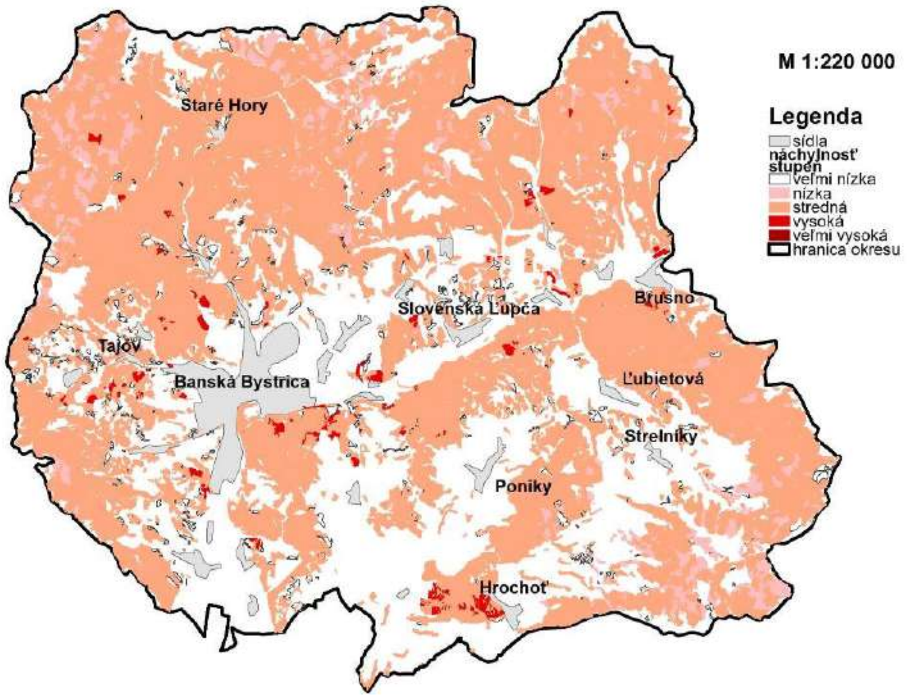

Figure 81 Results of the analysis of the susceptibility of the Banská Bystrica district in terms of the social factors

Table 20 Results of the susceptibility analysis of the Banská Bystrica district - social factors

Category	Degree	Characteristics	Area (ha)	Representation (%)
0	very low	unlikely occurrence of fire	1,315.53	2.96
1	low	low probability of fire	2,937.15	6.61
2	medium	probable occurrence of a fire	39,641.46	89.24
3	high	fire very likely to occur	527.65	1.19
4	very high	high probability of fire	0.00	0,00
Total			44,421.79	100.00

In terms of the results of the analysis of social factors (Figure 81), it can be stated that the majority of the Banská Bystrica district falls into the medium level of susceptibility to fire (89%). The highest susceptibility values were recorded for the factors distance from the nearest road and fruit picking, where sites with blueberries, raspberries, cranberries, etc. were selected based on a polygon vector layer of forest types and their analysis from the available phytocenological literature.

Fire spread modelling in the FARSITE

To verify the suitability of deployment of the FARSITE software in the practice of crisis management and management and coordination of rescue services, a retrospective simulation or modelling of a forest fire that occurred in the cadastral area of the municipality of Staré Hory in 2011 was carried out.

On 10.4.2011 at 14.25 h a forest fire in Horne Jelenec was reported to the operational centre of the Regional Directorate of FRS in Banská Bystrica (Figure 24). This fire was successfully suppressed on 12.4.2011 at 16.30 h. In this case it was a surface fire and an underground fire.

A view of the character of the area is provided in Figure 82, 83. Figure 84 provides a view of the fire site.

Figure 82 View of the nature of the fire in the locality of Staré Hory in 2011 (Source: District Directorate of FRS in Banska Bystrica)

Figure 83 View of the character of the area in the locality of Staré Hory (Source: District Directorate of FRS in Banska Bystrica)

Figure 84 View of the location of the fire in the locality of Staré Hory in 2011 (Source: District Directorate of FRS in Banska Bystrica)

Stands No. 402, 403, 404, 405, 408, 409 and 410 were damaged by fire (Figure 85). The fire damaged an area of 43,88 ha and the total fire damage was of 222,974 EUR.

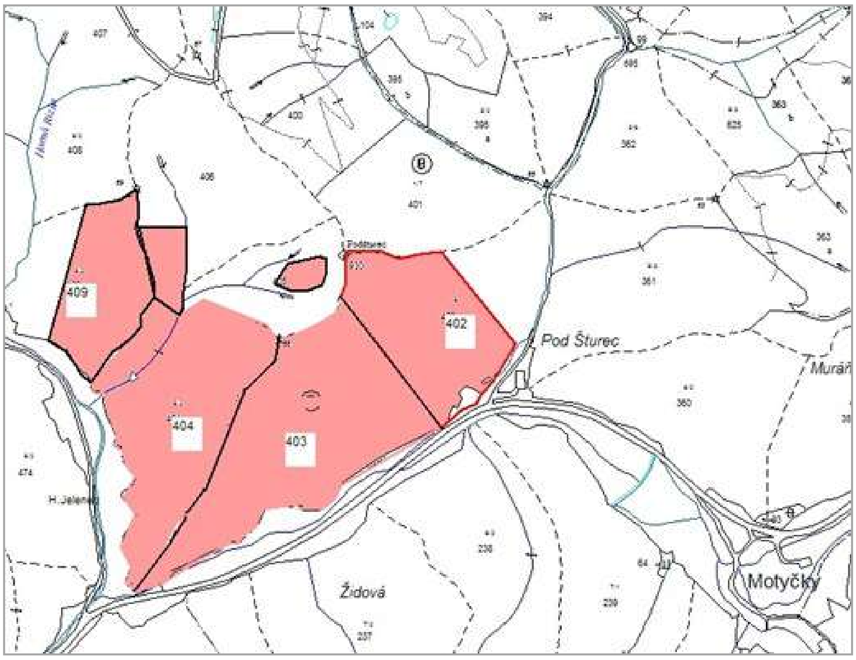

Figure 85 View of the area affected by the fire (Source: Forests SR S.E., 2011)

Table 21 provides a basic overview of the deployed forces.

Table 21 Overview of deployed forces for firefighting in the cadastre of Staré Hory in 2011 (Source: District Directorate of FRS in Banska Bystrica)

Intervening personnel	Number
Fire and Rescue Service	497
Forests SR, S.E.	38
Municipal fire brigades	43
Aviation Department of the MoI SR	32
Police Corps	26
Total	636

A total of 20 pieces of tanker equipment and about 70 pieces of other equipment were deployed to localize and suppress the fire. A total of 166 airdrops were made using aircrafts, which represents a total of 301,500 litres of water delivered to the fireground.

On 11.4.2011 3 military helicopters Mi-17 and 2 helicopters of the Ministry of Interior of the Slovak Republic (Mi-171) intervened, through which a total of 259,500 l of water was dropped on the fire area. The following day, 12.4.2011, only 2 military helicopters intervened, with the help of which a total of 42,000 l of water was delivered to the fire area. Both helicopters made 14 drops.

To verify the functionality and correctness of the solutions proposed, data from tactical exercises and interventions related to forest fires in different mountain areas of Slovakia in the past were used.

The actual modelling of forest fire behaviour was carried out in the FARSITE environment.

The modelling of forest fire behaviour in the FARSITE environment is input in ASCII raster format with terrain data - a digital terrain model, a raster layer of terrain slope and terrain exposure, stand cover data and fuels present in the study area.

Raster layers of slope and terrain exposure were derived from a digital terrain model in ArcGIS Desktop 10 environment using the Slope and Aspect tools. Stand cover data were obtained by classifying orthophotos from the study area. The raster fuel layer was created according to the methodology for classification of fuel (biomass) in the territory of Slovakia into fuel models (Majlingová, Vida 2008).

The basis of this methodology is the classification of fuel (biomass) in the area into fuel models according to the geobiocenological classification of forests in Slovakia, which is the most detailed classification of forests based on the principles of development, vegetation indication, differentiation, and indication according to the characteristics of the environment. The basic unit is the forest type (LT), characterised by the type of permanent ecological conditions. The superordinate unit is the group of forest types (SLT), which defines the natural distribution of tree species within their range in Slovakia.

One of the other parameters entering the modelling process is fuel quantity data. For fuel quantification, the methodology published by Brown, Oberheu and Johnston (1982) [70]. This methodology is based on destructive field surveys (measurements) of characteristics related to the following fuel types - humus, fallout, live herbaceous and herbaceous vegetation, undergrowth and dead (dry) fuel.

Within the 4 m diameter circular bite plot, the depth of humus on the 2 m transect, the number of fallen twigs and other dead fuel, the characteristics of the fallen material, the number of small trees and shrubs, and the number of herbs and their characteristics were recorded. Smaller 30 x 60 cm bite plots were established at the corners of the square in an adjacent 2 m square transect to survey vegetation cover characteristics, vegetation cover, herb species and height, humus, and fallout. Material was taken from each plot for laboratory tests to determine the moisture and physical (fire-technical) parameters of the fuel.

Within a 1 m square bite plot, we surveyed the depth of the soil humus layer, ridges, fallen branches and their thickness, the number and size of fruits and seeds, the percentage cover of mosses, herbs, grasses, fallen branches and rocks, the height of herbs and grasses as well as the number of saplings and shrubs. The sampled material was weighed directly in the field with a KERN HCB 20K10 digital weighing balance. From each bite plot we took material (fuel) for laboratory tests to determine the moisture and physical (fire-technical) parameters of this fuel. In addition, the moisture contents of the different fuel types were determined directly in the field using a resistive hygrometer.

The modelling in FARSITE was preceded by pre-processing of the geo-data, which represent the basic inputs to the modelling in ArcGIS Desktop. These inputs were: an ASCII raster representing the spatial distribution of elevation values in space, an ASCII raster of exposures, terrain slope, and the spatial distribution of fuel models in the area. Fuel data were obtained by processing forest type data in the study area, field, and laboratory surveys.

To quantifying forest fuel in the area, we applied the geostatistical tools offered by the ArcGIS Desktop 10 environment. To create a raster layer of the spatial distribution of fuel and to determine its quantity in the study area, we used the regression analysis method. The starting point was the data on the amount of the assessed forest fuel types in the individual bite plots and the geographical parameters of these plots.

Fuel quality parameters were determined during the field survey as well as in laboratory conditions. During the field survey, the moisture content of the different fuel types was determined. For this purpose, we used a moisture meter for measuring the moisture of fine fuel ME 2000 from Wiltronics. The moisture meter was designed for use in the field by firefighters responsible for managing controlled burns and forest fires. The purpose of this moisture meter is to determine the percentage moisture content of leaves, twigs and bark found on the soil surface in the forest, as well as the moisture content of live and dead wood fuel (e.g., shrubs) as quickly and accurately as possible. This material represents a group of fuels called fine fuels and is one of the most important factors in determining the rate at which a fire will spread and determining where spot fires are likely to develop.

Methodology for determination of fire properties of selected types of surface fuels

Other fire properties of fuel or fuel types (grasses, herbs, twigs, bark, and tree wood depending on the type of tree species), which are necessary for fire modelling in the FARSITE environment, were determined in laboratory conditions. These parameters included the mass loss when the fuel was dried in a Memmert UFE 400 oven at temperatures between 103 and 105 °C according to EN 14774-3: Solid biofuels; determination of moisture content; oven-drying method [190].

The mass loss of the sample (of each fuel type) was recorded after 1 hour, 10 hours and 100 hours of drying. The sample weight data were then used to derive fuel moisture contents at defined time intervals.

Another parameter that needs to be determined is the calorific value of the fuel, or its individual types. These values have been calculated based on the calculation of the heat of combustion values determined in accordance with STN ISO 1928: Solid fuels; Determination of the heat of combustion by the calorimetric method in a pressure vessel, using the IKA 5000 calorimeter, and the moisture content values of the fuel (fuel types).

The entire study area is in the fuel model (PM 30), which is characterized by grasses and forbs up to 30 cm in height. To refine the fuel quantity results, a total of 21 study plots were established in the study area. Based on the factor of relief curvature affecting spatial distribution and fuel quantity, the study area was divided into 4 fuel models. The first two fuel models represent ridges, differentiated according to ridge curvature value, into high curvature value ridges (HNK), mainly characterized by the most obvious ridges, and low curvature value ridges (DNK), which represent more moderate convex landforms. The other two fuel models characterize valleys, equally differentiated by curvature value into valleys with high curvature (HNK) and low curvature ridges (DNK) (Figure 86).

