Dispatching and modeling of fires in Central European pine stands: New research and development approaches in Germany

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1. Introduction

Fire in the Central European coniferous forests has many different faces. On the one hand low- to medium intensity fires contribute to reducing of fuels, thinning overstocked stands, or inducing natural regeneration (Conrad 1925, Viro 1969). On the other hand, a uncontrolled high-severity forest fire may have catastrophic consequences for the ecosystem and the land owner (Missbach 1973, Liebeneiner 1981).

Although the forest fire hazard in Central Europe is relatively small compared to most of the forest lands of North America, Australia or the Mediterranean countries, catastrophic fires over 1,000 ha size are possible (Missbach 1973, Liebeneiner 1971). Fire statistics reveal that the average annual area affected by destructive wildfires and the average area burned per fire in Central Europe is rather low due to the availability and efficiency of fire-fighting resources and infrastructures (e.g., Lockert 1991, Lex 1995, König 2001, Gerth 2001, Goldammer und Lex 2001). However, expected changes in regional climate in the eastern parts of Central Europe and its neighbours Poland and Belarus presumably will lead to a more pronounced continental climate characterized by a higher occurrence of droughts and fire danger (Gerstengabe et al. 1999). Facing these climate-change projections it is advisable to proactively increase the preparedness for more extreme fire seasons. Consequently planning and fire management tools must be improved. For this purpose, fire simulation models are useful to assess the potential behaviour of forest fires and to support decision making for fire suppression. Additionally, simulation models can be used to identify effective prevention and suppression methods.

A number of countries have developed and updated fire models in the past to describe the development of a fire. Depending on the terrain, the climate and the ecosystem properties (fuel types) different modelling approaches have been made (e.g. Forestry Canada Fire Danger Group 1992, Rothermel 1972). However, these models are not directly applicable under European conditions.

Until recently the objective of forest fire experiments in Germany in the past intended to test the use of prescribed burning in young pine stands (Goldammer 1979) and new fire suppression methods and means (Goldammer 1982). Additionally, test fires to calibrate spaceborne fire sensors have been conducted (Goldammer 1995). These experiments did not document the those fire parameters that are essential to develop or adapt wildland fire models, i.e., rate of spread, fireline intensity, flame length in relation to different fuel types, etc.

A new research approach was therefore needed. Under the frame of the German Research Network for Natural Disasters (Deutsches Forschungsnetz Naturkatastrophen - DFNK) an interdisciplinary forest fire research cluster was established (DFNK 2002). A first of a series of experimental burn in pine stands [*Pinus sylvestris*] planned for the period 2001-2003 was conducted in the Lausitz region, State of Brandenburg, Germany, in August 2001. This region is located in the Eastern and most continental part of Germany and characterized by high fire danger (Preussner 2001, Missbach 1973). The research plots were provided by the *Lausitzer Braunkohle AG* (LAUBAG), a regional brown coal opencast mining company. Research partners included the Brandenburg State Forest Service, the German Weather Service (DWD) and a number of academic research institutions (GFMC 2002).

2. Methods

As there are no adequate models available to describe fire behaviour under central European conditions, existing models from other countries had to be used and adapted. In this modelling approach, we used the software BEHAVE, which was developed at the U.S. Forest Service Intermountain Sciences Laboratory (Rothermel 1972). Important factors for the fire behaviour were measured before the burn (stand and fuel data, weather situation), while during the burn, flame length and rate of fire spread were recorded. This allowed the comparison of modelled fire behaviour with the observations. In a second step, a custom fuel model was created to reconstruct the situation more precisely.

In a next step, a fire dispatching and modelling system was created with FARSITE (Finney 1998) on a forest district level. Stands were classified by their fuel structure and six different custom fuel models were created. Due to time and cost constraints, it was not possible to evaluate all of these fuel models by test fires - this will be done in the upcoming experiments in 2002+. The test area (~1500 ha) consisted of homogenous pine stands.

3. The BEHAVE and FARSITE Models

In the U.S.A. the BEHAVE model is the fire simulation tool most often used to predict fire behaviour. Since it’s development in 1972 it was adjusted a few times and the current versions provide high accuracy in fire behaviour prediction. The mathematical formulas behind the system are representative for homogenous ecosystems and fuel arrangements. To work effective with BEHAVE, it is important to consider the assumptions on which this software is based (Rothermel 1972):

- The fire is burning in a homogenous fuel bed
- Slope and aspect are constant
- Wind is constant, both in velocity and direction
- The model describes the flaming front only and not the smouldering combustion behind it
- Fire behaviour is not influenced by ignition source or suppression activities

BEHAVE contains a module to simulate fire in different types of ecosystems, called fuel models. This allows a classification of every land cover type into on of the 13 standard fuel types and reduces the work load for the modelling process. The standard fuel models consist of

- Grass fuels
- Forest fuels
- Forest fuels with slash

and are further divided into sub-types (Anderson 1982). Next to numerical description of fuel amounts visual and text support is available to allow and adequate classification of the ecosystem to model the fire in (Main and Haines 1983). For this experiment, fuel Model # 2 (Pine with grass in understory) fits best (Fig.1).

