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The influence of climate and land cover on wildfire patterns in the conterminous United States

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Master degree thesis, 30 credits in Geomatics

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ABSTRACT

The occurrence of wildfires is greatly dependent on an ecoregions typical climate and land cover type. To investigate whether climate or land cover primarily lead to wildfires in the conterminous United States, wildfire events from 1999- 2010 are analyzed.

Wildfires are divided into years and eco-divisions, a sub-form of ecoregions. To assess whether warmer and dryer divisions are more severely affected by wildfires, the characteristic fire size is determined for every division. Smaller to medium sized fires are found to contribute most to the area burnt but no relationship between the fire size and the climate could be found.

The Nesterov Fire Index, Growing Degree Days and precipitation are calculated for all years at a 0.5° resolution and are pooled together with elevation, the fractions of land cover classes and the area burned per cell. Envelopes are created for all factors to assess the threshold from whereon fire bigger than $700m^2$ are not affected by fire anymore. Fire events seem to occur randomly, whereby evergreen forest and shrub land are identified to burn easily.

A Pearson correlation is performed between the parameters but only weak correlations are found. A weighted logistic regression is then carried out to test if more significant results are present when applying a GLM-model. Only slightly better correlations are found whereby the Nesterov Index scores as the best factor. A model selection is then done to inspect which factors explain the occurrence of wildfires best. Again the Nesterov Index scores as the best predictor, followed by the "others" land cover class (infrastructure, barren land, water bodies), evergreen forest and the GDD. The impact of these factors is not strong enough to conclude that climate or land cover is determined to be the dominant factor causing wildfires. However, climate sets the frame on where fires might occur and where they certainly do not.

More factors over a longer time period and on a smaller scale must be taken into account to predict the wildfire occurrence.

Keywords: Geography, Physical Geography, Ecosystem Analysis, Geomatics, Spatial Analysis, Wildfire, United States, Climate, Land Cover

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1 INTRODUCTION

Having knowledge about wildfires is important because it aids the in comprehension of the biogeochemical cycle and helps to adopt protective measures for the environment and human beings (Bowman et al. 2009). Fires have an influence on the global ecosystem, carbon cycle, atmospheric chemistry and climate (Bowman et al. 2009). The relationship between wildfires and those components is interactive and the positive feedback is perceptible over millions of years (Chaloner 1989). The effect of wildfires on climate change and atmospheric chemistry hereby has been researched in more detail than the potential effect of a changed climate on fire regimes. A lot of uncertainties exist (Dwyer et al. 2000). «A changing climate will profoundly affect the frequency, size and severity of fires in many regions and ecosystems in response to factors such as earlier snowmelt and severe or prolonged droughts, it will alter the growth, structure and composition of existing vegetation, with resulting changes in fuel structure and dead fuel loads» (Sommers et al. 2011).

In this thesis, a closer look at wildfires in the conterminous USA over the years 1999 - 2010 is taken. Wildfires are unplanned, unwanted fires where the goal is to put them out (Sommers et al. 2011). Climate and land cover are known factors for having a large influence on wildfires (Dwyer at al. 2000; Pyne et al. 1996). The task is to investigate and analyze what kind of influence these factors have when working with a larger geographical scale and which of these factors primarily leads to wildfires.

The hypothesis **"Climate is the dominant factor in the interannual and spatial variation which leads to wildfires in the United States"** is tested.

Two sub questions are answered:

- Which climate zones and land cover types are affected most by wildfires?
- How strong and in what way do land cover and climate affect the occurrence of wildfire in the United States?

In the first four chapters some background information about wildfires and fire parameters is given, together with information about the climate, vegetation and land cover in the USA. In chapter 5, the data is presented, followed by a chapter about the methodology used in this thesis. The results are presented in chapter 7 and discussed in the ensuing chapter 8. In the final chapter, a conclusion is given.

2 BACKGROUND

«Fire behavior is a product of the environment in which the fire is burning» (Pyne et al. 1996). The occurrence of wildfires greatly depends on the ecoregion (defined through climate and vegetation types) and the land use (Pyne et al. 1996).
Fuel loads, dry conditions and an ignition source must be available for a fire to ignite. Common ignition sources are lightning strikes, however the majority of fires are due to human impact (Archibald et al. 2009, Levine et al. 1995). The fuel loads with its shape, arrangement and moisture content, the meteorological conditions and the topography have an effect on the expansion of wildfire and the annual area burned (Krawchuk et al. 2009; Dwyer et al. 2000).
Fire weather elements include temperature, wind, humidity and precipitation. A rainy season with sufficient net primary production followed by a period characterized by hot days, dry winds and a humidity below 30% set favorable preconditions for large fires to inflame (Archibald et al. 2009; SACFS(a)). Higher temperatures and lower precipitation are existent at lower elevation levels, leading to dryer fuel in the early season, however more lightning strikes occur in higher altitudes. South and southwest facing aspects are exposed to more sunshine and are more favorable for a fire to ignite. Nevertheless, north facing slopes often have the heavier fuel load and therefore can experience more severe wildfires (Pyne et al. 1996). The steeper the slope, the faster fires can spread. The spread of fires hereby goes faster uphill than downhill (SACFS (b)). Lakes, rivers, rocks, moist soil situations and roads can act as fire barrier and, depending on the site accessibility and remedies available, the fire can be suppressed (Archibald et al. 2009).