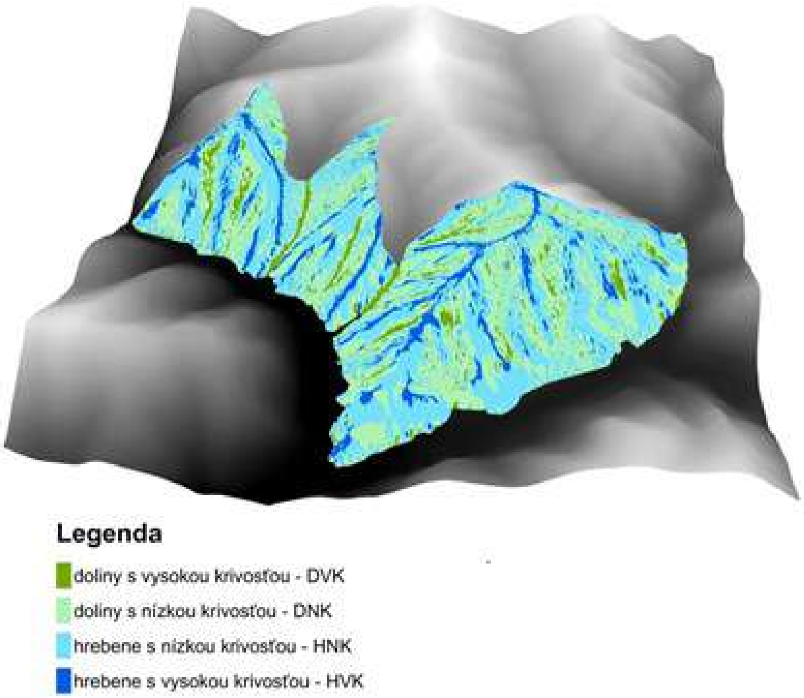

Figure 86 Visualization of the distribution of the area into different fuel models based on the curvature of the relief

Figure 87 shows the spatial distribution of fuel along with its total mass before drying for each fuel model in tonnes per hectare of area. The mass values shown represent the actual mass of fuel in tonnes per hectare before drying or the occurrence and effect of fire.

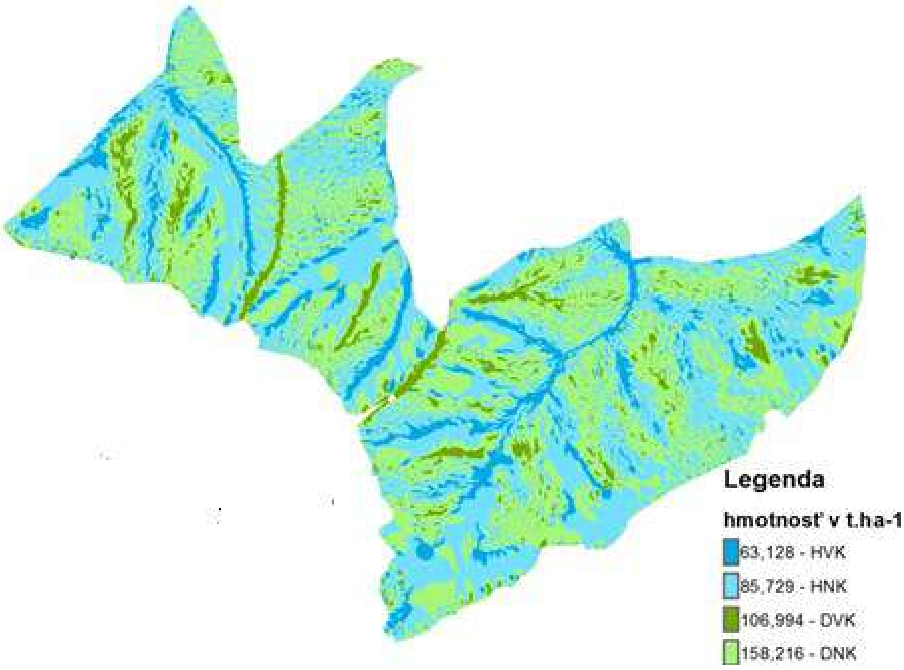

Figure 87 Forest fuel mass in t·ha-1 and its spatial distribution in the fire area in 2011

From the results obtained, the smallest amount of surface fuel (approximately 63 t·ha^{-1}) is found in high curvature ridges (HVK), i.e., in the area with the most convex landforms. The smallest amount of deposited material is most likely due to the frequent occurrence of parent rock at shallow depth below the soil surface or directly protruding to the surface. Other possible causes are the fact that these parts of the relief are exposed to the greatest climatic conditions, in particular wind, which can move some forest fuels, such as fallout, which is directly related to the formation of the humus and humus. The transport of material by gravity, especially by water runoff or snow in winter, can also be considered an important factor. The second lowest amount of fuel (approximately 86 t.ha^{-1} is found in low curvature ridges - HNK). In these areas, the same reasons for the smaller amount of deposited material as in the previous case can be considered, but the influence of gravity and climatic conditions is milder. The largest amount (approximately 158 t·ha^{-1}) is found in valleys with low relief curvature (DNK). The assumption is that it is in these areas that the accumulation of fuel from higher areas, such as ridges, occurs through the processes and factors described above. The amount of fuel in high curvature valleys (DVK) is approximately 107 t·ha^{-1}, which is a relatively low amount considering the DNK area. Theoretically, these areas are very well suited for forest fuel accumulation, as they form locally the lowest parts of the relief. The probable reason for the lower mass is the occurrence of these areas in the form of smaller and deeper depressions, in which the processes of material movement are not as intensive.

Table 22 gives the values of the fuel mass at different times of its drying, after the first hour t_1 , after ten hours t_{10} and after one hundred hours t_{100} in units of t·ha^{-1}. It also gives the percentages of the weight of the fuel. This percentage expresses the percentage of the fuel that has been preserved in each drying section since the start of drying. In practice, this value represents the proportion of the area that is potentially fuel after exposure to fire. The percentages show that the greatest loss in fuel mass is achieved after the first hour of drying. After this time, the weight or quantity of the fuel decreases to approximately one third of its pre-drying weight. Further drying did not cause any significant loss in fuel mass. After ten hours of drying, the weight dropped by 0.58 % on average. After one hundred hours, the loss is even smaller, averaging 0.17 %. This shows that most of the fuel is lost during the first hour of drying, with minimal mass loss during the following hours. The volume of fuel after each section of fuel is graphically shown in Figure 88.

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Table 22 Hmotnosť zložiek lesného paliva rozdelená podľa priestorovej distribúcie v teréne

Relief shape/ measurement time	t_0	t_1		t_{10}		t_{100}	
	mass [t·ha^{-1}]	mass [t·ha^{-1}]	share [%]	mass [t·ha^{-1}]	share [%]	mass [t·ha^{-1}]	share [%]
DVK	106.994	38.722	36.19	37.975	35.49	37.786	35.32
DNK	158.216	56.073	35.44	55.188	34.88	54.969	34.74
HNK	85.729	32.741	38.19	32.162	37.52	32.036	37.37
HVK	63.128	19.566	30.99	19.334	30.63	19.193	30.40

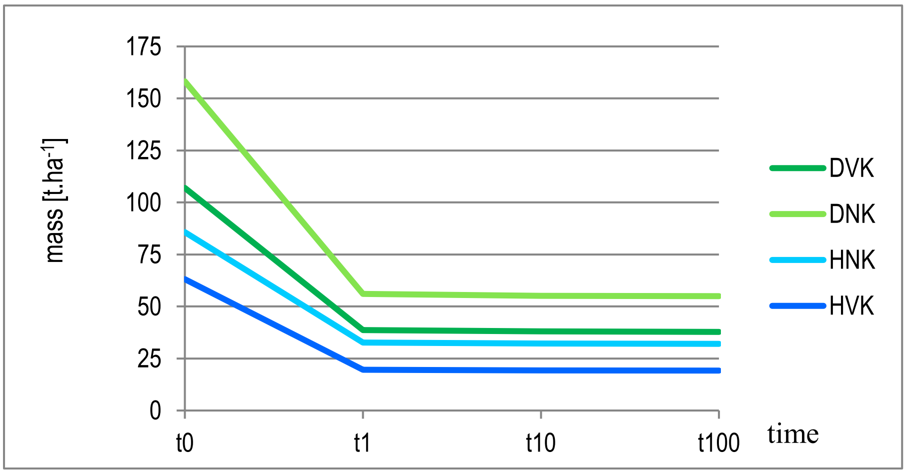

Figure 88 Forest fuel mass by drying time in t·ha-

Figure 89 shows the spatial distribution of forest fuel with respect to relief exposure in tonnes. Most of the fuel is located on the southern and south-eastern slopes. To a somewhat lesser extent, fuel is found on the western and southwestern slopes. On other exposures, the amount of fuel is very low. This is because most of the study area is oriented just between the west (Z)-southeast (JV) exposures.

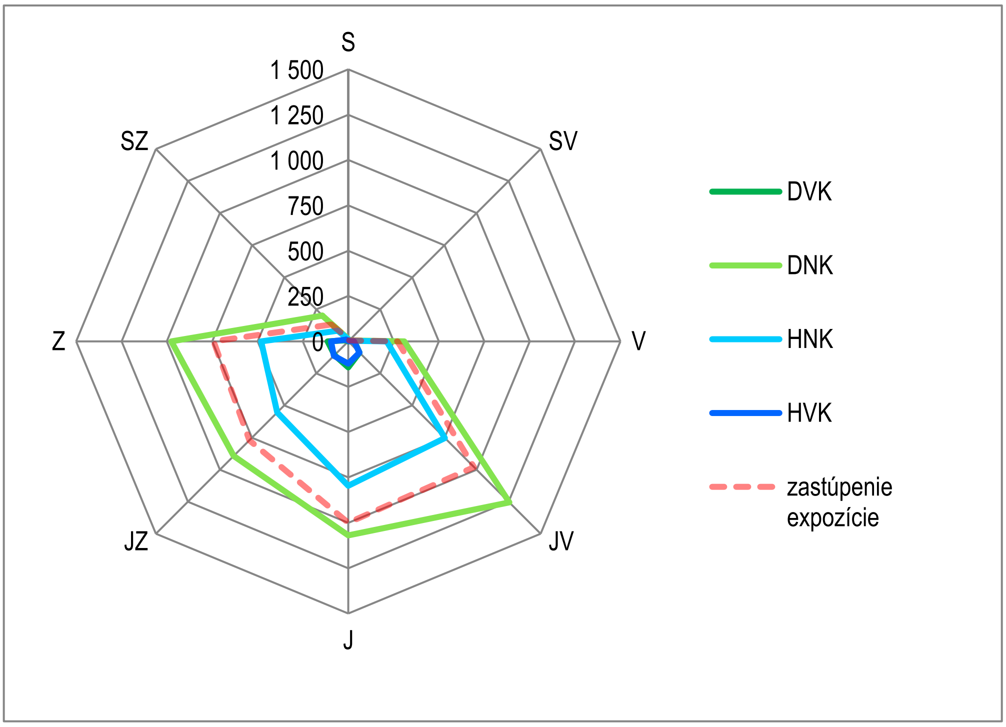

Figure 89 Mass of forest fuel relative to relief exposure in tonnes

The obtained results on the spatial distribution and amount of surface fuel are needed to define the characteristics of the fuel models of the FARSITE fire spread simulator.

In Table 23 we present the values of the fuel quality parameters entering the modelling.

Table 23 Forest fuel quality parameters

Fuel type	Sample weight (g)	Heat of combustion (kJ.kg^{-1})	Hydrogen	Oxygen	Nitrogen	Heating value (kJ.kg^{-1})
leaves (litter)	0.71	20,237.00	6.00	40.00	0.50	18,932.60
grass	0.73	18,446.00	5.90	40.00	1.30	17,162.20
mosses	0.93	17,253.00	5.90	40.00	1.30	15,969.20
branches	0.82	20,114.00	6.00	40.00	0.50	18,809.60
mix	0.96	19,371.00	6.00	40.00	0.50	18,066.60

In Table 24, there are presented the values that were derived for the fuel model during the laboratory experiments to be implemented in the FARSITE environment.