By using the standard fuel model the work load can be reduced a lot, just the measured amount of fuels, their moisture content and the weather situation have to be adjusted.

This paper aims to show, that (a) the BEHAVE model can be used under central European conditions, and (b) by adjusting of the detailed input parameter custom fuel models can be easily created. By using the FARSITE model, these fuel models can be used to dispatch and simulate forest fires on a landscape level.

Figure 1. Photo of a typical fuel Model # 2, as it is typical for areas with low precipitation in the western states of the U.S.A.

The FARSITE model contains the same algorithms and formulas as BEHAVE, but can be used to simulate fire on diverse landscapes with different fuel models. It uses a GIS-approach. Thus, the data have to be prepared in raster form. The input data sets contain information about elevation, slope, aspect, fuel type, crown closure, stand height and crown bulk density (Finney 1998). The fire itself is modelled as an moving elliptical wave, the shape of this ellipse is determined by wind and topography (*Huygens's principle*; cf. Richards 1990, 1995).

4. The First Step – Fire Modelling Using BEHAVE

4.1 The experimental plots

The LAUBAG provided three pine stands of sizes ranging from 0.3 to 1 ha. The areas were covered with ca. 80-years old pine trees (*Pinus sylvestris* L.). These stands, growing on sandy, dry sites have a low productivity and are representative for the general forest conditions in eastern Brandenburg. The forest floor vegetation consisted of *Calluna vulgaris*, *Vaccinium myrtillus*, *Vaccinium vitis-idaea*, *Corynephorus canescens*, *Helichrysum arenarium* and *Armeria maritima*. Over the last years, the fast spread of *Calamagrostis epigeios* has been observed. All plots were characterized by an inhomogeneous surface fuel layer.

Table 1 provides an overview of the fuel amounts in the plots. These values were sampled with the transect method by Brown (1974). Next to the total fuel amount the percentage of fine and coarse material is important for fire behaviour and intensity. The classification into fuel classes corresponds to the ability of the fuel to adapt it's moisture content to humidity and temperature. A classification is possible into one of the four time-lag classes (1, 10, 100 or 1000 hours). The time-lag is defined as the time period required for a fuel particle to reach app. 63% of the difference between the initial moisture content and the equilibrium moisture content in a different milieu (temperature, humidity). The 63% comes from the solution of a step response function and is given by 1-1/e = 0.63 (Byram 1963). This characteristic of the fuel particle is strongly correlated to its diameter, so in fire management one estimates the time-lag period by measuring the particles´ diameter. Dead and down woody fuels have been grouped into classes that reflect the rate at which they can respond to changes in atmospheric conditions. (i.e., 1-hour = <0.6cm, 10-h = 0.6-2.5 cm, 100-h = 2.5-7.6 cm and 1000-h = 7.6-20.3cm diameter).

Table 1. Overview of the fuel load on the three experimental plots. The fuel classes are created by type and size of the material (time-lag; s. Byram 1963). The time-lag class 1000-hours is divided into "sound" and "rotten".

Plot #	**Duff layer**	**Fuel load in t/ha - Classification by time-lag classes**						
	cm	**Grass**	**1**	**10**	**100**	**1000f**	**1000m**	**Total**
1	1.8	0.06	0.69	2.35	1.23	0.00	2.15	6.41
2	1.6	0.09	1.10	1.50	6.13	1.74	0.65	11.12
3	1.9	1.8	0.40	2.11	16.08	6.16	3.56	13.31

The duff layer was relatively shallow with only 2-4 cm on the sandy soils. Partly, thick layers of dead grass residues were observed.

4.2 Weather situation before and during the fire

All weather information important for the fire behaviour were recorded by a meteorological station of the German Weather Service located on a meadow, app. 30m away from the experimental plots. Parameters measured in 35 cm and 2 m height included air temperature, humidity, wind speed and wind direction. On the day of the fire, the fire danger index was moderate (II on a scale of IV), there was no extreme fire danger in the area. The most important weather parameters during the experimental fires, measured in 35 cm height, were temperature (26...30 °C) and humidity (40...45%). The wind was gusty and varied between 0.5...1.7 m s^{-1}. This was one reason for different rate of spread observed during the experiment.