It has been shown that a small number of large fires cause the majority of an area to become burnt (Archibald et al. 2009). Quantitatively, 10% of wildfires induced by lightning are responsible for about 90% of an area to become burnt in the United States (Dwyer et al. 2000; Crutzen & Andreae 1990). The burnt area is not necessarily lost area. Burning helps to shape the global biome distribution, to set desired conditions for early successional species to establish but also to keep the present species alive by preventing the vegetation from diseases and to give the biome the possibility to renew itself (see also chapter 3.3) (Bond & Keeley 2005).

Wildfires occur throughout the whole year and the burning seasons vary across the globe. Natural fires occur at the driest time of the year, which is normally at the end of the dry season, while human induced fires depend on management (Dwyer at al. 2000). Early dry season fires are ignited by pastoralists to stimulate re-growth or are set in natural parks around villages to prevent big fires and to reduce the total burnt area (Lehsten 2013; Archibald et al. 2009). Depending on the dryness of the fuel, different trace gases are released. Due to the higher amount of oxygen available in dry fuel, more carbon dioxide (CO_2) is released. Wetter fuel with less oxygen releases an augmented amount of volatile organic compounds (VOCs), carbon monoxide (CO) and methane (CH_4). Human controlled fires tend to be colder than natural fires and generate more trace gases (Scholes et al. 1996). Fires contribute largely to greenhouse gas emissions and can turn a carbon sink into a carbon source (See chapter 3.1 for more information about the impact of trace gases on the climate) (Archibald et al. 2009).

Different types of fires exist. Fires that smolder in the soil and burn organic material underneath the surface are so called ground fires. Surface fires burn, as the name states, at or near the surface where the lowest vegetation layer (grass, herbs) is present. Fires that burn above the surface through the canopy and arise from ground fire and surface fires are known as crown fires. In most instances a mix of ground, surface and crown fires appear (Pyne et al. 1996; Sommers et al. 2011).

2.1 FIRE REGIME

«Fire regimes are a critical foundation for understanding and describing the effects of changing climate on fire patterns and characterizing their combined impacts on vegetation and the carbon cycle» (Sommers et al. 2011). The regimes are useful to compare fires in different ecosystems (Sommers et al. 2011). There is a high probability that fire patterns will change in the near future since the occurrence of fire is tightly coupled with population density, land cover and global warming (Archibald et al. 2009). Fire regimes are defined by elements such as fuel type, intensity, severity, frequency, fire type, fire size or fire season (Bond & Keeley 2005).

Grass, dead leaf or stem material in the ground and on the surface are fuel types which the fire uses to obtain energy. The amount of energy released by a fire is called intensity. It is defined by fire heating, flame length and rate of spread. In combination with wind, fires have the capability to spread and extend very fast. Severity stands for the measure of ecosystem impact. The fire frequency tells how often an area is affected by fire and gives information about the time period. It can be divided into fire rotation interval (time required to burn the equivalent of an area, also called fire cycle) and fire return interval (time interval between fires at a site, also called Mean Fire Interval). Fire types distinguish different kinds of fires such as wildfires or suppression fires. The fire size gives information about the area burned and fire season about the start and end date of a fire (Bond & Keeley 2005; Chaloner 1989).

3 WILDFIRES IN THE UNITED STATES

In the United States, 60,000 to 80,000 fires (all kinds of fire types) ignite each year, burning up to approximately 25,000 km^2 a year (for the years 2000 - 2010). Extensive fires with large burnt areas are occurring in higher quantities than in past decades (National Interagency Fire Center 2009). However, smaller fires occur more often than larger fires (Malamud et al. 2005).

The United States is home to many different climate zones and microclimates. Because different climate zones are present, different land cover and vegetation types occur throughout the country. The occurrence, severity and size of wildfires are not uniform across the country and therefore a regional heterogeneity exists.

Within the United States, the south central states and the pacific west (including Arizona and the area between the Great Lakes up past Lake Winnipeg in Canada) are the regions that are most commonly affected by wildfires (Dwyer et al. 2000). Sommers et al. (2011) also identify the South Eastern U.S. to be severely affected. The fire season in most parts of North America typically takes place between May and August. The season becomes longer when moving southwards and persists throughout the majority of the year in the Southwest, southern California and southeastern states (Pyne et al. 1996). Larger fires take place more commonly in western USA and Florida when compared to the East. The East is more densely populated and landscapes are therefore more heterogeneous and fragmented, which reduces the fuel continuity and keeps fires at bay. Forests in the West have also become fragmented but the areas have been replaced with shrub and grassland, which are more flammable than the agricultural and urban land in the East. Furthermore, the West has favorable natural conditions such as hot summers with frequent droughts and steeper terrains than the East, which is characterized by deciduous forests, snowy winters and summer rainfalls. The Pacific Northwest, the area around the Great Lakes and the very north east show the largest fire intervals (Malamud et al. 2005; Archibald et al. 2009).