Table 24 Summary of obtained forest fuel parameters input to modelling

Parameter	PM 30
m_1 (t·ha^{-1})	6.60
m_2 (t·ha^{-1})	1.85
m_3 (t·ha^{-1})	0.00
m_4 (t·ha^{-1})	0.68
m_5 (t·ha^{-1})	1.57
σ_1 (cm^{-1})	60.36
σ_4 (cm^{-1})	49.20
σ_5 (cm^{-1})	49.20
δ (cm)	30
Mx (%)	25
Calorific value (kJ·kg^{-1})	17,778

*Explanation: m_1 - dead material 0-0.635 cm diameter, m_2 - dead material 0.635-2.54 cm diameter, m_3 - dead material 2.54-7.62 cm diameter, m_4 - live herbaceous syncytium 0-0.635 cm diameter, m_5 - live trees and shrubs 0-0.635 cm diameter, σ_1 - area to volume ratio of dead material with diameter 0-0.635 cm, σ_2 - area to volume ratio of living herbaceous synthesis with diameter 0-0.635 cm, σ_5 - area to volume ratio of living trees and shrubs with diameter 0-0.635 cm, δ - mean vegetation height of fuel models, Mx - moisture of extinction.

The modelled fire was reported to the Regional Operational Centre of IRS in Banská Bystrica on 10 April 2011 at 2.25 PM. According to the data of the Intervention Report, the fire was located on 12 April 2014 at 4.30 PM, i.e., after 50 hours of fire duration. At that time, the area of the fire area was determined to be 43.88 ha and the perimeter of the fire area to be 3.63 km (see Figure 51).

Based on the results of the modelling of this fire, the area of the fire at 16.30 h was calculated in the FARSITE software to be 44.6 ha (area calculated in the horizontal direction) and 51.3 ha (topography was considered in the calculation), and the perimeter to be 3.9 km and 4.2 km (topography was considered in the calculation), respectively. Based on these data, the accuracy of the fire area determination from the FARSITE modelling was determined to be at 98.2 %. It was determined in terms of a comparison of the areas determined in the horizontal direction, as these are derived from 2D representations of the data in the Intervention Report.

This is a relatively very high modelling accuracy if we consider the comparison of the extent of the actual fire area with the modelled one.

However, the correctness of the simulation must also be verified with respect to the shape of the fireground, i.e., visually.

In Figure 51, we present a view of the vegetation affected by the fire and the perimeter of the fire area, which we obtained from the modelling in the FARSITE environment.

Here it is necessary to mention the fact that we did not have the area of the actual fire area necessary for the visual assessment of the correctness of the modelling, as none of the queried data providers (Regional Directorate of Fire and Rescue Service in Banská Bystrica, Forests of the Slovak Republic in

Banská Bystrica) has such a layer. We were only able to obtain a map of the vegetation affected by the fire, which was not damaged in the whole area, but some of them only partially.

As can be seen from Figure 90, even in the case of fire modelling, in which we implemented data on ground and aerial intervention of firefighting teams in the form of creating barriers through which the fire did not break through in the modelling process, the fire affected all the stands, but did not destroy all of them.

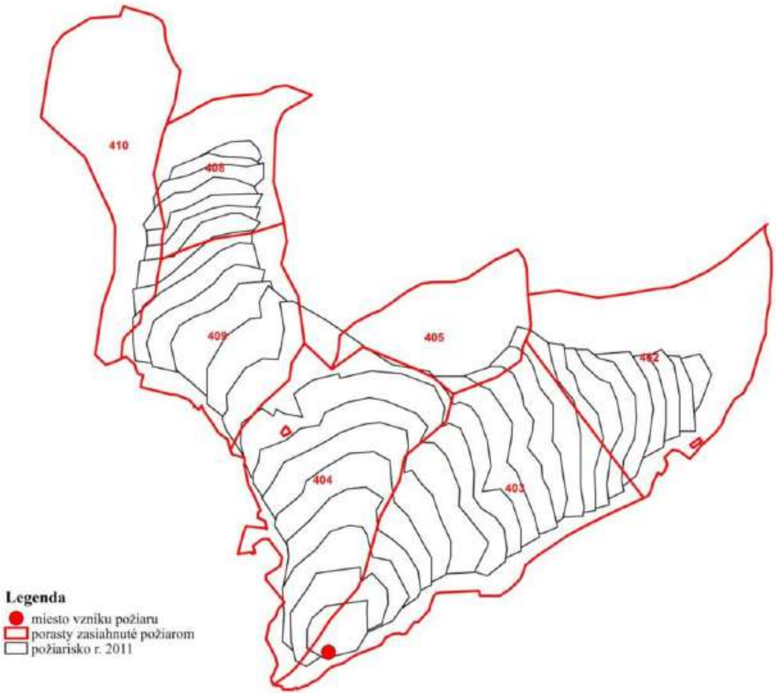

Figure 90 Výsledná plocha požiariska získaného modelovaním z FARSITE v porovnaní z plochou požiarom postihnutých porastov

In the Rapid Fire Report (hereinafter referred to as the Rapid Report) sent by the Forestry of the Slovak Republic in Banská Bystrica at that time to the Ministry of Agriculture of the Slovak Republic, it is stated that the stands were affected by fire in the range of 20 % - 100 %.

Table 25 shows the area and extent of damage to these stands, as determined based on the modelling results.

Table 25 Extent of damage to stands affected by fire in 2011

Stand	Total area (ha)	Fire damaged area (ha)	Damaged area percentage (%)
402	12.14	4.77	39.30
403	15.76	13.59	86.23
404	13.07	11.79	90.21
405	5.42	0.81	14.95
408	5.78	3.15	54.50
409	8.71	7.38	84.73
410	8.86	0.45	0.45

We should consider the data reported in the Rapid Reporting to be relevant for determining the accuracy of the modelling, then it should be noted that the data reported in Table 23 is quite an underestimate compared to reality. This is particularly evident for stands 403 and 404, where we can deduct from the Rapid Reporting data that these are the stands where the entire stand area (100 %) was affected by the fire. However, the modelling results show that in the case of stand 403 the area affected was 13,59 ha, which is only 86,23 % of the total area of the stand, and in the case of stand 404 it was 11,79 ha, or 90,21 % of the total area of the stand.

Similarly, in the Rapid Reporting, the information that the minimum extent of damage to the stand is 20 % appears. However, it is clear from the data presented in Table 24 that there has been a significant decrease in this extent for stands 405 and 410, which was determined based on the results of the FARSITE modelling.

Therefore, the overall accuracy of the simulation should be reduced. Based on the data presented in Table 23, it is not possible to determine the overall modelling accuracy strictly. Deviations in the determination of the area of damage of individual stands are only a relative indicator that is not supported by unambiguous data. Nevertheless, both in terms of the visual assessment and the deviations in the determination of the area of damaged parts of the stands, we have established the overall accuracy of the simulation at 85 %.

We considered only one fire outbreak in the fire modelling, although overall there were two localised outbreaks in the fire. The latter occurred in the northwest of the area because of an underground fire. We did not have information on the location of its surface penetration, so we excluded it from the modelling.

Forest opening-up analyses

The problem of forest opening-up analyses focusing the possibilities of fire-fighting vehicles deployment is not very often solved by authors, even in the world. The forest opening-up analyses are performed for timber logging purposes. There exist also many scientific works dealing with this issue.

Important parameters for determining the efficiency of tactics of forest fires suppression is understanding the environment in which the fire occurred, sufficiency of manpower and resources for firefighting, the parameters of which are suitable for its deployment into the specific terrain and natural conditions.

At home conditions, Chromek [183] tackled the tactical procedures of localization and suppression of fires in the natural environment applying the aerial technique.

With the issue of transport of extinguishing agents to large fires and identification of critical points in the pro-cess and the selection of ground mobile fire-fighting vehicles for fire suppression in the mountains dealt Lanďák, Monoši, Kapusniak [184], Lanďák, Monoši, Polorecký [185], Kapusniak, Monoši [186].

With the issue of opening-up analysis of area for the deployment of ground mobile fire-fighting vehicles dealt Dvorščák and Böhmer [187]. This work is one of the few contributions to solving the issue of opening-up analysis for purposes of deployment of mobile fire-fighting vehicles in our conditions, while the method is based on traditional approaches to opening-up the forest for timber logging activities. The authors introduced a methodology for the evaluation and optimization of opening-up forest to deploy the mobile fire-fighting vehicles (Cistern Automobile Pump - CAS and transportable pump PS 12). The evaluation was carried out without the use of information technology, using only the traditional numerical methods.

In 2012 Majlingová [188] published a methodology for assessing the level of opening-up the mountain area for the deployment of ground mobile fire-fighting vehicles in GIS environment.

The experimental area was represented by the territory of the Slovenska Lupca forest management unit is in the central part of Slovakia. It is situated at the altitudes between 308 - 2008 m above sea level.

The cadastral area is 89,739 ha, with forest cover of 59 %. In the tree species composition are represented as coniferous (56 %) as broadleaves (44 %) tree species.

In the territory there are also significant protected areas: Low Tatras Mts., Polana, Great Fatra Mts., Badinsky primaeval forest.

The distribution of the roads in the experimental area is introduced in the Figure 91.

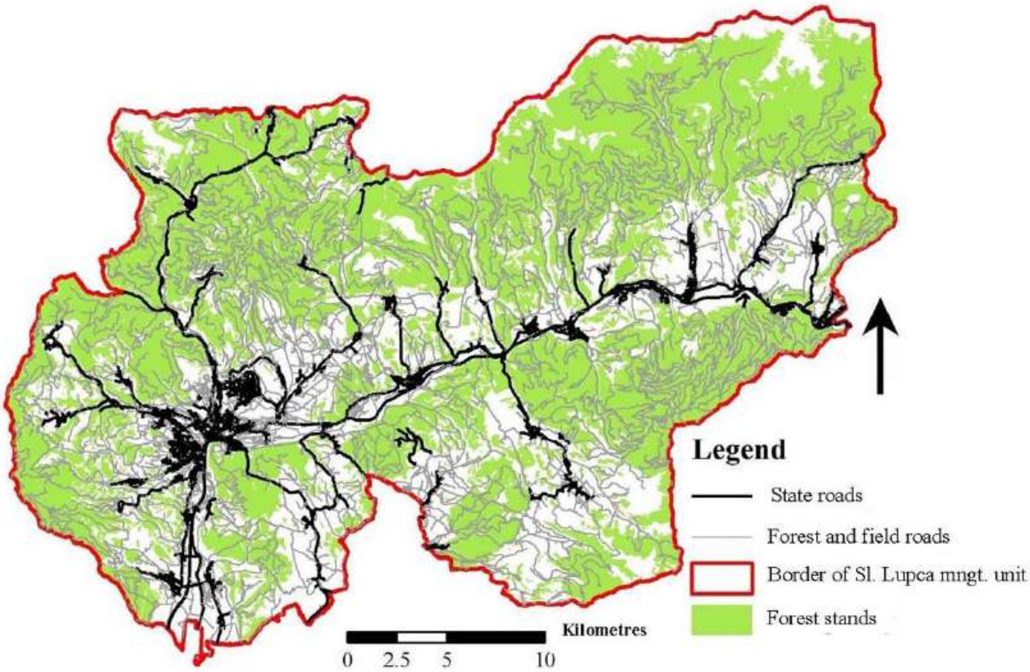

Figure 91 Actual state of road network development

For purposes of addressing the issue of optimizing the distribution of fire-fighting vehicles used for suppression of forest fires in mountainous conditions of the Slovak Republic, there has been also designed and built an optimization model for the selection suitable fire-fighting vehicles based on the multi-criteria evaluation of selected types of fire-fighting vehicles. The model was built in NetWeaver environment. It was built as a dependency network, which consists of the data links connected by logical functions. In the model, the types of fire-fighting equipment are evaluated based on three main groups of factors: natural (terrain factors and factors of soil) and operational and technical parameters, as well as the parameters of the road network, which are directly related to the issue of opening-up of the area for the deployment of ground mobile fire-fighting vehicles.

In terms of operational and technical parameters were included to further assessment the following vehicles.

Among the forest specials were included: UNIMOG forest specials on chassis of Mercedes Benz - U1550L, U4000, and U5000.

Among the vehicles to ensure the shuttle and long-distance water relay were included: CAS 32Tatra 148, CAS 32 Tatra 815 6x6, CAS 30 Tatra 815-7 6x6, CAS 30 Iveco Trakker.

For purposes of forest opening-up analysis was necessary to carry out the survey of the forest road network in the experimental area, first. As a basis for the field survey were used the ortho-photos from area of interest and vector data layers representing state road sections as well as forest and field roads. Those were obtained from the Central spatial database provided by the Topography Institute in Banska Bystrica. In the framework of the field survey, data on forest road types, their parameters (width of the road, inclination, etc.), surface and condition were recorded.