4.3 Observations

Although the fuel was not extreme dry and the fire danger index was moderate, the situation was typical for a summer day in the region - most fires occur on a background like this. Additionally, it was the aim of this study, to create a moderate surface fire and not an intensive crowning fire. Table 2 shows the fuel load for the three plots and the fuel humidity right before the fire was started.

Table 2. Overview of fuel load and fuel moisture, as they were used as input parameters in the fire simulator BEHAVE. The fuel is composed of dead branches, needles, grass and the top duff layer (O_L and O_F). Additionally the weather parameters used for the fire modelling, derived from the weather data (air temperature and humidity, wind speed [min, mean, max] in a height of 35 cm).

Plot #	**Fuel load** **[Grass + litter + Duff (O_L und O_F)]**			**Moisture content (%)**					**Air Temp.**	**Humidity**	**Wind speed**
	1-h	**10-h**	**100-h**	**Grass (dead)**	**Grass (live)**	**1**	**10**	**100**	**°C**	**%**	**km h^{-1}**
I	3.49	5.09	1.23	28	100	9.7	12.8	13.0	28	44	3..6..10
II	3.85	4.24	6.13						29	42	5..8..12
III	694	4.85	16.08						25	47	4..7..11

The first plot was ignited at 13:47 under gusty wind conditions. A fireline at the border of the plot produced a continuous, rushing fire in the entire stand. Especially a thick grass belt (*Calamagrostis epigeios*) burned very intensive and accelerate the fire spread. Flames of up to 1.5 m length were recorded in this area.

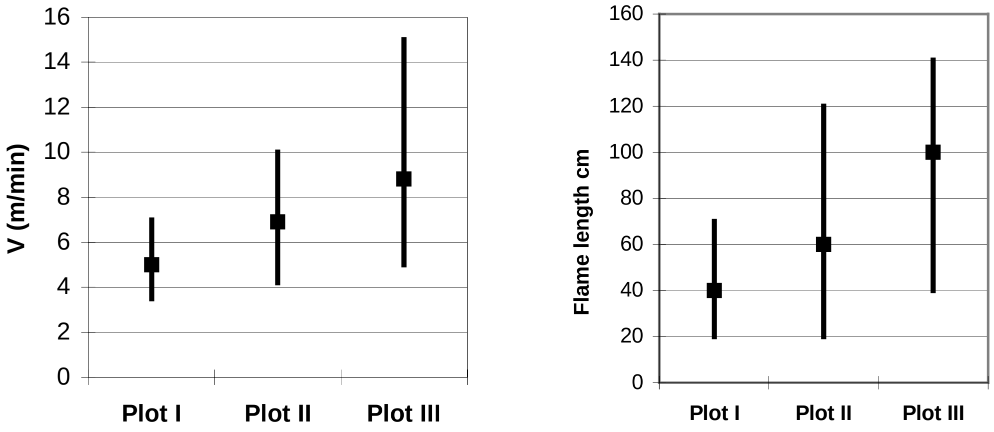

Figure 2. Rate of Spread (V) and Flame Length of the fire front observed in the three sites.

But after a while, the inhomogeneous distributed fuel caused a high diverse fire behaviour within the plot. Although the main fireline was proceeding steadily through the stand, the fire showed many different faces. Always driven by the wind, some parts with much grass or dry branches with red needles on them caused an intensive fire with flames up to 1.5 m. Other parts with less fuel load burned slowly and with very small flames - at some places the fire went out lacking fuel. Behind the fire front, smouldering combustion of the duff layer caused thick smoke plumes, the soil was covered with a thin, grey ash layer. Partially, thick branches or old stumps remained burning for a longer period. The fire consumed the entire litter layer, including needles, cones and grasses. Thick branches and the deeper duff layer was consumed partially.

Similar observations were made in Plot II, which was ignited afterwards and which had a similar fuel layer. Plot III showed some differences in fuel structure and total load. Although the pines had the same age as in the other both plots, the fuel load was higher due to a thinning five years before the experiment. A lot of logging residues were laying on the surface (higher amount of 100- and 1000-hr fuels), because of the higher light on the surface, a continuous grass layer had developed (Tab.2). Immediately after ignition a high intensity fire front roamed through the stand, carried by the grass layer. The heat ignited the logging residues, which burned long and produced a lot of energy.