3.1 WILDFIRE AND CLIMATE

A system often used to classify common vegetation and climate characteristics are "eco-divisions", a subclass of the "ecoregions" introduced by Robert G. Bailey in the year 1995.

Ecoregions vary over space and time and are a useful classification system to estimate the scale at which climate patterns impact an ecoregion (Bailey 1995). Eco-divisions are applicable from several months through multiple years, providing information about interannual climate variations and climate change, taking fire seasons and fire regime changes into account (Sommers et al. 2011).
The Eastern United States is dominated by a humid subtropical climate and the middle to northern East by a humid continental and boreal climate. The Middle to Western part of the United States is mainly dominated by semi-arid to arid climate and alpine climate in the mountains. In the pacific West, an oceanic climate can be found in the north and a Mediterranean climate in the south (Bailey 1995). The south pacific coast for instance experiences moderate temperatures throughout the whole year. Moving a few kilometers inland, the winter temperatures are lower and considerably higher temperatures and droughts mark the summers. Several synoptic weather types such as Santa Ana fall-winds in southern California favor wildfire (Pyne et al. 1996). Detailed descriptive information about different climates across the United States can be found in appendix A.

The increasing number of wildfires and the typical climate patterns reinforce each other via a positive feedback loop (Levine et al. 1995). «Weather and climate are the most important factors influencing the geographical distribution of wildfires and fire activity and these factors are changing due to anthropogenic climate change» (Flannigan et al. 2006). Fire management could become more challenging as climate change modifies the meteorological conditions and vegetation types, which will affect the fire regimes (Bowman et al. 2009). A warmer climate and precipitation changes lead to severe fire weather with decreased fuel moisture, increased fuel load, larger burned areas, favorable ignition conditions, a longer fire season and a greater risk of extreme fire events (Flannigan et al. 2006; IPCC 2007).
El Niño/Southern Oscillation events (ENSO) are climatic events which have an influence on the occurrence of wildfires (Baldenhofer 2014). While a typical La Niña year is characterized by hard winters with above-average rain and snowfall in several parts of the United States, Southern California and the Eastern states are affected by warmer and drier winters with only 70% of normal rainfall which favors the emergence of wildfires (Beckage et al. 2003; Kitzberger et al. 2001; Baldenhofer 2014). Beckage et al. (2003) found that in the Everglades (Florida) a higher frequency of lightning strikes occur during La Niña events which increases

the chance of a fire to fan. Kitzberger et al. (2001) note that an increased lightning frequency during La Niña events is also characteristic of the south-western United States. ENSO events are presumed to become more intense and to reappear more frequently in the future as a result of climate change (Timmermann et al. 1999).

In turn, wildfires release trace gases and aerosols which impact the climate. Through biomass burning, large amounts of CO_2 and black carbon aerosols (BC) are emitted. While CO_2 acts as a greenhouse gas, BC reduces the snow albedo and, with its strong solar radiation absorption properties, BC has a warming impact on the climate (Keywood et al. 2013; Dwyer et al. 2000; Bowman et al. 2009). By hampering the formation of cloud droplets for instance, BC have an impact on the precipitation regime (Arora & Boer 2005). Other chemically active gases released through biomass burning, including CH_4, CO, nitrogen oxides (NOx), VOC or carbonaceous and sulfate containing particles are less significant than CO_2 but still have a considerable impact on climate change (see figure 1). These compounds lead to the production of ozone (O_3) in the troposphere, which serves as a greenhouse gas. On the other hand, methyl chloride (CH_3Cl) destroys stratospheric ozone, which is needed to protect living organisms from UVB-rays (Levine et al. 1995; Keywood et al. 2013; Crutzen & Andreae 1990). «Present estimates suggest that global wildfires contribute about 20% of fossil fuel carbon emissions into the atmosphere» (Keywood et al. 2013). Pyne et al (1996) state that 39% of the total amount of organic carbon released to the atmosphere is due to biomass burning. Fire emissions in the United States are estimated to release 2-3% of the total U.S. CO_2 emission and around 30% of the total U.S. BC emission (Larkin et al. 2014). The emitted gases and smoke plumes have more than just a regional impact. The