Analysis of opening-up of area for the deployment of ground mobile fire-fighting vehicles was carried out according to the methodology published by Majlingová (2012). This is a methodological approach based to pro-cessing data in geographic information systems, which consider the parameters and traffic-ability of the road network of the assessed ground mobile fire-fighting vehicles and the parameters of the terrain, in which firefighting will be realized. The result of this analysis is a map representing forest stands that can be extinguished by ground fire-fighting vehicles (fire-fighting zone). These were identified based on the maximum length of hose system and accessibility of the area, which is assessed based on parameters such as the slope of the terrain and the presence of obstacles such as rocks, cliffs, and ravines. In the paper, introduced procedure was based on an analysis processing in the Idrisi environment. Here we present an approach that has been modified in and redesigned for the purpose of processing the analysis in ArcGIS Desktop environment.

In the context of pre-processing the data, they were converted into the form in which they entered the analysis. From the digital elevation model was derived raster of terrain slope, which was converted to radians. Raster of forest road network was converted to binary form, where the roads passable for specific type of technology had distinguished them from others (1 - passable road, 0 - other roads).

The next step was to derive sloping distances (distance analysis) of each grid cell to the nearest cell of a road by applying the principle of cost distances. For the shuttle and long-distance water relay vehicles and equipment we considered to use the following categories of roads: state roads, forest roads of 1L and 2L category, and in the case of forest special vehicles deployment we considered to use the state roads and forest roads of categories 1L, 2L, 3L and hauling roads. Due to the same range of hosing system in uphill and downhill direction, it was not necessary to distinguish roads by location on the slope and direction of water transport to the fire site. There was performed also the analysis in terms of potential deployment of "system of lakes" used for long-distance transport of water to fire area located in high altitude locations.

At the end, for the considered types of fire-fighting vehicles were calculated the rasters of derived sloping distances using the map algebra tools, reduced to area extinguishable with chosen vehicle type - thus the area opened-up. Finally, we extracted the maximum slope distance values, applying module *Zonal Statistics As Table*, for the individual stands, which were compared with the maximum sloping length of the hose system and then were chosen only those that are fully reachable from the existing road network - extinguishing zone.

First, we introduce the results of field survey focusing the basic parameters of forest roads. The total length of roads within the territory is 3,340,490.740 m; of those 279,474.240 m of state roads (8 %), 466,616.890 m of reinforced (paved) forest roads (14 %) and 2,594,399.610 m of unpaved forest roads (78 %).

Results of opening-up analysis to deploy the fire-fighting vehicles for the territory of the Slovenska Lupca Forest Management Unit are introduced in the Figures 2, 3 and 4.

In assessing the possibilities of ground mobile fire-fighting vehicles required for suppression of forest fires from reinforced roads, as well as for ensuring water shuttle relay, were considered as terrain conditions, condition, and parameters of road network as basic parameters of vehicles and their equipment. There were assessed following vehicles: CAS 30 Tatra 148, CAS 30 Tatra 815-7 6x6, CAS 32 Tatra 815 6x6, CAS 30 Iveco Trakker.

The results of the opening-up analysis (Figure 92) of the territory of the Slovenska Lupca Forest Management Unit showed that opened-up area is represented only by 0.06% of the area (30.74 ha).

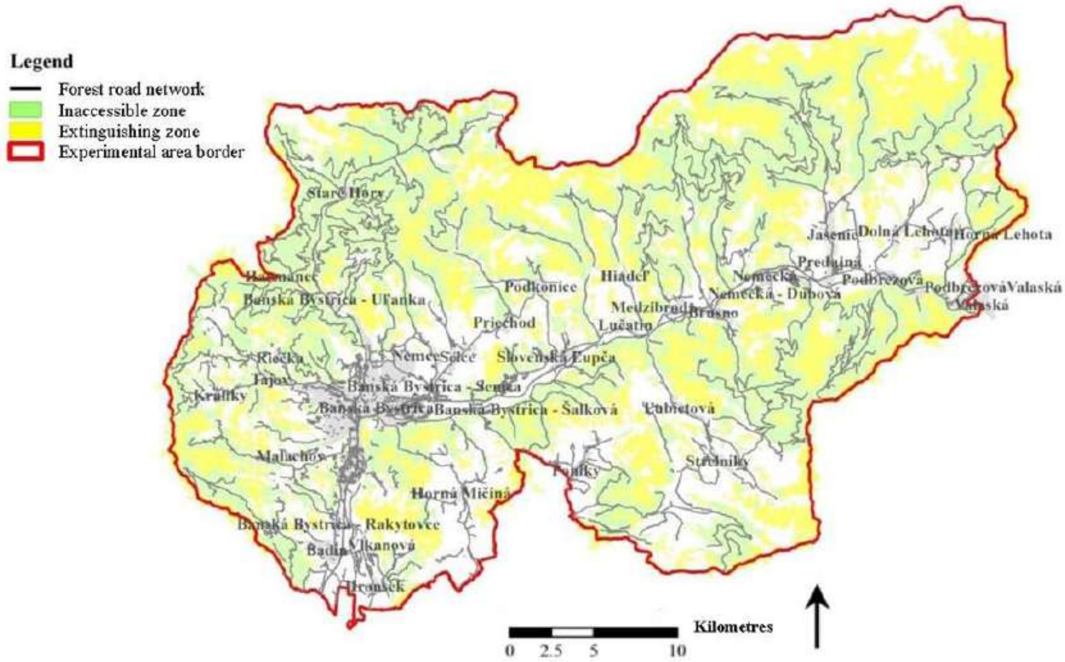

Figure 92 Results of area opening-up analysis for vehicles ensuring the shuttle water relay

In process of analyses the possibilities to deploy the forest special vehicles (UNIMOG forest specials on Mer-cedes Benz chassis) we considered two types of opening-up analyses. First analysis is focusing the conditions, when the surface of unpaved forest roads is dry (or frozen) and trafficable. The second analysis was performed for wet, waterlogged surface of unpaved forest roads.

The results of the first analysis are presented in the Figure 93. In this case, there was included the entire forest road network into the analysis. The territory of Slovenska Lupca Forest Management Unit is opened-up to 89.86 % (48,954.55 ha).

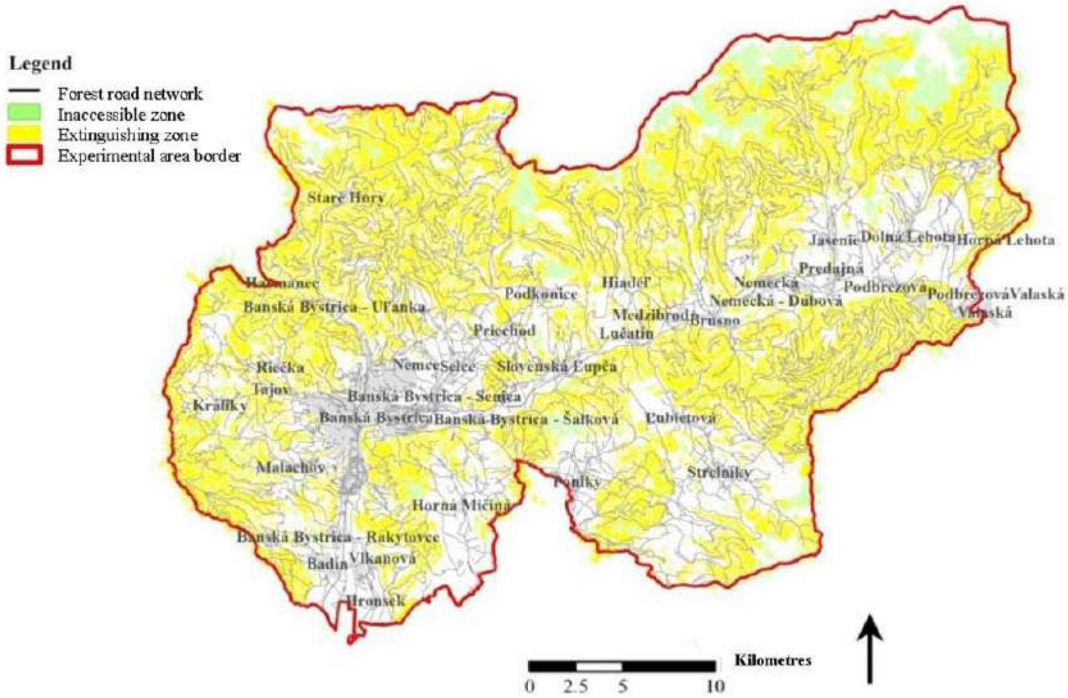

Figure 93 Results of area opening-up analysis for deployment of special forest vehicles in dry season

In the Figure 94, there are in graphical form presented results of Slovenska Lupca territory opening-up analysis to deploy the ground mobile fire-fighting vehicles – the forest special vehicles in conditions of wet, waterlogged surface of ground roads. Those roads are not trafficable, even for forest special vehicles, in these conditions. That is also confirmed by fact that that the level of area opening-up came down to 59.84 % (32,602 ha).

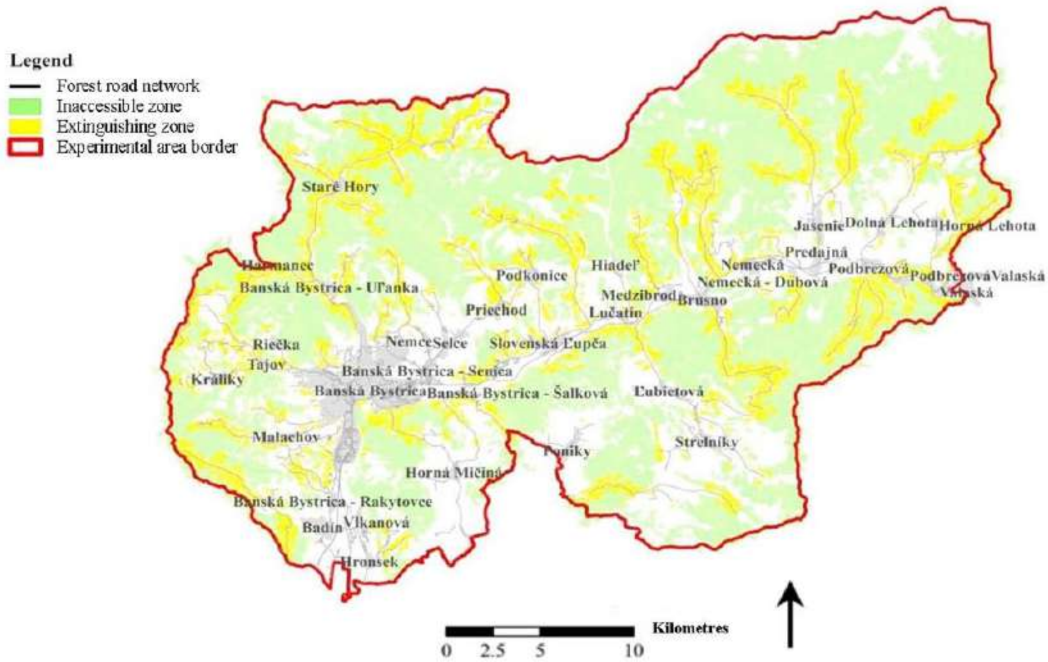

Figure 94 Results of area opening-up analysis for deployment of special forest vehicles in wet conditions

Results of Slovenska Lupca Forest Management Unit opening-up analysis in case of applying the “system of lakes” to long-distance transport of water to the fire site (Figure 95), including the entire forest road network, showed that the territory is opened-up to 94.79 % (51,640.74 ha). In case of including only reinforced roads into the analysis, the opening-up level came down to 73.55 % (40,072.32 %).

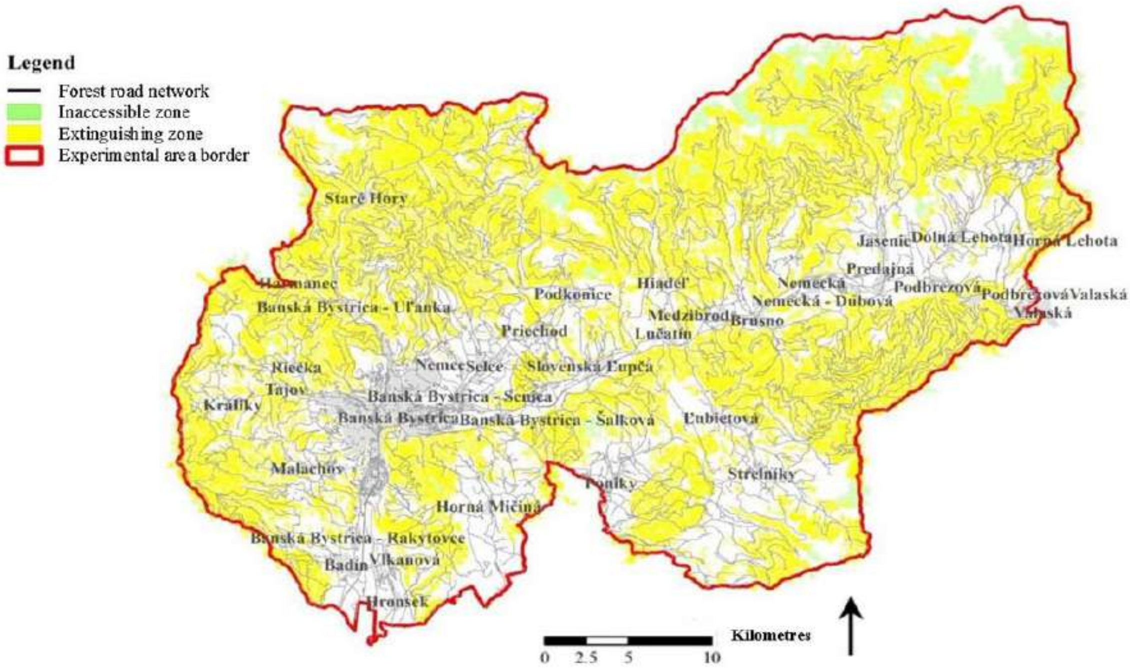

Figure 95 Results of area opening-up analysis for deployment of “lake system” of long-distance water transport

Conclusions

The paper presents very current and interesting topic of optimizing the deployment of fire-fighting vehicles in mountainous terrain. To optimize their deployment, we need to dispose with information on results of territory opening-up analysis.