A visual impression of the high variability of flame length and rate of spread gives Figure 3. Depending on ground vegetation and actual wind speed flames varied between 20 and 150 cm in length (Fig.5), the rate of spread between 3 and 9.5 m min^{-1} (Fig.5). Given a certain wind speed, grass layers accelerated fire spread. The top litter layer (O_L) and the grass were the main carrier of the fire. It should be noted, that the grass load on these plots were relatively low (0.3…1 t ha^{-1}), in similar pine stands grass loads of more than 12 t ha^{-1} have been observed (Millbacher 1992, in Bergmann 1993).

Figure 3. Visual impressions of the surface fires during the Brandenburg fire experiment.

4.4 Fire Modelling with BEHAVE

The main objective of the modelling approach was to describe the variables *Flame Length* and *Rate of Spread*. Most of the other fire characteristics and -effects (e.g. *Energy Release*, *Tree mortality* or *Probability of crown fire occurrence*) can be accurately derived from these two variables. For the validation of the BEHAVE-Model the measured input parameters of fuel load, fuel moisture content and the wind speed during the burn, were used (Tab.2). The BEHAVE output was then compared to the observed fire characteristics. The irregular wind speed during the experiment caused a high variance in observed fire spread, so that a simple comparison of mean values was not adequate. After comparing the observations with the predictions for fuel Model # 2 (Pine with grass), a custom fuel Model (#20) with adjusted parameters was created. Table 3 gives an overview of the input parameters used and the differences between Model # 2 and Model # 20.

The fuel bed depth as the average height of fuels above the top mineral soil varied within the plots, average values of 20 cm (Plot I and II) and 40 cm (Plot III) were calculated and used in the model.

Although the values for the Area/Volume Ratio can be adapted to the local conditions (similar species and similar ecosystem structure, pine with grass), the values for dead and live fuel heat content have to be adjusted. Missbach (1973) gives information about litter heat contents of European trees, herbs and grasses. According to his measurements, pine litter contains 21.259 kJ kg^{-1}, *Calamagrostis* sp. and *Deschampsia flexuosa* 19,380 and 18,711 kJ kg^{-1}, respectively. As an adjustment, the input value was chosen to be 21,000 kJ kg^{-1} for dead fuels.

Figures 4 and 5 show the simulation results and the observed fire characteristics. The BEHAVE-model calculates a fast increase of fire spread for higher wind speeds, with a range from 3 to 18 m min^{-1} under the observed wind speeds.

Table 3. Overview of all important input parameters for the BEHAVE simulation.

	Variable	**Unit**	**Standard-value [Mod2]**	**Sim.- Value [Mod20]**
Fuel/ Vegetation	1-h (0-0.6 cm)*	t ha^{-1}	4.48	s. Tab. 2
	10-h (0.6-2.5 cm)*	t ha^{-1}	2.24	
	100-h (2.5-7.6 cm)*	t ha^{-1}	1.12	
	Live Herbaceous Fuel Load	t ha^{-1}	1.12	
	Live Woody Fuel Load	t/ha^{-1}	0	0
	1-h Surface A/V Ratio**	m² m-³	9.843	9.843
	Live Herb A/V Ratio**	m² m-³	4.921	4.921
	Live Woody A/V Ratio**	m² m-³	4.921	4.921
	Fuel Bed Depth***	cm	30	20/20/40
	Dead Fuel Moist. of Ext.****	%	15	15
	Dead Fuel Heat Content	kJ kg^{-1}	18.622	21.000
	Live Fuel Heat Content	kJ kg^{-1}	18.622	19.000
Fuel Moisture	1-h / 10-h / 100-h*	%		s. Tab. 3
	Live Herbaceous	%		
	Live Woody	%		
Wetter	Midflame Wind Speed	km h^{-1}		s. Tab. 3
Terrain	Slope Steepness	%		0

*Time Lag classes
**Ratio Area/Volume (A/V)
***The average depth of the surface fuel
****The moisture content of the fuel above which a steady state rate of fire spread is not attainable

The high variance of observed spread rates is caused by fuel inhomogeneity and short-time changes in wind speed. Therefore, the observed values are visualized by red rectangle (Fig.4). Nevertheless it can be expected, that high spread rates are related to high wind speeds.

Given the high variability of fuel and wind, the fire behaviour is well met with the model. The calculated spread rates and flame lengths are in range of the observed values. It becomes visible, that Fuel Model # 2 overestimated the observed values, while the adjusted Model # 20 fits very well.