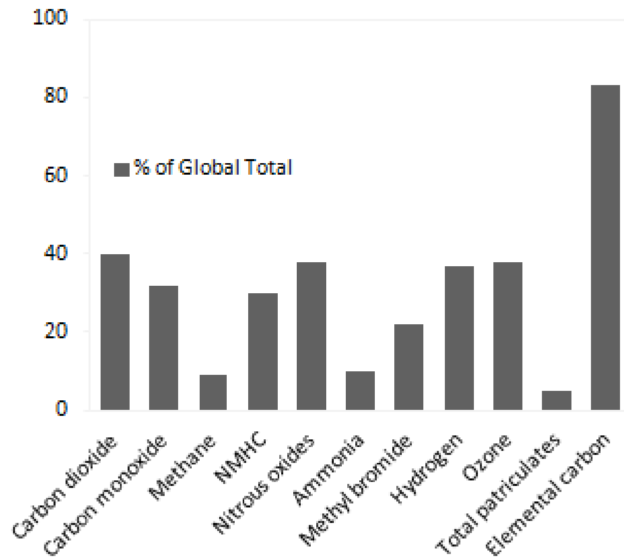


Figure 1: Contribution of biomass burning (as percentage of global emissions) to atmospheric chemistry (Cicerone 1994)

consequences on atmospheric composition and climate are globally perceptible (Keywood et al. 2013).

If the present condition continues without change, in the year 2100 the United States predicts that the greatest temperature rise will occur at high latitudes during the winter season. The snowpack will be reduced and snowmelts will begin earlier. Precipitation changes (frequency, intensity) will vary across the country. During the summer, the inner continent and the South West will experience less precipitation than the summer months experience today. They will become dryer, whilst other areas will experience an increase in precipitation in both frequency and intensity. Humidity, wind speed (increases), ignitions, cloudiness and fuel conditions will change with a significant impact on fire activity (Flannigan et al. 2006; IPCC 2007).
The Southwest will undergo the most significant change. It will move towards a more arid climate and will experience a change in the fire regime. Fires are assumed to become more frequent, intense and extensive. In the United States widely spread mixed conifer forests will experience larger fire activities (Evans et al. 2011). Climate change can be held to account for reduced biomass growth, increased mortality and a change in fauna that will alter the cohabitation of species. Beetles will proliferate and damage trees, which is only one example of how the vegetation will become more combustible to wildfire events (Evans et al. 2011).

3.2 Wildfire and Land Cover

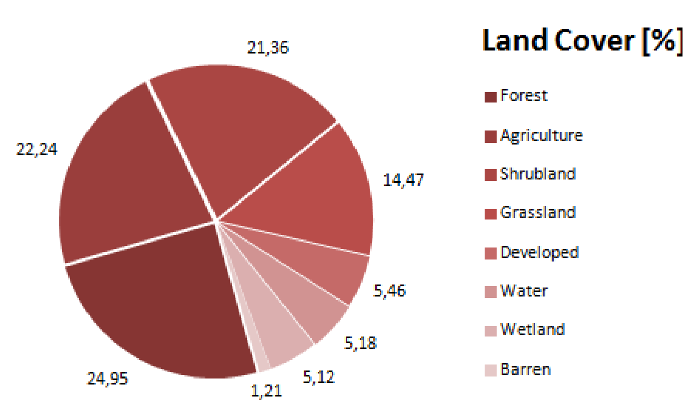


Figure 2: Land Cover in the U.S., 2006 (MRLC 2013)

Land cover deals with physical land types and describes the surface cover on the ground. Figure 2 gives an overview of the major land cover types in the U.S. as documented in the year 2006. The dominant land cover classes are deciduous, evergreen and mixed forests (24.95%), agricultural land such as pasture and cropland (22.24%), shrubland (21.36%) and grasslands (14.47%) followed by developed areas (5.46%), water bodies (5.18%), wetlands (5.12%) and barren land (1.21%) (MRLC 2013; USDA 2013).

The East is characterized by humid forest landscapes, temperate broadleaf and mixed forests are preponderant. Temperate conifer forests are found in the Southeast. Towards the West, grassland and arid areas become more present. Conifer forests can further be found in mountain landscapes and in the Northwest. Deciduous and mixed forests as well as chaparral occur in the pacific west (Gebhardt et al. 2007; Lee et al. 2009; Bailey 1995). An illustration of different land cover types across the United States can be found in chapter 5.3.

Land cover type has an effect on the spread of wildfires. Developed areas or barren land for instance provide less fuel than forests and are therefore less flammable (Pyne et al. 1996). If a fire ignites, the fires will in turn have an effect on the land cover type and vegetation by altering the soil composition for example. The land use form has also an effect on fire behavior. Humans use fire as a tool in land management for various reasons such as clearing the ground for crops, the installation of fire breaks, the extirpation of parasites and to prepare the field for re-growth (see Chapter 2) (Dwyer et al. 2000). Apart from all the benefits that fire brings to land use, several unwanted transformations can occur when combining fire management with excessive grazing and unfavorable weather conditions, including losing control over the fire spread. Soil erosions, changes in hydrological cycles, increased water runoff and modifications in the soil's nutrient status are just a few examples (Dwyer et al. 2000).