Except the introduction of a GIS based approach to analysis, the paper presents a review of works dealing with the issue of forest opening-up in home conditions. All over the world, there is not enough literature sources dealing with the issue of opening-up of forest to deploy the fire-fighting equipment.

But there are many sources dealing with planning of forest road network, timber logging technologies optimization from forestry point of view. According to the analogy of those issues – the vehicles and other equipment have often the same parameters; it is possible to rationalize the opening-up process focusing the fire-fighting equipment based on the existing results of forestry research.

The results of the opening-up analysis showed that the area is opened-up only to 0.06 % if we take into con-sideration only the reinforced roads to deploy the ground mobile fire-fighting vehicles to fight the forest fires. If we consider the entire road network in the territory, dry season and deployment of forest special vehicles, the territory opening-up index increases to 89.86 %. In reverse, taking into consideration the wet season the opening-up index decreases to 59.84 %. The best results were achieved, when the “lake system” of forest fire extinguishing was involved into the analysis. In case of involvement of the entire territory road network we reached the opening-up index of 94.79 %.

The results of opening-up analysis can be used as the decision support for planning new sections of road network in any territory, for planning the purchase of new fire-fighting equipment suitable to the natural conditions of territory, where it should be located and used, etc.

Based on the previous experience of authors and analyses results we recommend the following to be applied in the fire services practice:

- To reappraise the spatial distribution of fire-fighting vehicles in the Fire and Rescue Service in the intervention districts with mountainous conditions to mass forest special vehicles with 4x4 chassis and to the lowlands intervention districts to mass the firefighting vehicles with chassis 6x6, 8x8 respectively.
- For long-distance water transport to use CAS 32 Tatra 815 6x6 and CAS 30 Tatra 815-7 6x6. For shuttle water relay purposes to use CAS 30 Tatra 815-7 6x6 or the alternatives Iveco Trakker and Mercedes Benz Zetros.

Introduction to the SILVANUS project

SILVANUS [189] envisages to deliver an environmentally sustainable and climate resilient forest management platform through innovative capabilities to prevent and combat against the ignition and spread of forest fires. The platform will cater to the demands of efficient resource utilisation and provide protection against threats of wildfires encountered globally. The project will establish synergies between (i) environmental; (ii) technology and (iii) social science experts for enhancing the ability of regional and national authorities to monitor forest resources, evaluate biodiversity, generate more accurate fire risk indicators, and promote safety regulations among citizens through awareness campaigns. The novelty of SILVANUS lies in the development and integration of advanced semantic technologies to systematically formalise the knowledge of forest administration and resource utilisation.

Additionally, the platform will integrate a big-data processing framework capable of analysing heterogeneous data sources including earth observation resources, climate models and weather data, continuous on-board computation of multi-spectral video streams. Also, the project integrates a series of sensor and actuator technologies using innovative wireless communication infrastructure through the coordination of aerial vehicles and ground robots.

The technological platform will be complemented with the integration of resilience models, and the results of environmental and ecological studies carried out for the assessment of fire risk indicators based on continuous surveys of forest regions. The surveys are designed to take into consideration the expertise and experience of frontline fire fighter organisations who collectively provide support for 47,504x104 m^2 of forest area within Europe and across international communities. The project innovation will be validated through 11 pilot demonstrations across Europe and internationally using a two-sprint cycle.

The interdisciplinary project enablers categorised across Phase A, B and C activities are presented in Figure 96.

Figure 96 Technical building blocks and interdisciplinary enablers for environmentally sustainable and resilient forest management

The technical and scientific innovation will encompass the ability to process large volume of heterogeneous data sources to deliver real-time insights into forest status.

Phase A: The Prevention and Preparedness activities will include the continuous evaluation of the fire danger index metrics supported on advanced computer based mathematical models. Subsequently, stakeholder engagement activities will deliver advanced training programme for the frontline fire fighters with the use of virtual reality and augmented reality (VR/AR) content. Moreover, mobile applications, built within SILVANUS, will gather insights on the citizens, awareness about dangers of forest fires and their global impact on climate change. In addition, developed Cloud services for communities and companies - e.g., Utilities - will foster new strategies for fire prevention by minimizing interaction between critical infrastructure and surrounding vegetation. Finally, activities in Phase A will also include a detailed review of the EU legislative regulations on environmental protection and policies adopted by the regional public administration authorities. The project will adopt the use of participatory process framework for stakeholder engagement to maximise the impact of information gathered within the project.

Phase B: Detection and Response activities will include: the development of an ICT platform that offers advanced capabilities for the first responders (fire fighters, medical response teams, public administration authorities and other relevant stakeholders); the development of a mechanism to detect ignition of forest fire, model the spread of fire considering the impact from climate and weather services and coordinate a response among the mobile command centres to effectively and efficiently subdue and contain the spread of forest fire. The technological innovation in the protection of first responders will include knowledge gathered from Earth Observation repositories, granular predictive models of weather and climate conditions, use of autonomous systems to obtain insights on the spread of fire.

The implementation of high-level mission-critical command centre will enable the practitioners to identify critical regions to deploy resources with maximum impact.

Phase C: Restoration and Adaptation activities will build on recent innovations in simulation models that address the need for evaluating the forest resilience to fires, as well as other factors (climate change, human land use, droughts, etc.) based on their impact on natural resources.

The use of Earth Observation (EO) provides alternative ways to collect wildfire information. EO technologies using both space and surface networks, have demonstrated not only their maturity, but their critical role in supporting fire managers, first responders and risk managers by providing effective tools to predict severe fire danger conditions, rapidly map natural hazards, and assess impacts. Although there is an increasing amount of spatial data and information on wildfires from different sources and often collected at the national, regional, and global levels, there is currently no international initiative to amalgamate and harmonize such information, and to distribute it to users worldwide.

Technical university in Zvolen as a partner of the project consortium was responsible for coordination of tasks and elaboration of deliverable [190] which aim was to gather and collect information on existing data, system, services, and technology used in the Pilot Sites for combating the wildfires in the framework of 3 phases: Phase A (Preparedness and Prevention), Phase B (Detection and Response) and Phase C (Restoration and Adaptation). Another task was to gather and collect information about functional requirements on the SILVANUS Platform being built in the framework of SILVANUS project.

To gather this information, participatory processes were established, both between internal and external stakeholders. For establishment of participatory processes, a methodology was developed to be further used when involving stakeholders to activities related to the other SILVANUS work packages and their tasks. According to the methodology developed, there was implemented the process of stakeholders interviewing and filling the proposed questionnaire tables/forms in JotForm. Information was collected from totally ten pilots. The (current) status related to the data, systems, services, and technology used for combating the wildfires was summarized. The functional requirements were collected, summarized, analysed, and validated by the external stakeholders and interdisciplinary experts.

There were evaluated the functional requirements for SILVANUS Platform (for each phase A/B/C) by internal and external stakeholders. The classification of those requirements (must /should /could) was introduced in the sections related to each Pilot Site.

In the following sections, there are introduced the aggregated tables for all the phases (A/B/C) including their cross validation.

Forest Landscape models

The information on the biodiversity richness available within the forest is an important factor. Despite the significance, there is a clear lack of existing tools and techniques that can be used as a baseline for the stakeholders to provide relevant requirements for the application.

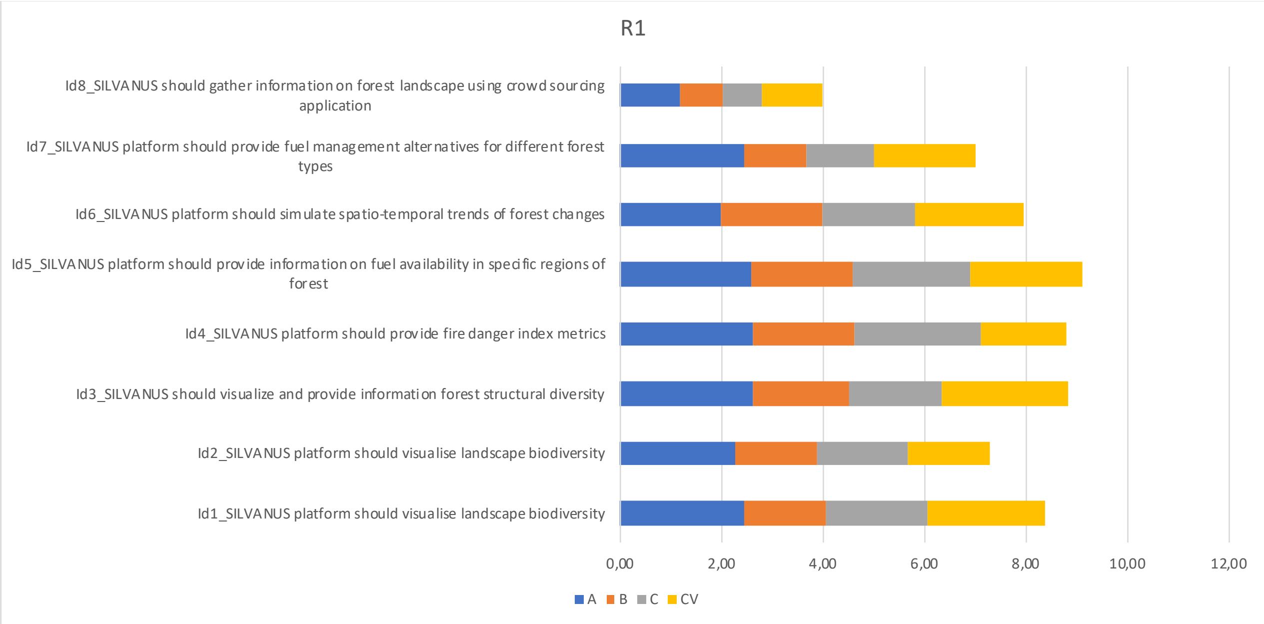

Figure 97 Forest Landscape models

Climate sensitive forest management

Following interactions with stakeholders and external project representatives (such as Firelinks, Fire-RES, FIREURISK and FireLogue), it is widely acknowledged that, there is a direct correlation between the impact of climate sensitivity on the forest management. The impact of environmental factors such as wind could play a key role in strategically designing how and where the first line of defence could be established that could prevent and/or mitigate the spread of fire. The knowledge that can be gained from using such insights have been accepted to play a key role in effectively combating against wildfires.