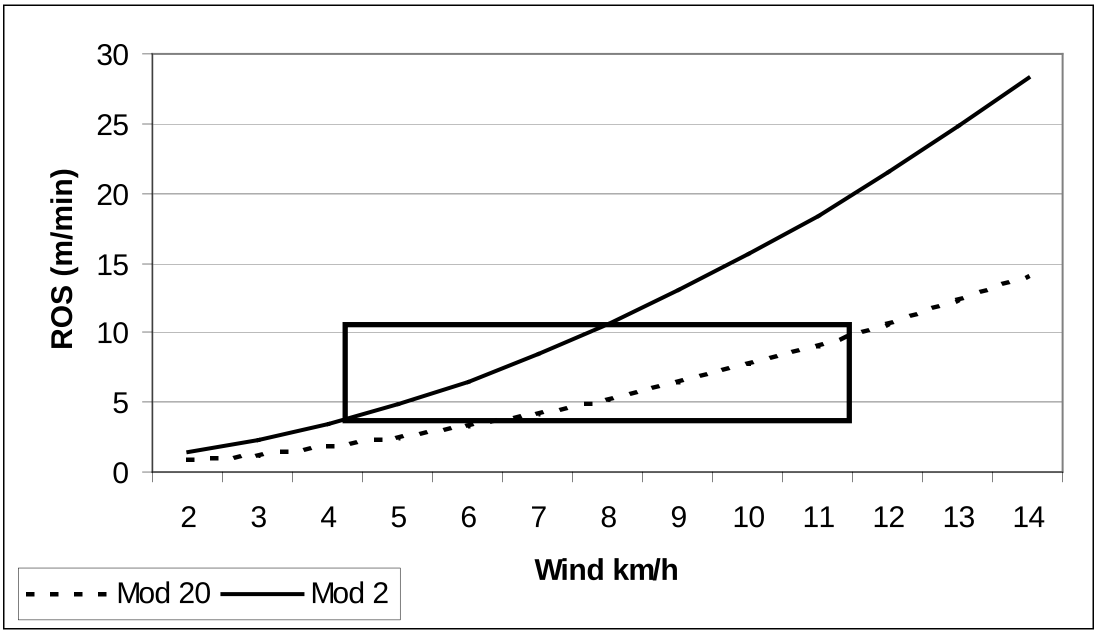

***Figure 4**.* Rate of Spread of the flaming front, modelled in BEHAVE over the wind speed. Comparative standard Model # 2 and the custom Model # 20. The red frame contains all observed spread rates/wind speed combinations.

The flame length as the second important fire characteristics, is modelled in both fuel models almost linear increasing. The observed values (red frame) are overestimated by the standard fuel Model # 2, the custom Model # 20 fits much better (Fig.6).

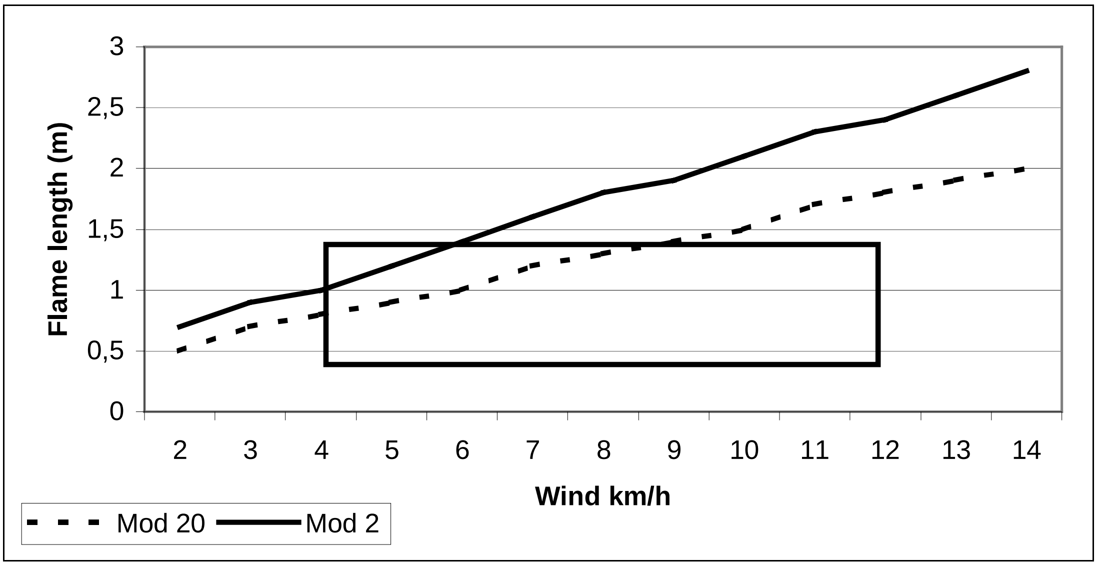

Figure 5. Simulated flame length of the fuel models used in this approach over the wind speed. The red frame contains all observed flame length/wind speed combinations. Model # 20 fits the reality best.