As stated earlier, reduced fuel continuity and fragmented landscapes caused by intensive land use result in smaller fires. However, a greater human activity in land management can also alter the ignition regime and result in an increase of fire occurrences (Archibald et al. 2009). Archibald et al. (2009) state that it is unproven which effect should be given greater weight in determining the total burnt area. In their research, which is based in Africa, less area was burned in densely populated domains with a higher human impact.

3.3 WILDFIRE AND VEGETATION

Alongside climate and soil, wildfires have a large influence over the occurrence of vegetation. In turn, vegetation again influences the wildfire activity (Malamud et al. 2005). Not all vegetation types are equally flammable and different vegetation compositions show different burning patterns. High tree cover delivers fuel but also indicates that a moist environment is present, which leads to unfavorable burning conditions. Low tree cover on the other hand indicates that dry conditions mark the environment leading to low fuel production and infrequent fires (Lehsten et al. 2010). A diversified vegetation composition with fuel heterogeneity has the greatest chance of withstanding wildfires (Evans et al. 2011). Woody plant structures are more affected by fire than other plant structures. Savannah fires for instance are predominant among all vegetation types worldwide (Levine et al. 1995). Chaparral shrubland, which is shaped by a Mediterranean climate, experiences large crown fires that free sizeable areas. Other vegetation types found in the western USA such as the mixed conifer forests show a different burning pattern. Mixed conifer forests burn with a mix of fire types. Surface fires normally leave big trees alive while crown fires destroy the whole forest (Dwyer et al. 2000; Bond & Keeley 2005).

The regeneration process differs between vegetation types. Chaparral forest and grasslands regenerate easily while the mixed conifer forest requires a certain distance to parent trees to assure re-growth. Burned vegetation has a greater chance of survival in a changing climate. The gaps created by fire disturbances are less affected by fires since a certain amount of fuel must be re-accumulated to make it burnable. This enables young vegetation to grow big enough to withstand certain fires. The height of the plants therefore is lower when fires occur frequently (Bond & Keeley 2005; Malamud et al. 2005; Evans et al. 2011). Not only does the vegetation type determine on how fast regeneration is possible but it also determines the fire intensity (Flannigan et al. 2006). High-intensity fires may create inhospitable habitats whereas less intense fires result in a more diversified environment with favorable cover, food and resources. However, this is strongly dependant on the species and some plants might require high intensity fires to germinate (Pyne et al. 1996).

The impact fire has on the vegetation and ecosystem is more complex than just the number of fires detected and the area burnt. Even though grassland burns extensively on a frequent basis (roughly once in ten years), the amount of biomass destroyed is most likely still smaller than the amount of biomass burned in a coniferous forest fire (Dwyer et al. 2000).

4 FIRE PARAMETERS

Two fire parameters are introduced in this section to facilitate the understanding of the methodology, presented in chapter 6. The fire weather elements (temperature, humidity and precipitation) are used to calculate the fire parameters (Nesterov Index and GDD (also precipitation is referred to as fire parameter)), which represent the climate.

4.1 FIRE DANGER

Fire danger sums up the risk that is persistent for a fire to ignite and spread in an area. Different fire danger indices exist to assess the daily fire potential (Sommers et al. 2011; Chandler et al. 1983; Langholz & Schmidtmayer 1993). Because of the simple structure and application, the Nesterov Index (I_N) often is used to estimate fire danger (table 1). The Nesterov fire-hazard-index (I_N) takes the daily mean temperature [T, °C], the dew point temperature [D, °C] (calculated from humidity) and precipitation into account. The sum is calculated for all days with positive temperatures and precipitation less than 3mm [W]. The index drops back to zero and the process starts over new when a day with precipitation greater than 3 mm occurs. The threshold of 3 mm is set by default and is used in most research (Lehsten et al. 2010 (research in Africa); Nesterov 1949 (research in boreal areas)) working with the Nesterov Index. The Formula is $I_N = \sum_{i=1}^{W}(Ti - Di) * Ti$ (Lehsten et al. 2010; Nesterov 1949).

Table 1: Nesterov Fire Index Classification

Fire Danger	Nesterov Index
Minimal	0 - 300
Moderate	301 - 1000
High	1001 - 4000
Extreme	> 4000

4.2 GROWING DEGREE DAYS

Growing degree days (GDD) can be used as an approximate measure of the growth of vegetation during the growing season. Vegetation grows only when the temperature is high enough. The value obtained is however used for the whole year. A base temperature of 5 °C is taken as threshold (set by default) (McMaster et al. 1997). The GDD are calculated by comparing the daily mean temperature (average of the maximum temperature (T_{max}) and minimum temperature (T_{min}) of each day) to the base temperature (T_{base}). The formula is GDD $= \frac{Tmax+Tmin}{2} - T_{base}$. If the daily temperature is lower than T_{base}, the daily degree day is set to zero. Adding the daily degree day of all previous days including the actual day gives the GDD for a particular day (McMaster et al. 1997; Lehsten et al. 2013). The temperature summation can be used to compare the heat resources of regions to one other.