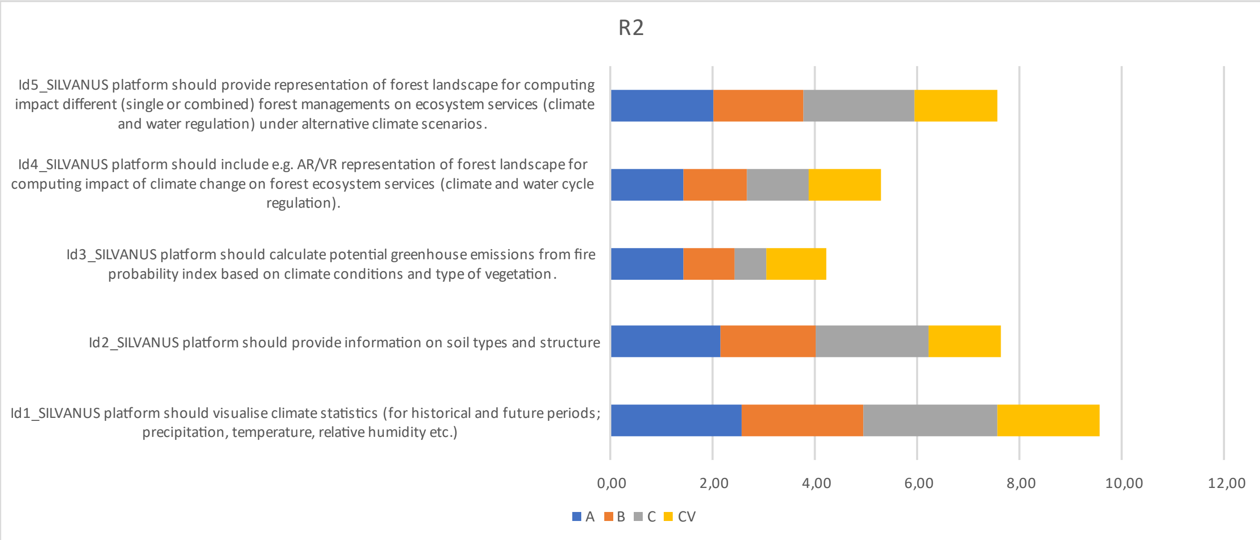

Figure 98 Climate sensitive forest management

Forest resilience models

Forest resilience against wildfires is an important research topic which has come under severe scrutiny among the conversationists in recent years. The definition of forest resilience is still under debate among the experts and one such interpretation includes the consumption rate of forest biomass fuel and the rate of combustion of different forest species. To effectively capture such information, it is important to model the biodiversity of the forest species, which extends beyond the natural growth of forest to include insect's species and other supported livelihood.

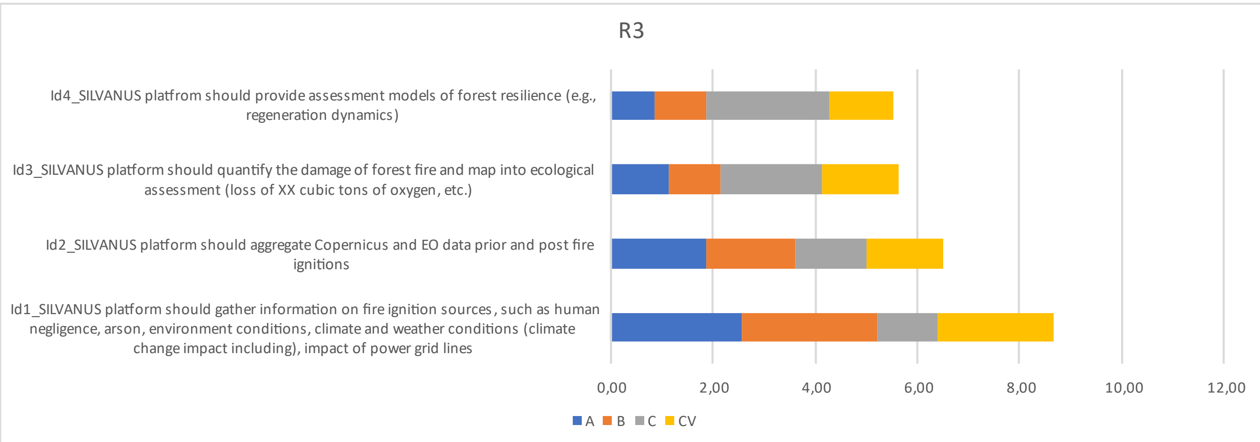

Figure 99 Forest resilience models

Forest fire ignition models

Fire ignition models have been studied in the literature based on historical case-studies. The six (6) causes of fire ignition cited by a white paper includes human negligence, natural causes, and others. Therefore, for each of these scenarios, it is important to develop representative models that would enable the determination of fire spread. It is widely acknowledged that the motivation of the fire ignition plays a significant role in the amount of fuel that would be used to cause the fire. As an example, the instance of human negligence would disproportionately include the fuel which is a result of an arson. Similarly, the strength and magnitude of fire caused by natural sources will also depend on the relevant causes.

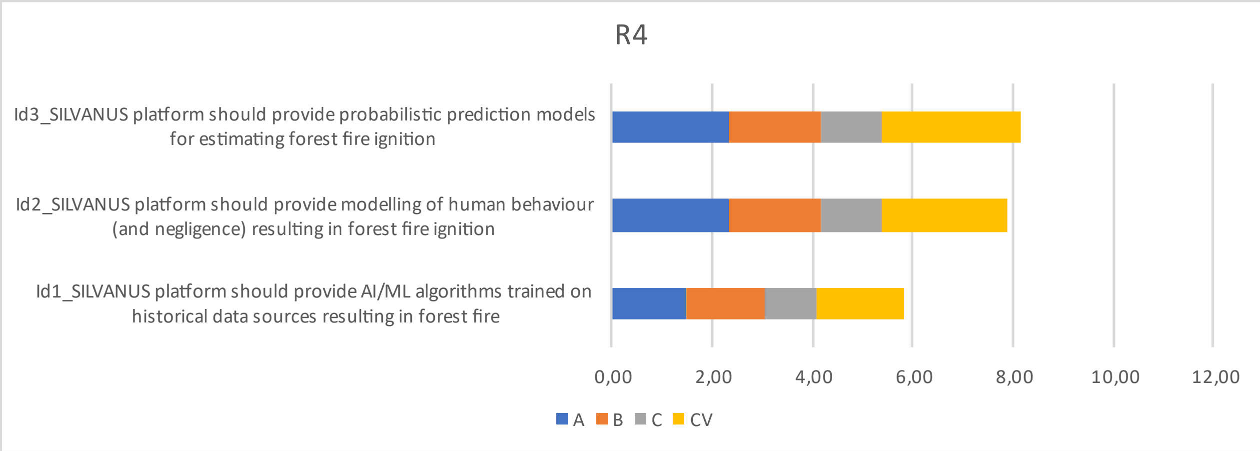

Figure 100 Forest fire ignition models

Prevention methodologies

Across the global community, it is widely acknowledged that prevention is better than post fire detection and mitigation. While several methodologies have been identified and reported in the literature, there still does not exist a unified methodology that brings tools and other services to promote fire safety among wider public and deliver intelligent training to the fire-fighters. Additionally, there still lacks systematic tools in implementing these methodologies. The scope of SILVANUS includes gathering requirements for addressing such shortcomings.

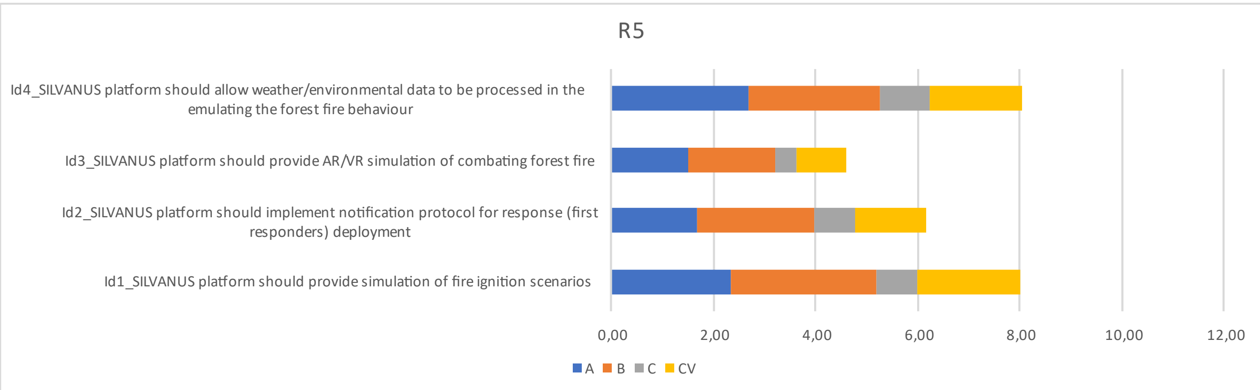

Figure 101 Prevention methodologies

Citizen engagement and awareness programme

As cited earlier, human negligence is often cited as a source of forest fire, which are ignited in regions of low probability and low levels of preparedness. Therefore, to mitigate against such threats, the citizen engagement programme within the project aims to develop a systematic approach in which specific methodologies and relevant tools would be developed that address the challenges of communicating fire safety to a wide group of European and Global citizens. The requirements identified for addressing citizen engagement aims to encompass a holistic overview of the various needs and requirements including culture, geographical area and other parameters.

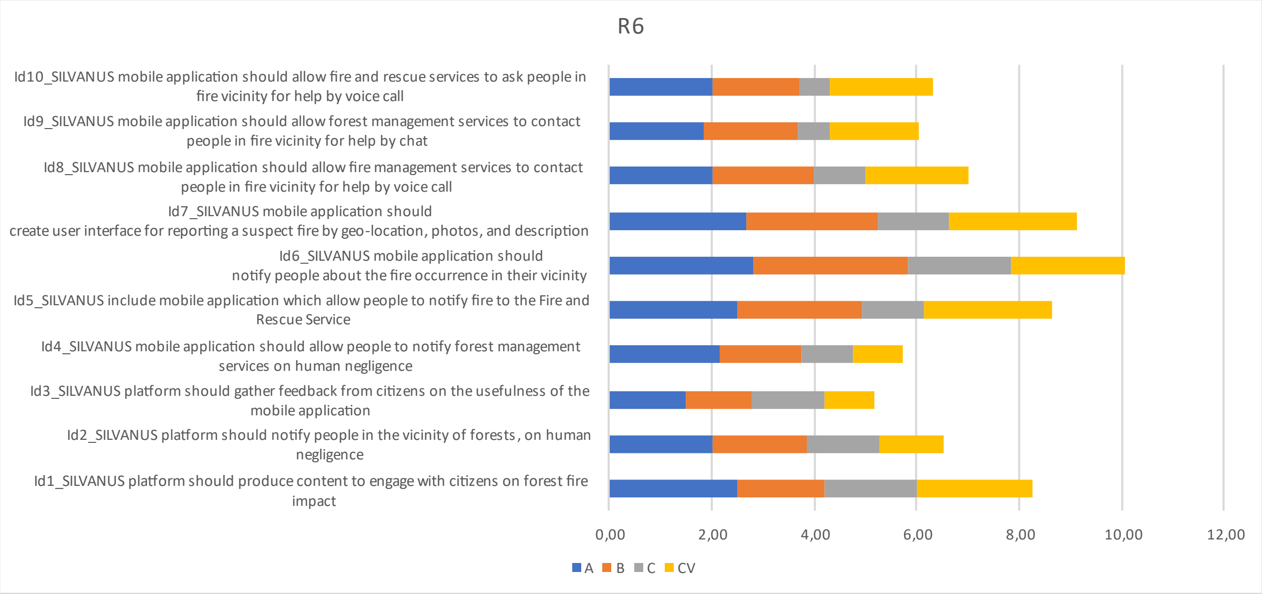

Figure 102 Citizen engagement and awareness programme

Tailored weather/climate models for forest fire threat/risk assessment

The threat of wildfire can be attributed to a wide range of parameters which are often complex and needs to be modelled using advanced ML and AI algorithms. As noted earlier, the impact of climate and weather data plays a crucial role in the ability of observe the threat level across a geographic region. To this end, the SILVANUS project has gathered relevant requirement on the overall modelling of the intelligent systems that could accurately predict the threat of wildfire and offer stakeholders an advance warning system towards improved forest maintenance.

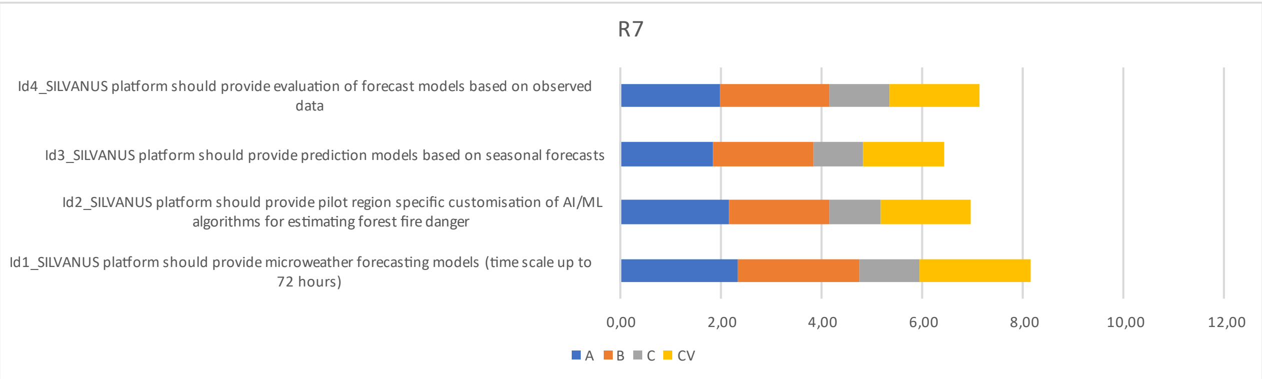

Figure 103 Tailored weather/climate models for forest fire threat/risk assessment

In-Situ data analytics

Following the user requirements aggregation process being completed it was observed that there is a critical lack of in-situ devices which are already installed and are available to collect relevant data from the field. In discussion with the stakeholders, it was identified that one of the biggest limitations of installing in-situ devices on the field relates to the lack of power supplies, upon which a large proportion of digital devices depend upon. Therefore, there is a general lack of awareness and ability to install and collect relevant data sources. Subsequently, it was agreed that within the scope of the project, appropriate field visits will be carried out to further enhance and enrich the knowledge on in-situ device installation capacity and bring forward relevant devices.