5. Second Step – Fire Modelling with FARSITE

Fire simulation on a landscape level

Using the results and the gained experience of the BEHAVE modelling, a FARSITE simulation was created. On a 1500 ha forest district (Federal forest in the Lausitz region, eastern Germany) fuel and stand information was collected to allow a classification into fuel models (Burgan and Rothermel 1984). Variables measured included fuel load, stand density, stand age and time since last thinning. Analysing the collected data, two parameters displayed a major role in determining fuel load and fuel structure. By knowing the stand age and the time since last thinning, an accurate prediction about the fuel situation in the stand can be given (Fig. 6,7).

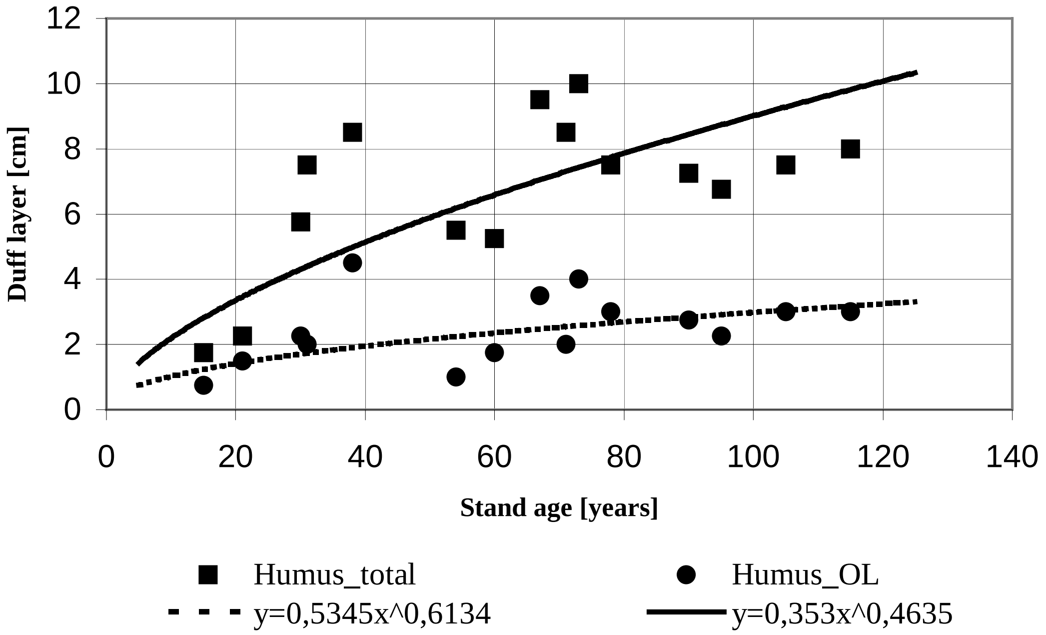

Figure 6. Duff layer amounts in relation to stand age. A steady built-up of dead material on the forest floor can be observed. Regression lines are for litter (OL) and duff (OF and OH).

The app. 140 stands of the sampling area were therefore classified into six groups by their age and the time since last thinning. In young pine stands (<20yrs.), the litter layer consisted mainly of 1 and 10 h fuels, grasses were not established yet. Older stands (21-40 yrs.) are similar structured, but with higher amounts of easily burnable fuels. In later stand stages (41-60 yrs.) grasses and shrubs invade due to increased light availability on the forest floor. Old stands are characterised by thick duff layers, a continuous grass layer and less dead and down material. In stands, where a thinning operation was conducted before < 5 years, very high amounts of dead and down material was observed (Tab.4). Usually, thinnings take place from stand age 35, so that younger stands are not effected.