5 DATA

All data used in this thesis is composed to the same extent and transformed to the following geographical coordinate system and datum:

Geographic Coordinate System: GCS_WGS_1984
Datum: D_WGS_1984

The "USA Contiguous Albers Equal Area Conic USGS" projected coordinate system is used to perform area calculations with the fire data.

5.1 FIRE DATA

The fire data is taken from Landfire (http://www.landfire.gov/index.php). Landfire is an interagency vegetation, fire and fuel characteristic mapping program, supported by the United States Geology Service (USGS). Landfire data products are best used at national, regional or large landscape scale (Landfire 2014). The fire data is delivered as a vector format and distinguishes different fire types, whereas only wildfires (ground, surface and crown wildfires) are taken into account in this study. All fire events bigger than 0.02 acres (≈ 80m^2) that occurred in the United States between 1999 and 2010 are included in the data set (figure 3). Landfire compiled the data from different sources, including Landsat satellite imagery and user contributed data. Due to the different sources used to compile the data set and due to the poor quality of very small fires, only fires bigger than 700m^2 are selected in this thesis to avoid wrongly classified fire events (Malamud et al. 2005). The data provides the information of the agency that reported the fire, the year the fire took place, the exact coordinates, the burned area [m^2] and, for some fires, the exact start and end date of each fire and its severity.

5.2 BAILEY'S ECOREGIONS

The data set for Bailey's ecoregions is created by the USDA Forest Service and the National Atlas of the United States (NAUS) and is downloaded as a shapefile from the NAUS webpage (http://nationalatlas.gov/atlasftp.html). Eco-divisions represent climate regions and are differentiated based on precipitation levels and temperature (appendix A) (NAUS 2013). The data available is classified into eco-divisions to allow spatial analyses with regard to factors that alter fire regimes at the national level and for large regional areas (Malamud et al. 2005).

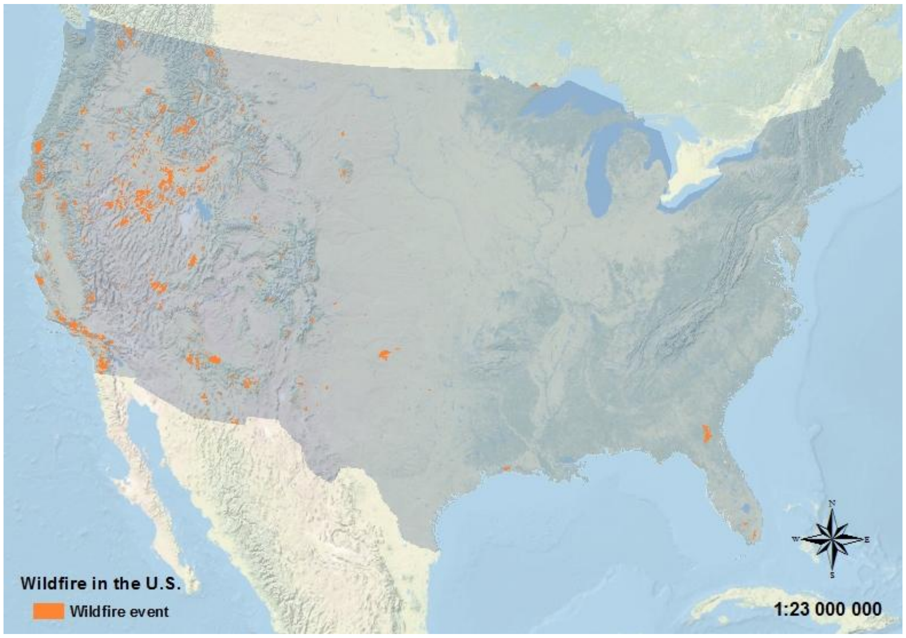


Figure 3: Wildfires in the U.S (1999 - 2010)