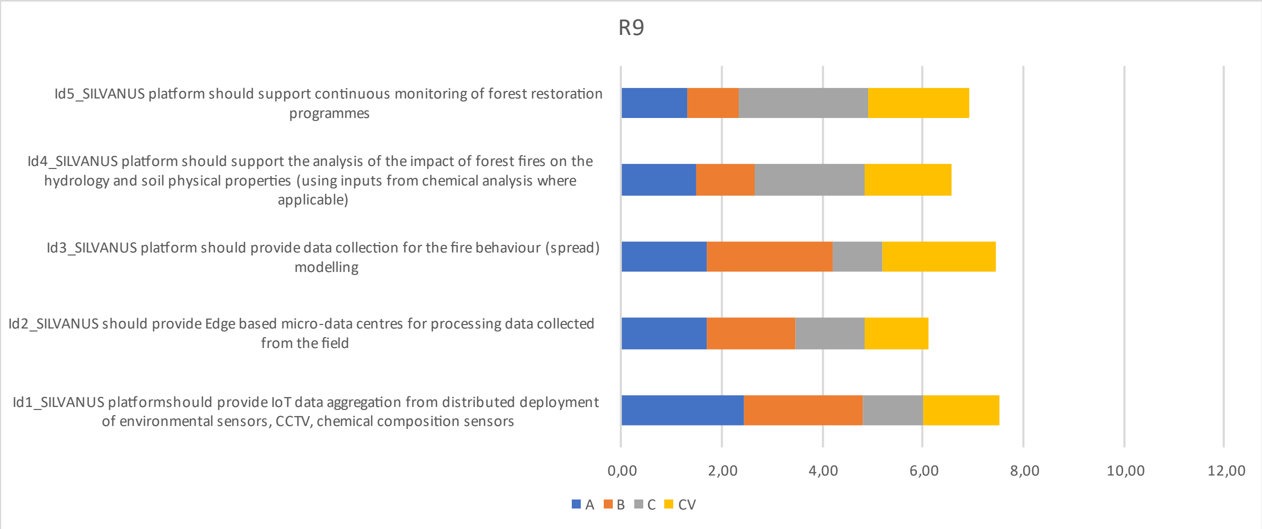

Figure 104 In-Situ data analytics

Social sensing and conceptual extraction

Social media has become a big part of our day-to-day life and visits to forest offers a great opportunity for the public to share and promote awareness on climate change, ecological balance, and biodiversity among relevant social groups. Therefore, if there is a fire being cited, crawling social media for such citing offers a unique advantage to the relevant firefighters and stakeholders to engage citizens as a first line of defence. To this end, the requirements collected within SILVANUS offers such a unique capability to detect such citing gathered from social media.

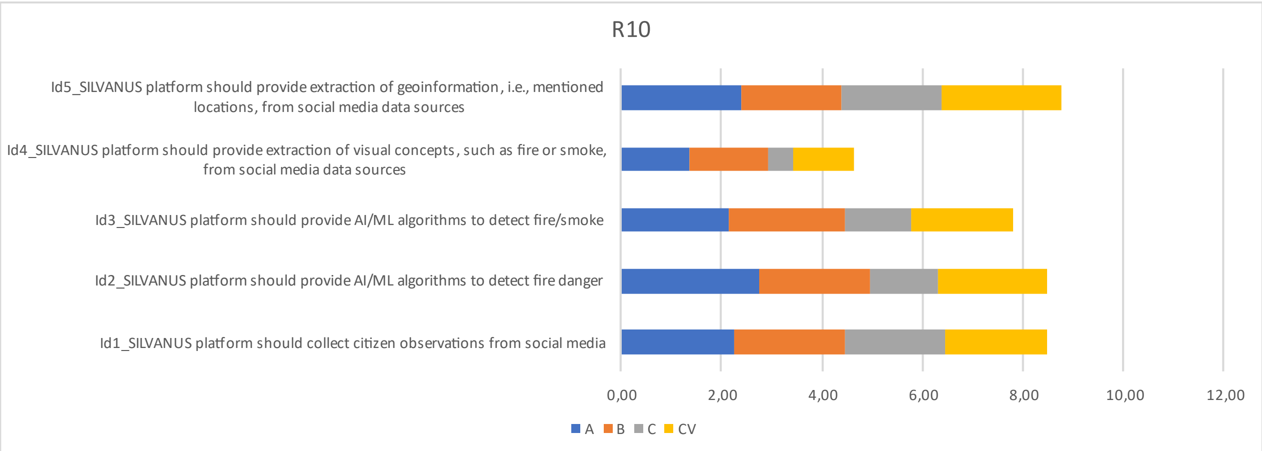

Figure 105 Social sensing and conceptual extraction

UGV monitoring of wildfire behaviour

The advancement in the field of robots and aerial vehicles have offered a unique opportunity to deploy these systems either autonomously or through pilots to be able to gather vital information from the wildfire front lines. To this end, UGVs and UAVs will be deployed to undertake surveillance and aid in the knowledge aggregation process to suitably supplement the relevant information which could be obtained from in-situ devices. Requirements from the stakeholders provides support to enhance the ability of data processing onboard.

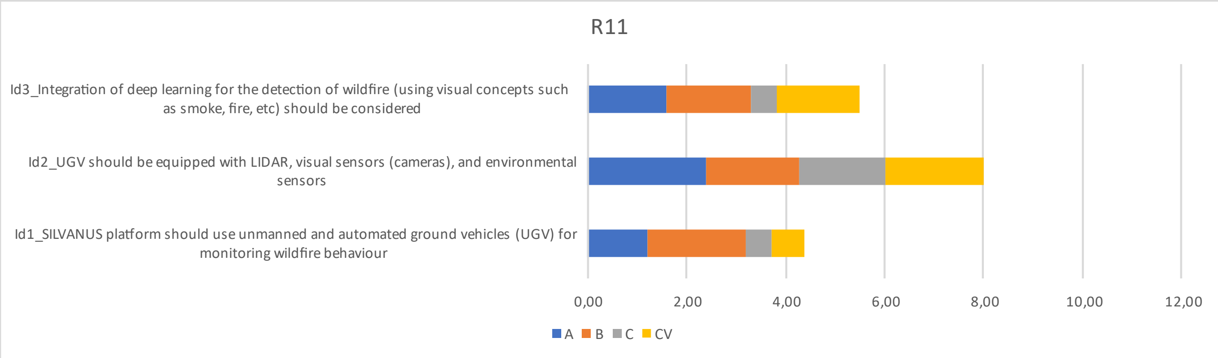

Figure 106 UGV monitoring of wildfire behaviour

UAVs deployment for remote sensing

UAVs offer the capacity to be deployed for conducting a large-scale aerial surveillance for detecting the boundaries of the wildfire, but also to detect any personnel and/or any manmade structures, which could be vulnerable to the spread of wildfire.

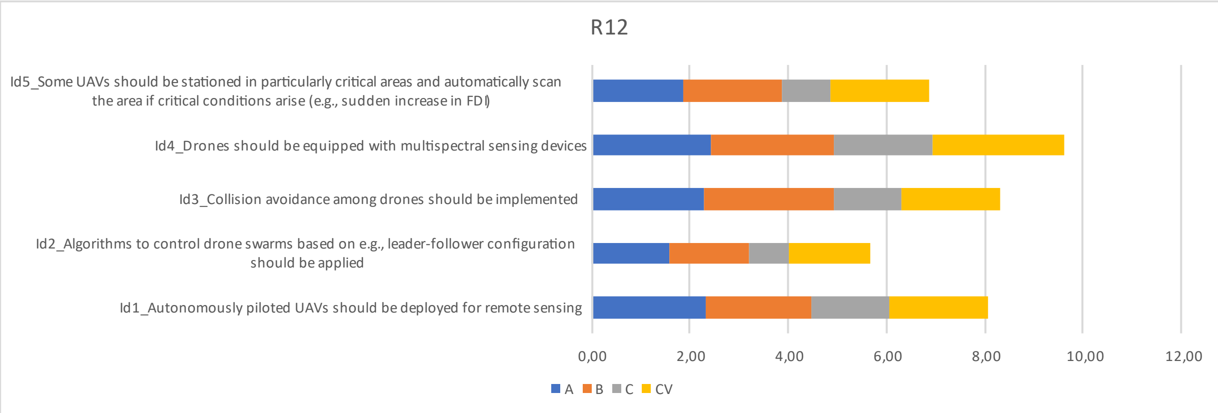

Figure 107 UAVs deployment for remote sensing

Earth observation data analytics

For gathering information on the overall state of forest at a macro scale, earth observation repositories provide a reliable source of information.

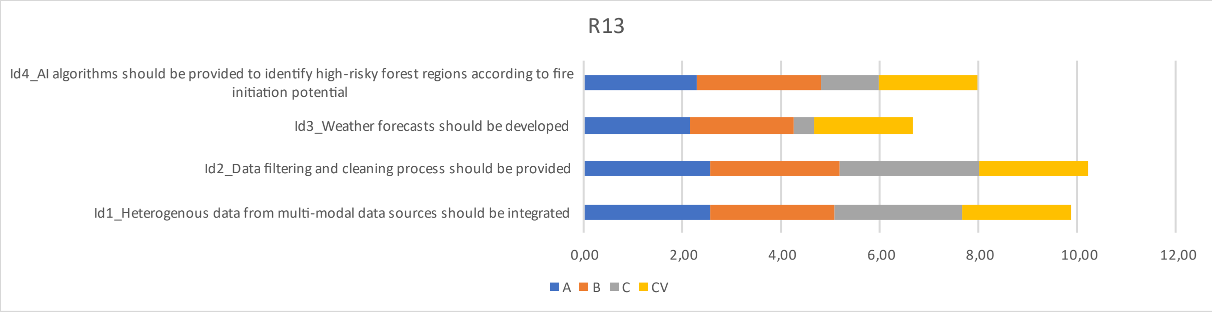

Figure 108 Earth observation data analytics

Situational awareness of fire danger index

Upon the detection of a fire ignition, the situational awareness of fire danger index should integrate relevant AI/ML algorithms that can demonstrate the potential fire spread across geographical regions. Such predictions should be evolved in time to aid in the process of accurate modelling across temporal scale, against the on-field data being collected.

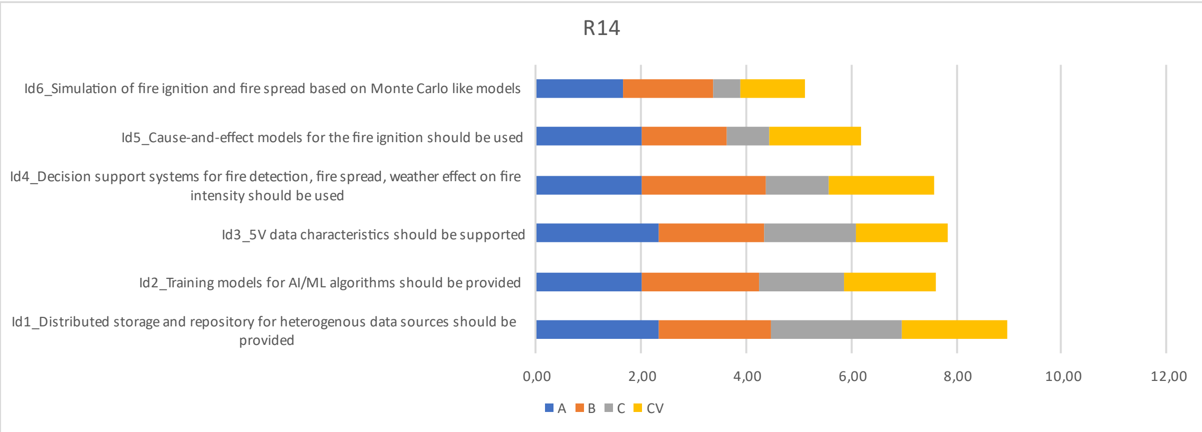

Figure 109 Situational awareness of fire danger index

Real-time monitoring of fire behaviour for response coordination

Monitoring of real-time spread of wildfire plays a crucial role in the determination of the fire spread. The use of cause-and-effects models and Monte-Carlo simulation on the fire datasets would be further evaluated in the scope of the project.

