**Updated Dissertation Proposal:**
**Forest Fire Hazard Modeling in Germany**

## 1. Introduction

Wildfire is a disturbance in the ecological context. It plays a fundamental role in many ecosystems around the globe but not in Central Europe (Goldammer and Page, 2000). Neither local flora, nor fauna, nor human systems in Central Europe are adapted to it. Fire in this region is almost exclusively caused by human behavior, either purposefully or accidentally[1]. Climate change affects the ecosystems in which these fires burn. Extended drought periods and heat waves during spring and summer push vegetation to the limits of vitality, making it susceptible to fire and other disturbances. Hence, potential damages caused by fire are naturally expected to be amplified with more extreme climate conditions (Pachauri et al., 2015). Developments in recent decades in Germany show an increasing number of climatologically extreme summers with both more and larger wildfires (Bundesanstalt für Landwirtschaft und Ernährung, 2019).

While fires can cause ecological and economic damages in forests, they may also affect human-made structures. This is especially the case in the wildland-urban interface, degrading livelihoods of local population. Unlike countries with a long fire history (e.g. US, Canada, Portugal, Spain), German fire brigades are still in the process of building capacity in counteracting vegetation fires. Fire prevention built on an understanding of spatial variability in wildfire hazard plays a key role in Germany‘s path to adapting to this threat.

From a physical perspective, fire in a landscape is driven by three main components: terrain, climate and fuels (= burnable biomass) (Finney  et al., 2010). Comprehensive data on terrain and climate does exist for most locations on the planet, including Germany. The contrary is the case for fuels. Knowledge on their characteristics, however, is essential for understanding how fire moves through space and time. Consequently, it plays a crucial role when analyzing related hazard potential (Keane et al., 2001). Fuels can be distinguished into surface and canopy fuels. Canopy fuel characteristics, e.g. cover, can be investigated using modern remote sensing data like multi-spectral satellite imagery or Light-Detection-And-Ranging (LiDAR) point clouds. Surface fuels, typically located below two meters above ground, require different data collection methods. Standardized field sampling designs are employed to collect fine fuel components in forest stands (e.g. biomass of litter, duff, live/dead herbs and shrubs, branch wood). Their quantities depend on species composition, stand age and other site-specific conditions (Keane et al., 2001).

Forest fire hazard potential can be estimated by modeling fire behavior. Information on terrain, climate and fuels is involved in computer simulations of possible wildfire events. Fire behavior is expressed by intensity (flame length) and the rate of spread. Paired with information on burn probability one can draw conclusions on present fire hazard (Dillon et al., 2015). Further, fire risk can be assessed by integrating highly valued resources and assets (e.g. residential areas, infrastructure or habitats) (Thompson et al., 2011). Information on location and potential consequences of wildfires can help to inform strategic wildfire planning. It can pose a significantly more accurate planning tool compared to the existing, purely climatological fire danger indices as commonly used in Germany. Fire hazard information may help forest managers in adapting their stands to the challenges of climate change and in designing a more resilient environment. Further, it may support policy makers or landscape planners in making informed decisions regarding fire safety and livelihood.

1 Over 98 % of the area burned in 2019 was attributed to human behavior if the cause could be determined (Bundesanstalt für Landwirtschaft und Ernährung, 2019).

## 2. Related Work

2.1 Fire Behavior Models

The advancement of commonly used fire behavior models such as BEHAVE (Andrews, 1986), FARSITE (Finney, 1998), FSim (Finney et al., 2011) and FlamMap (Finney, 2015) has benefited from increased computational capabilities in recent decades. Yet, Rothermel's (1972) fire spread equation is still the central component of the majority of fire behavior models.