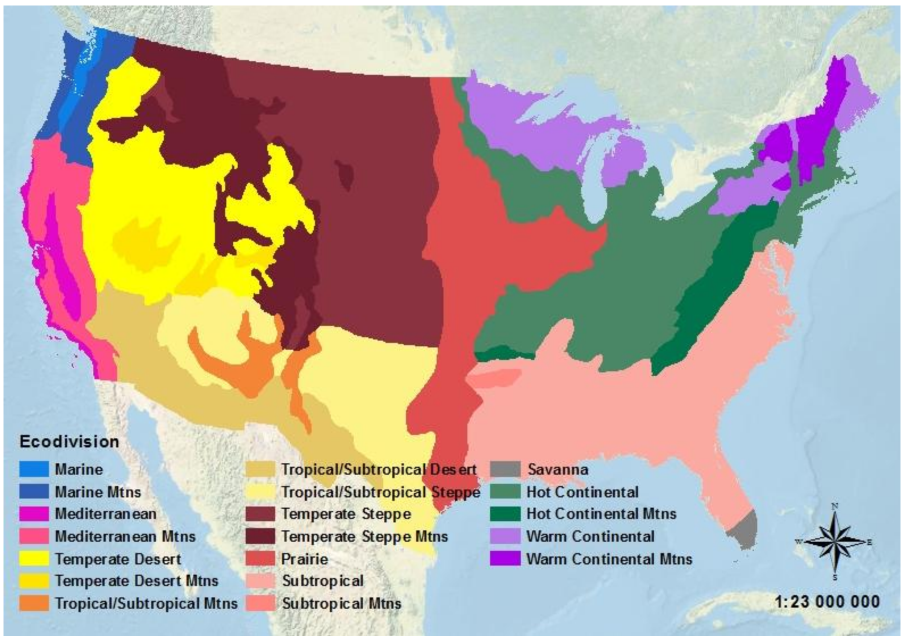


Figure 4: Bailey's eco-division in the U.S. (NAUS 2013)

5.3 LAND COVER DATA

The National Land Cover Database 2006 (NLCD 2006) data is taken from the multi-resolution land characteristics consortium webpage (http://www.mrlc.gov/) which is supported by the USGS. The data set is available in raster format and distinguishes 16 different land cover classes for the conterminous U.S. in the year 2006. It is delivered at a 30m pixel resolution. The NLCD 2006 is based on the unsupervised classification of the Landsat ETM+ satellite (2013). Figure 5 gives an overview of the NLCD 2006 data set for the whole of the United States, showing the 11 most common land cover types.

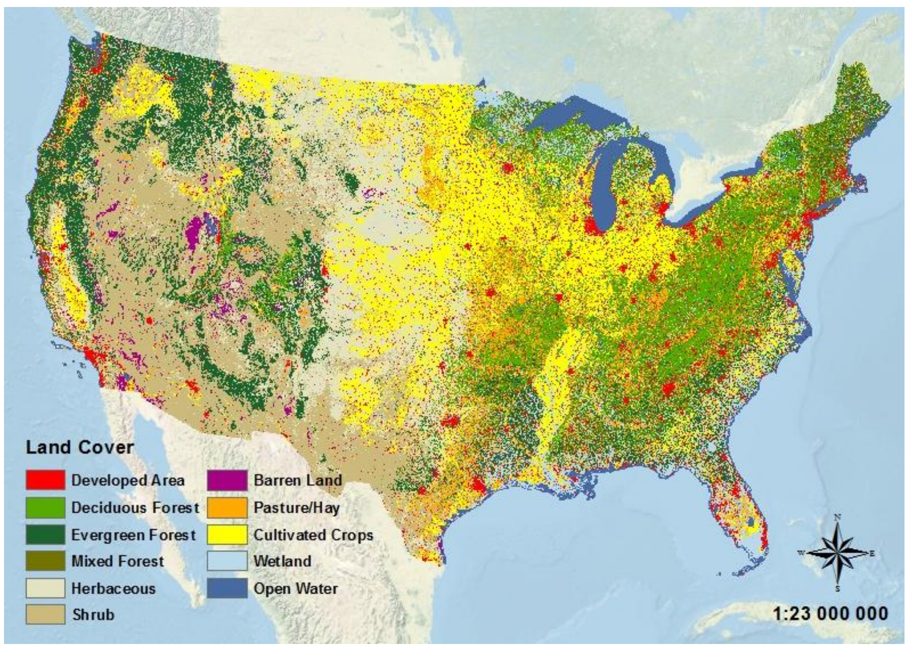


Figure 5: NLCD2006 - Land Cover of the United States (MRLC 2013)

5.4 CLIMATE DATA

The WATCH-Forcing-Data-ERA-Interim (WFDEI) climate data set hosted by the International Institute for Applied System Analysis (IIASA) (ftp.iiasa.ac.at) is used in this thesis. WFDEI data is delivered in a netCDF format in the WSG84 geographical coordinate system with a 0.5° grid resolution. It includes eight meteorological variables at a 3-hour time interval with daily averages. The data is available for the years 1979 - 2010 (WFDEI 2012).

The air temperature, humidity and precipitation (fire weather elements) from the years 2000 - 2010 are taken from this data set.

- Air temperature (tair_WFDEI):2m (above surface) instantaneous air temperature [K]
- Humidity (Qair_WFDEI): 2m instantaneous specific humidity [kg/kg]
- Precipitation (Rainf_WFDEI_GPCC): Rainfall rate [kg/m^2s]
  (WFDEI 2012)

5.5 ELEVATION

The elevation data is also made available through IIASA. The data set is simultaneously delivered in the netCDF format with a 0.5° grid resolution. The average elevation in each grid cell is given in meters. No information about how the data is collected, errors and omissions of the data measurement is stated. The elevation does not change interannually but is still included in this thesis because it can increase the explanatory power of the multiple GLMs (see chapter 6.3) by enhancing the altitudinal effect of changes in precipitation and GDD.