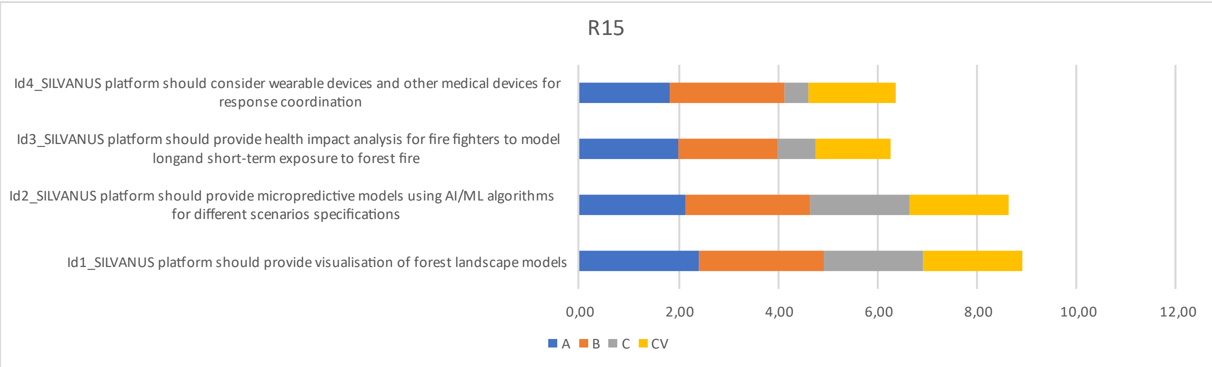

Figure 110 Real-time monitoring of fire behaviour for response coordination

Decision support systems for detecting and preventing forest fires and forest restoration

The outcome from the SILVANUS platform implementation is the decision support system for detecting and preventing forest fires. The requirements gathered will emulate real-world scenarios from the historical case-studies to demonstrate the effectiveness of the SILVANUS technological intervention.

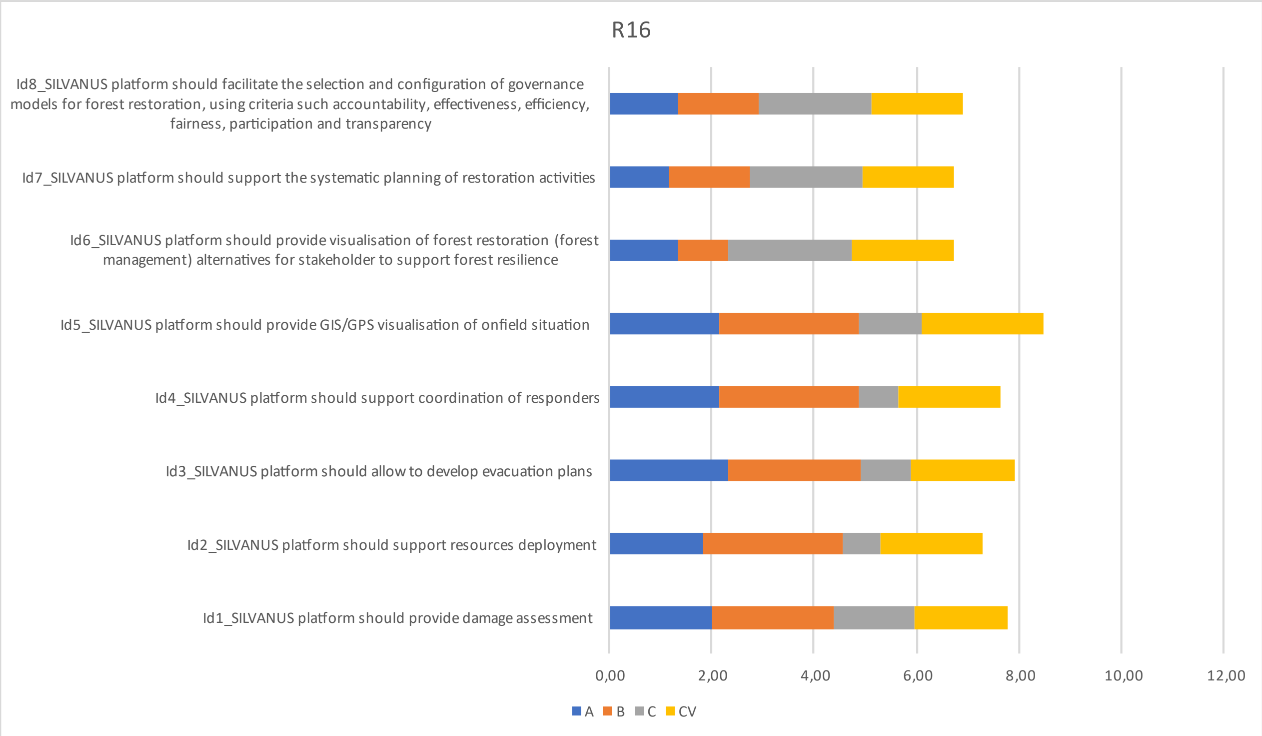

Figure 111 Decision support systems for detecting and preventing forest fires and forest restoration

Results of validation provided by foresters showed the consensus was found at level of 50% when considering the Phase A, 31% for Phase B, 31% for Phase C and 58% for cross-validation values. The reason is the high level of subjectivity which is given to the question asked. The aim of this survey was to identify the priority given by stakeholders to the provided options which are considered important by SILVANUS Consortium. Results of validation provided by firefighters showed the consensus was found at level of 36% when considering the Phase A, 46% for Phase B, 28% for Phase C and 39% for cross-validation values. The reason is the high level of subjectivity which is given to the question asked. The aim of this survey was to identify the priority given by stakeholders to the provided options which are considered important by SILVANUS Consortium. Results of validation provided by civil protection experts showed the consensus was found at level of 40% when considering the Phase A, 33% for Phase B, 24% for Phase C and 36% for cross-validation values. The reason is the high level of subjectivity which is given to the question asked. The aim of this survey was to identify the priority given by stakeholders to the provided options which are considered important by SILVANUS Consortium.

CONCLUSIONS

This publication presents selected issues from the broader field of wildfires. It also presents the theoretical background of the addressed issues, complemented by the results of research on several issues in the field of prevention and study of forest fire behaviour. The research was carried out in specialized laboratories of the Department of Fire Protection, which is an integral part of the Faculty of Wood Technology of the Technical University of Zvolen.

With its focus on forest fires and the application of geoinformatics tools and computer-aided modelling of fire spread, the Department represents a unique workplace within the Visegrád Group countries.

The department employees continue with the research activities presented in this publication, developing new progressive methods of studying the fire characteristics of forest fuels, the behaviour of surface fire and derives new insights that form an invaluable source of knowledge for firefighting practice.

The publication summarises knowledge that can be used as input data for the development of fire and forest management models within the SILVANUS project (HORIZON 2020), whose main objective is to increase the resilience of forest stands to fires and to promote sustainable forest management.

The Technical University of Zvolen is a full member of the SILVANUS consortium of partners and is responsible for both, forest fire modelling as well as finding the optimal forest management practices, strategies, and policies to support the sustainable forest management and biodiversity of European forests.

GLOSSARY

AERIAL ATTACK	Fire suppression operation involving the use of aircraft to release water or retardant on or near a wildland fire
CONTROLLED FIRE	A fire with a secure perimeter, where no breakouts are anticipated.
DEBRIS	Dead and dying fuel, consisting of both fine and coarse fuels, and inclusive of twigs and any vegetation. Debris is usually found lying on the ground but can also be found at various levels within the vertical arrangement of fuels.
DUFF	A surface fuel consisting of partly or fully decomposed organic material lying on the mineral soil.
FINE FUEL	Fast-drying dead fuels which are less than 6mm in diameter. Fine fuels ignite readily and are rapidly consumed by fire when dry. Examples of fine fuels include grass, leaves, ferns, mosses, pine needles and small twigs. When dried, fine fuels are referred to as flash fuels.
FIRE	Fire is the product of the chemical reaction of combustion. The three factors of fuel, oxygen and heat must all be present in the correct proportions for combustion to occur. When the combustion process is initiated, heat and light are emitted, and a fire occurs.
FIRE BEHAVIOUR	The reaction of a fire to the influences of fuel, weather, and topography.
FIRE DYNAMICS	The detailed study of how chemistry, fire science, and the engineering disciplines of fluid mechanics and heat transfer interact to influence fire behaviour.
FIRE HISTORY	The reconstruction and interpretation of the chronology of wildland fire occurrence and the causes and impacts of wildland fires within a specified area.
FIRE INTENSITY	The rate at which a fire releases energy in the form of heat at a given location and at a specific point in time ($kW \cdot m^{-1}$ or $kJ \cdot m^{-1} \cdot s^{-1}$).
FIRE REGIME	The pattern of fire occurrence, fire frequency, fire seasons, fire size, fire intensity, and fire type that is characteristic of a particular geographical area and/or vegetation type.
FIRE RISK	The probability of a wildland fire occurring and its potential impact on a particular location at a particular time.

FIRE SEASON — The period or periods within a year when wildland fires are likely or most likely to occur.

FLANK FIRE — A fire spreading or predicted to spread parallel (approximately at a right angle) to the prevailing wind direction or a slope.

FUEL — Any material that can support combustion within a wildland fire environment. Fuel is usually measured in $t \cdot ha^{-1}$.

FUEL MODEL — A mathematical representation of fuel properties within a specified location, often used to predict and plot likely fire spread and intensity.

HOT SPOT — A small burning area within a fire perimeter which requires suppression action as part of the mop-up phase of suppression.

LITTER — The top layer of debris fuels consisting of twigs, sticks and branches, it can also include recently fallen leaves and needles. The structure of the material within the litter layer has not been altered significantly by the process of decomposition.

POINT OF IGNITION — The precise physical location where the source of ignition met materials first ignited.

RECONNAISSANCE — The act of gathering information about a wildland fire incident to monitor fire behaviour and suppression activities. The primary reasons for completing reconnaissance should be to maintain safety and to assess the effectiveness of a fire suppression plan.

RUNNING FIRE — A fire that is rapidly spreading with a well-defined head.

SPOTTING — Fire behaviour characterised by sparks and embers that are transported through the air by the wind or convection column. Spotting can be classified as short range or long range.

TACTICS — The deployment of resources at a wildland fire incident to achieve the aims of a strategic plan.

WILDLAND FIRE — Any uncontrolled vegetation fire which requires a decision or action regarding suppression.

LIST OF ABBREVIATIONS AND SYMBOLS

AOGCMs	Coupled Atmosphere Ocean Global Climate Models
b	*b* – universal constant 2.898 ($mm \cdot K^{-1}$)
C	Carbon
CAS	Pumping appliance
CCTV	Closed-circuit television camera
CFCs	Chlorofluorocarbons
CO_2	Carbon dioxide
Coll.	Collection
DBP	disinfection by-product
DNK	Low Curvature Value Ridges
DOC	dissolved organic carbon
DVK	Low Curvature Value Valeys
EC	European Commision
EFFIS	European Forest Fire System
EMDS	Ecosystem Management Decision Support
EO	Earth Observation
ESMs	Earth System Models
EU	European Union
FBFM	Fire Behaviour Fuel Models
FCCS	Fuel Characteristic Classification System
GCMs	Global Circulation Models
GIS	Geographicac Information System
HNK	High Curvature Value Ridges
HVK	High Curvature Value Valeys
JRC	Joint Research Centre
L_{fk}	Height of continuous flame (m)
L_{fp}	Flame height (m)
L_{fp}	Height of pulsating flame (m)
MoI	Ministry of Interior
NFFL	Northern Forest Fire Laboratory
NOx	nitrogen oxides
RCMs	Regional Climate Models
S.E.	State Enterprise
T	*T* – thermodynamic temperature on surface of the material (°C)
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
w	Absolute fuel moisture content (%),
w_m	Mass of wet fuel (g),
WMS	Web Map Service
w_s	Mass of dry fuel (g).
$\Delta\tau$	Time interval in which the weights are recorded (s)
λ_{max}	Wavelength at which, at temperature (*T*), the radiation intensity is
v_r	Relative rate of burning ($\% \cdot s^{-1}$)
$\delta_m(\tau + \Delta\tau)$	Relative mass loss in time (%)
$\delta_m(\tau)$	Relative mass loss over time (%)

REGISTER

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