2.2 Vegetative Fuels

Fire behavior models require surface fuel information in the form of fire behavior fuel models (FBFMs). They can be understood as lists of physical parameters characterizing each surface fuel type (Albini, 1976). Sampling surface fuels is time- and cost-intensive (Keane et al., 2001) as they are highly variable in space (Keane et al., 2012). Several sets of standard FBFMs have been developed for the use of spatial fire behavior modeling software (Anderson, 1982, Scott and Burgan, 2005). Despite originating from field sampling, standard FBFMs are rather manipulated inputs calibrated to expected fire behavior results (Keane et al., 2001). Existing FBFMs originate from countries in which wildfires and their investigation have substantial history. Their physical parameters, hence, represent vegetation typical for these regions (e.g. North America, Australia, Mediterranean). Efforts have been made to translate existing FBFMs to new locations (Salis et al., 2009) or to establish custom FBFMs for new study areas (Dobrinkova et al., 2013, Brouwer et al., 2020), including locations in Germany (Hille, 2006). Olson (2020) investigated differences in fire behavior among three dominant tree species and two management regimes based on surface fuel sampling in the Haard forest (Northrhine-Westphalia (NRW), Germany).
Contributions of remote sensing methods to wildfire sciences include a wide range of sensors (e.g. multi- and hyper-spectral, laser scanning or radar) and platforms (e.g. satellites, aircraft or Unmanned Aerial Vehicles) (Chuvieco et al., 2020). Surface and canopy fuels were mapped regularly for the United States since the early 2000s within the LANDFIRE program using Landsat multi-spectral imagery (Rollins, 2009). These data products form the basis for national-scale fire hazard calculations (Dillon et al., 2015). Recently, most studies apply hybrid approaches by supporting spectral information with structural vegetation properties derived from LiDAR observations (Chuvieco et al., 2020).
Surface fuel type classification has been achieved using combinations of LiDAR and imagery from Sentinel-2 (Domingo et al., 2020, Sánchez Sánchez et al., 2018), Landsat 8 (Marino et al., 2016), QuickBird (Mutlu et al. 2008) or high-resolution airborne sensors (Erdody and Moskal, 2010, Garcia et al., 2011). Others highlight the limited benefit of optical information and rely exclusively on LiDAR point clouds for characterization of fuels (Stefanidou et al., 2020). Fuel types are consequently assigned to respective fuel models. As LiDAR data acquisition is cost-intensive it typically does not cover spatial extents of national or continental scale. Yet, efforts have been made to produce global (Pettinari and Chuvieco, 2016) and pan-European (Lanorte et al., 2001) surface fuel maps.
Canopy fuel characteristics are required by modeling software to predict fire initiation, propagation and growth (Chamberlain et al. 2021). Common variables include canopy cover (CC), canopy height (CH), canopy base height (CBH) and crown bulk density (CBD). Again, LiDAR data is adequate for deriving these forest structure variables (Anderson et al. 2005). CC [%], CH and CBH [both meters] can be derived from point clouds directly or through regression by calculating descriptive statistics and quantile bins in the vertical dimension. Numerous forest structure studies have yielded high accuracy with this approach (Hudak et al., 2016, Bright et al., 2017, Anderson et

al., 2005). In contrast, CBD [kg/m³] needs to be inferred as neither imagery nor laser returns can estimate canopy density directly. Yet, Riano et al. (2004) and Chamberlain et al. (2021) report good agreements in their LiDAR-based models ($R^2 > 0.65$). Few studies have leveraged full-waveform space-borne LiDAR-systems (as opposed to previously described discrete-return LiDAR) like GEDI for estimating global CH (Popatov et al., 2021) or ICESat-GLAS for deriving CC and CBD (Garcia et al., 2012). Alternatively, allometric equations from empirical field studies can be used to calculate CBD at plot-level if species, CH and CBH are known (Chamberlain et al., 2021). These are implemented e.g. in the Forest Vegetation Simulator software (Crookston and Dixon, 2005) and its Fire and Fuels Extension (Rebain et al., 2015), a tool predominantly used by forest managers. While the benefits of LiDAR for canopy fuel characterization have been demonstrated, these data are usually not available at larger scales. To map canopy fuels for the United States, Riley et al. (2021) used multi-spectral vegetation information, bio-physical variables and topography to impute the most similar forest inventory plot to each 30-meter-pixel. To improve their accuracy, Peterson et al. (2015) developed a tool which calibrates large canopy fuel data products using LiDAR point clouds which cover only subsets of the study area.

### 2.3 Fire Hazard Mapping

Wildfire hazard mapping has been conducted at regional scale to support wildlife conservation efforts in Canada (Stockdale et al., 2019). An optimal fire management strategy was developed by assessing a range of fuel treatment scenarios. The concept of continental-scale fire hazard calculations was previously proven by Finney et al. (2010). They used the Large Fire Simulator (FSim) to model burn probability and intensity for several thousand iterations of a contemporary fire season. Climatological conditions were artificially generated from historic climate data, while fire history data served for calibration. Adopting this method, Dillon et al. (2015) produced a wildfire hazard potential map at 270 meter pixel size for the United States. By introducing five intuitive magnitude levels they increased practicality for a large audience in the forest-, fire- and fuel management community.

## 3. Research Questions and Objectives

The objective of this dissertation research is to map wildfire hazard in Germany. Research questions focus on i) predicting characteristics of vegetative fuels using remote sensing and ii) estimating wildfire hazard in German landscapes through the application of fire behavior models. Specific research questions are:

i) How can remote sensing help quantify wildfire fuels?
  a) Which geospatial methods and technologies are suitable to assess fuels at regional or national scale?

ii) Which locations in Germany are most prone to wildfire under current climatic conditions?
  a) Which fuel characteristics promote high fire hazard?
  b) How might climate change affect fire hazard in the future?