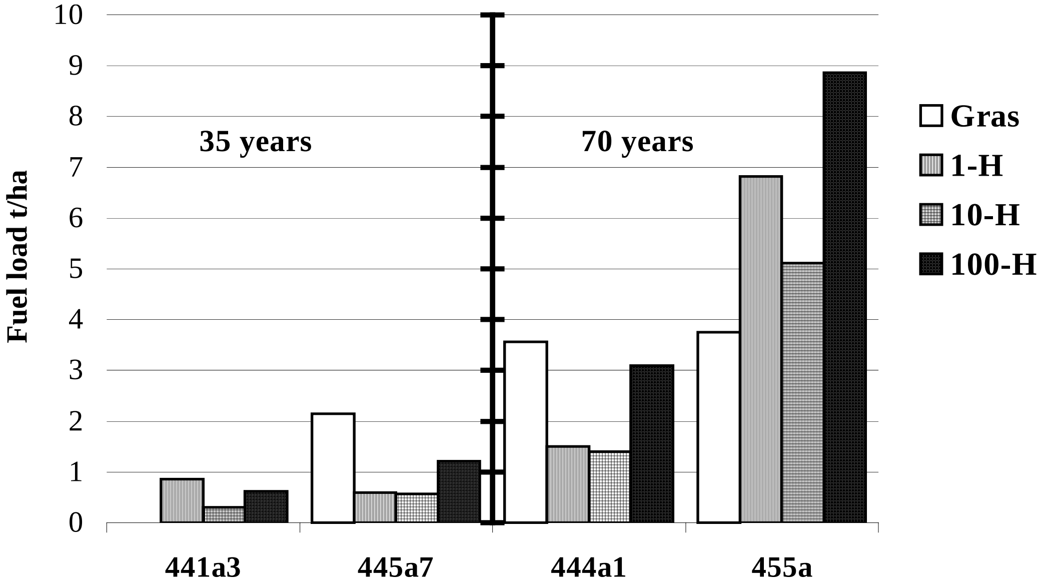

Figure 7. Fuel load in stands with different time since thinning. In young stands (35 years) a thinning and the increased light availability causes a grass invasion. In older stands (70 years) the thinning increases the dead and down material.

Table 4. Custom fuel models for pine stands of different age. Fuel loads of the different fuel classes were used as input parameter in FARSITE. All other simulation parameters were adapted from the evaluated BEHAVE model (Tab.3).

Model #	**Stand Age & Thinning Regime**	**Grass**	**1-h**	**10-h**	**100-h**	**Fuel bed depth cm**
			t ha^{-1}			
21	<20 J.	0	7.81	7.61	0	0.15
22	21-60 J.	0	8.06	11.7	4.09	0.2
23	61-100 J.	0.78	8,13	13.43	2.56	0.2
24	>101 J.	0.54	11.61	17.84	1.02	0.15
25	Thinning< 5J.	0.42	10.27	20.57	6.47	0.3

For the fire simulation, a digital landscape was created, using available information such as maps, DEM`s, stand boundaries, roads etc. A raster grid of 10 x 10 m was chosen to model the area accurately. Figure 8 shows the workable raster view of parts of the simulation area.

The fire simulation under a moderate fire danger situation shows the spread of the flaming front. Circles around the ignition point are the locations of the front in 1-hr intervals. The wind acts as the driving force of speed and direction of fire spread. The forest road north of the ignition point acts as a fire barrier, whereas roads south of the fire can not stop it. The simulation predicts that the fire will reach the young pine stand within nine hours, causing spot fires there, which will set the houses and the village on risk (Fig. 8).

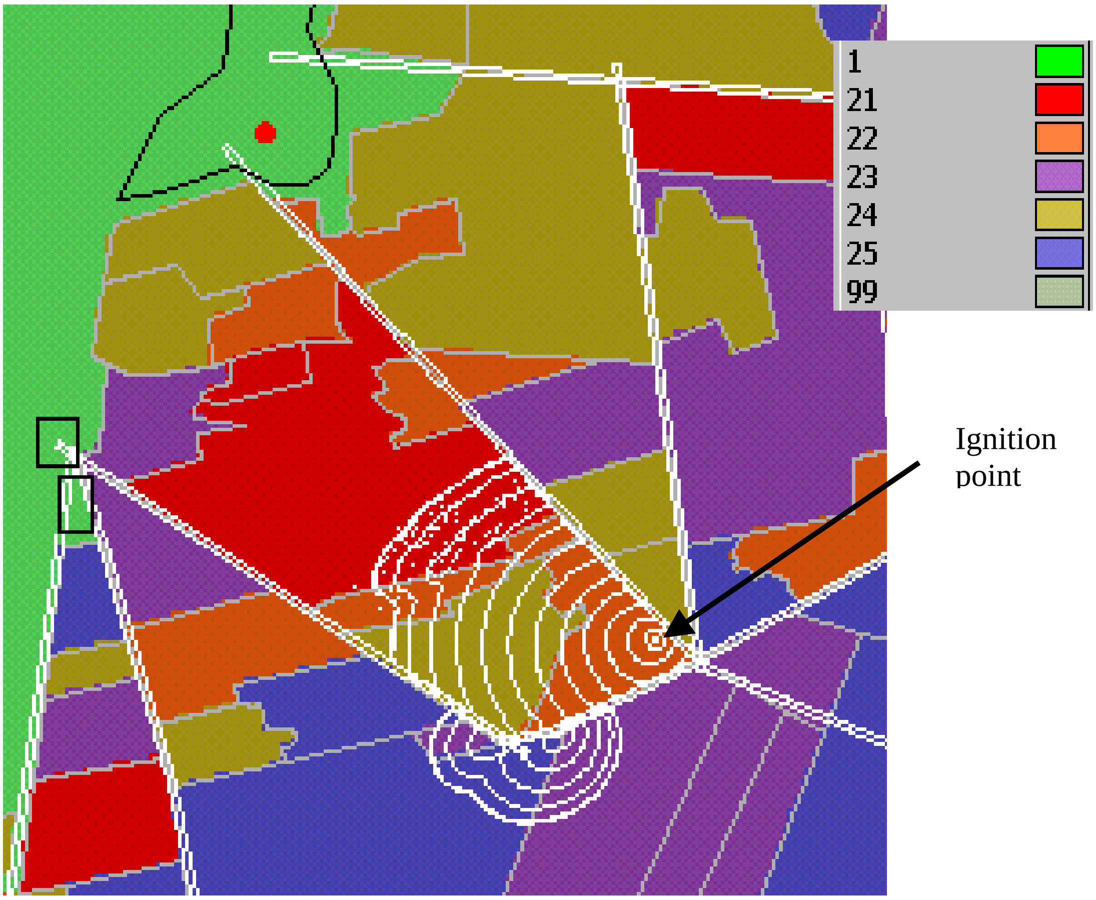

Figure 8. Visualization of parts of the simulation area. The forested area consists of stands, which were classified into different fuel models (Legend, Tab. 4). White lines are stand boundaries, black rectangles are houses or villages at risk. Big white lines are access roads, important for firefighting actions.

The fire simulation with FARSITE provides a lot of insight of what has to be expected from a particular fire situation. In this case, dispatching of fire fighting resources will be made much easier and effective. The focal points of suppression activities have to be the southern corner and the western part to protect the young stand from crowning fires. Available resources can be set into action where they can handle the situation (e.g. hand crews on the north side, fire engines on the south side, aerial attack in the western part).

6. Discussion

The complexity of forested ecosystems and the big number of (most time) dependent variables can cause much problems in the attempt to model a forest fire. Missbach

(1973) already reported about more or less successful attempts of Russian scientists to bring forest fire behaviour into mathematical equations (Sofronov 1965). The BEHAVE model, based on physical fire basics, was the first precise and easy-to-use tool to model fire behaviour.

Based on the results of this project, it can be assumed, that BEHAVE can be used under European conditions. A few adjustments to the actual fuel situation allow precise predictions about fire behaviour. Despite the mentioned high variability of fuels and wind conditions during the burn, the model output met the on-site observations. Rate of spread and the flame length were modelled accurately.

It should be noted, that these results are valid for only one type of forest ecosystem, with a certain structure. Other forest types with high fire hazards, such as young pine plantations have not been taken into account yet. Just the different fuel-structures and -loads of pine stands create a enormous research potential. Results of this research can be used to e.g. develop silvicultural methods to reduce fire hazards.

With the background of high nitrogen and calcium inputs in European forest ecosystems and the observed increase of grass dominance (Heinsdorf 1993, Bergmann 1993), the results of this project a frightening. Living and dead grasses are the main carrier of the fire front and are mainly responsible for the fast spread of the fire. On our research plots, the grass load can be classified as low, on more fertile soils with higher grass coverage a much higher fire intensity can be expected.

The wind and the directing factor for fire spread must be taken into special consideration. Slower winds cause a slow fire spread, therefore every object that reduces wind has an influence of a potential fire. From this point of view, silvicultural methods, such as thick understories or forest borders, become important.

The creation of a FARSITE simulation, based on the outcomes of the BEHAVE modelling approach and the good fit to the observed fire behaviour, should show clearly the potential of such a simulation. Although the produced fuel models have not been tested yet, the simulation results should not be too far from reality, as the same techniques have been used as in the BEHAVE model. However, the described methods and simulation tools offer a possibility to react on disasters such as forest fires. They allow an effective use of available resources and can give further insight in forest fire effects on the vegetation.

It should be also noted, that forest fire research, as described in this paper, is very intensive in planning and preparation. Not many forest land owner are willing to allow these kind of research, especially because they are most time destructive.

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