## 4. Methods and Work Packages

### 4.1 WP1: Modeling Fire Behavior in the Haard Forest

This work package intends to demonstrate the potential for mapping fire behavior in a relatively small study area where both high quality field and remote sensing data are accessible. It is intended to tackle research questions i) and ii a).

Surface fuel samples (n=210) equally distributed among three dominant tree species (*Pinus sylvestris, Fagus sylvatica, Quercus rubra*) are available from Olson (2020). Resulting custom fuel models are assigned to the respective species in a land cover classification based on Sentinel-2 imagery. Field locations will be revisited to complement sampling data with measurements of diameter at breast height (DBH), CH and CBH for each tree inside the plot perimeter. Additional observations serve as input to allometric equations. This way canopy fuel metrics (CC, CH, CBH and CBD) will be calculated at plot level and serve as training and validation data for spatial predictions. Open LiDAR data for the state of NRW (~10 pts/m$^2$) will be used to i) predict canopy fuel metrics and ii) derive topography variables (elevation, slope, aspect). Predictors for application i) comprise up to 70 metrics describing point cloud characteristics and, hence, vertical forest structure. Both applications are accommodated by the lidR-package (Roussel et al. 2020) within the R-programming language.

Fire behavior is then calculated by running a large number of fire spread simulations within the study area using FlamMap6 software (Finney, 2015). Fuel and terrain variables described above serve as inputs. The climatological setting will be simplified significantly by defining representative wind speed and direction for the entire study area. For both parameters typical values for recent years will be extracted from the closest weather station. Different sets of parameters will describe individual scenarios of local weather throughout the fire season. Ignition points will be distributed randomly.

### 4.2 WP2: Mapping Canopy Fuels for Germany

The goal of this work package is to produce high-resolution canopy fuel variables for Germany, which will form the basis for future regional- and national-scale fire behavior modeling efforts. It intends to tackle research question i).

The national forest inventory program (Bundeswaldinventur, BWI) samples and publishes forest attributes at ~56,000 locations in ten-year-intervals (BMEL, 2016). From these data CH will be extracted directly, while CBH and CBD will again be approximated via species-specific allometric equations. To derive CC, LiDAR point clouds will be processed at sampling locations where available (NRW, Thüringen, potentially Brandenburg). Canopy characteristics at field sampling locations will serve as training points. Based on spatially continuous predictors from satellite observations the best-suitable BWI plot will be imputed. Predictors will include Sentinel-2 bands; several spectral vegetation indices (VIs), e.g. Normalized Difference VI, Enhanced VI, Soil-Adjusted VI; soil moisture; and different polarizations from Sentinel-1 data. This selection is intended to target both spectral and structural forest characteristics. Nearest-Neighbor imputation will be performed using the yaImpute-R-package (Crookston and Finley, 2008), specifically tailored to the purpose of forest attribute mapping.

4.3 WP3: Quantifying Forest Fire Hazard in Germany

This final work package intends to develop a fire hazard map at national scale. It intends to tackle research question ii).
Fire behavior calculations will rely on canopy fuel data produced in WP2. Additionally, topographic and climatic variables will be involved. Elevation, slope and aspect will be accessed via the Shuttle Radar Topography Mission (SRTM). Climate is represented by daily data from weather stations collected over the last 20 years, accessible through the German Weather Service (DWD). Temperature, relative humidity, solar radiation and precipitation are required to estimate fuel moisture. Wind speed and direction complete the climatic setting. The fire simulation software FSim will be used to model ten-thousands of hypothetical fire seasons. Artificial weather sequences with the same statistical properties as current records will be generated. Probability of ignition and fire behavior will be calculated based on daily weather scenarios. Final fire perimeters (spatial polygons) and gridded rate of spread and flame length will be aggregated over all seasons. Hazard potential values will reflect the frequency and intensity of fire in a given place. Fire history data from the past two decades will serve as calibration (mean fire size) and validation (point locations). As this information is collected by state administrations independently, quality and completeness may vary by region. The study area may be adjusted depending on the accessibility of fire history data.

## 5. Expected Results and Evaluation

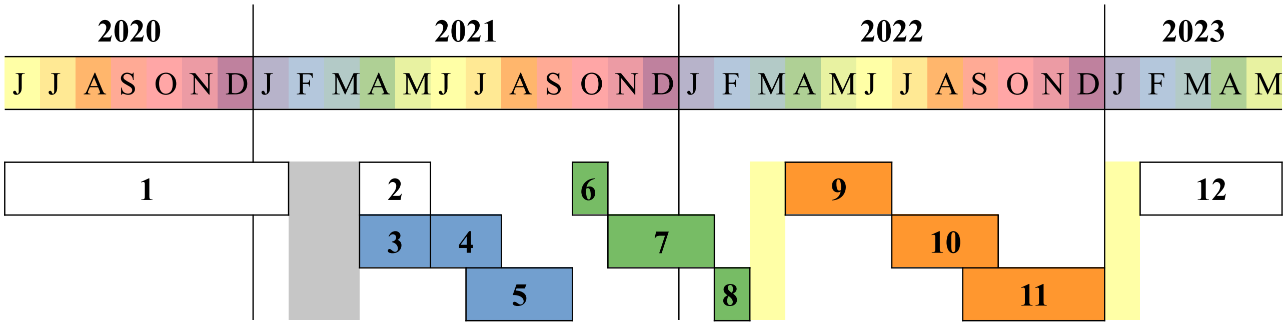
Results from WP1 will consist of pixel-based outputs of fire behavior characteristics across the landscape of interest. These include measures of fire intensity, rate of spread, and fire type (surface or crown). Maps of relative burn probability for specific weather conditions are also possible. Outputs cannot be validated with fire history data as the study area has not experienced fire in recent decades. However, model outputs from different climatological settings will be compared. Further, results based on a standard FBFM will be used to validate the sampled surface fuel models. Canopy structure derived from LiDAR will be validated previous to fire modeling using field data. The feasibility of canopy fuel predictions will be assessed using the Area Of Applicability concept (Meyer and Pebesma, 2021). More frequent and intense fire behavior is expected in needle-leaf dominated stands on steep terrain with significant understory.

Outcome of WP2 will be a spatial raster data set at 20 meter resolution covering the spatial extent of Germany. Each cell will contain the BWI plot ID that matches local vegetation properties best. All BWI field measurements can be extrapolated through a join operation. Mentioned LiDAR-derived metrics of CH and CC will serve as validation data. The final data product shall be distributed online for open access, e.g. via Google Earth Engine (community data set accompanied by an app) or Zenodo. It is intended to be openly accessible for future fire modeling efforts in Germany.

The final work package will produce a national wildfire hazard map. It will be displayed as i) continuous index values and ii) categorized in hazard classes. Low values will indicate that the area is unlikely to experience fire. Medium to high values indicate either a high probability of fire or an increased potential severity or both. Historic fire location data (2000-2020) collected by state forestry administrations serves as validation. Areas dominated by pine with a prevalent continental climate and soils susceptible to drought are expected to show the most extreme hazard rating. These areas can typically be found in north-eastern Germany. Results will be a suitable tool for forest and fire management. They, hence, will be communicated to forestry administrations.

**Schedule**

| Nr | Time | WP | Task |
|---|---|---|---|
| 1 | 06/20 - 01/21 | 1, 2, 3 | Literature review, data exploration, research questions |
| 2 | 04/21 - 05/21 | 1, 2, 3 | Proposal update |
| 3 | 04/21 - 05/21 | 1 | Skill-adaptation and processing LiDAR |
| 4 | 06/21 - 07/21 | 1 | Field sampling Haard forest, canopy fuel quantification, fire behavior modeling |
| 5 | 07/21 - 09/21 | 1 | Manuscript 1 |
| 6 | 10/21 | 2 | Generation of predictor variables |
| 7 | 11/21 – 01/22 | 2 | Canopy fuel imputation analysis |
| 8 | 02/22 | 2 | Manuscript 2 |
| 9 | 04/22 – 06/22 | 3 | Preparation climatic & topographic variables |
| 10 | 07/22 – 09/22 | 3 | Research visit Missoula Fire Science Lab*,<br>Fire hazard simulations with HPC |
| 11 | 09/22 – 12/22 | 3 | Manuscript 3 |
| 12 | 02/23 – 05/23 | 1, 2, 3 | Wrap-up and dissertation composition |
| | 02/21 - 03/21 | | Parental leave |
| | 03/22; 01/23 | | Buffer |




*A research visit to the Missoula Fire Sciences Laboratory, MT, USA, is planned in slot 10. Gregory Dillon, director of the Fire Modeling Institute, is willing to host me as a visiting researcher. He and his colleagues will assist and advise me in preparing data and modeling fire hazard using a high performance computation cluster. Funding will be applied for at DAAD and at the Fulbright Commission in fall 2021.

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