6 METHODOLOGY

In the first part of the methodology, an exploratory analysis is carried out. A closer look at the data is taken. The number of fires and area burned are investigated in more detail. The characteristic fire size is determined for each year and eco-division to see if there is a relationship between climate and the fire occurrences. The United States is then gridded into a 0.5° resolution. The fractions of each land cover and the area burned are calculated for each cell.

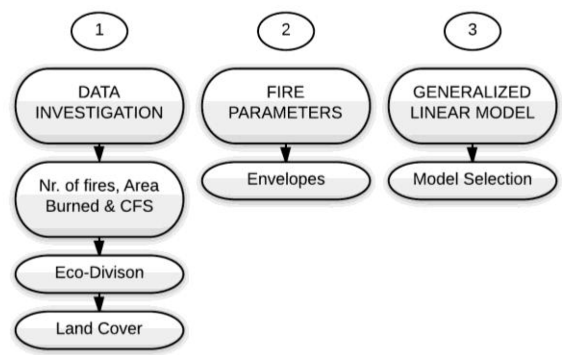


Figure 6: Methodology Flowchart

In the second part, the fire parameter and elevation values are calculated for each cell and pooled together with the fractions of land cover and area burned. Calculations concerning the area burned and the factors are then performed. Envelopes are created for each factor, assessing the thresholds where fires are no longer detected.

In the last part, a GLM regression is carried out to assess which factor primarily influences the occurrence of wildfires in the United States. A model selection is then completed in order to see which factors significantly improve the prediction of fire patterns (see figure 6).

The R 3.1.0 -script (including the steps carried out in ArcGIS 10) and the Matlab R2013a-script can be found in appendix B.

6.1 DATA INVESTIGATION

An explorative analysis is carried out in order to obtain an impression of the temporal and spatial distribution of the fire events.

6.1.1 NUMBER OF FIRES, AREA BURNED AND CHARACTERISTIC FIRE SIZE

A look at the number of fires and the size of the area burned per year and for the decade is taken. Because the start date of too many fire months is not stated, no analysis for the fire season within the years is performed.

In the next step the characteristic fire size (CFS) is calculated. The CFS indicates the fire class which contributes the most to the total area burned (see figure 7). It is an implement which registers important facets of the fire characteristics and therefore can be used to research the causes of the relationship between fire regimes to both ecoregions as well as climate. First, the fires are grouped according to their size (30 groups are created, based on the natural variation). The number of fires per group is then multiplied with the mean fire size of each group. The data follows a normal distribution when working with the logarithmic scale. The CFS is the value where the maximum of the normal distributed density histogram is reached (Lehsten et al. 2014).

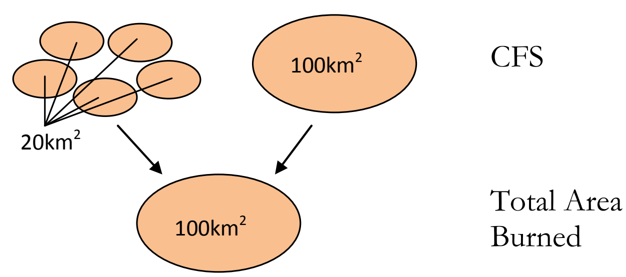


Figure 7: Schematic Illustration of CFS

Example: Either one big fire occurs and burns an area of 100km² or several small fires occur of 20km² each and burn an area of 100km². In the first case, 100km² is the characteristic fire size, in the second case, 20km² is he CFS.

To see if the characteristic size depends on the year, a time series analysis with a two year moving average window is performed to appraise if and how the characteristic fire size changed over the decade.

6.1.2 ECO-DIVISION

In ArcGIS, an overlay with the fire data and the eco-divisions is performed in order to investigate the number of fires and the burned areas in each eco-division, as well as to see which climate zones are affected the most by wildfires. Correlations between the area burned per eco-division and the mean values (years 2000 - 2010) of the fire parameters are performed to assess if a relationship exists.

The characteristic fire size for each eco-division with more than 100 fire events (Malamud et al. 2005) is estimated to highlight the climatic and biome influence on the area burned. A threshold of 100 fire events is chosen to minimize the uncertainties in estimates for the characteristic fire sizes.

A correlation between the CFS and the mean values of the GDD, precipitation and Nesterov Fire Index is then performed to assess if there is a relationship between the division-climate and the CFS.

6.1.3 LAND COVER

The land cover data was recorded in the year 2006 but is used for all years covered in this thesis. Because the land cover raster is large in size and fires do not occur in all 16 classes, similar classes are combined, resulting in eight main classes (evergreen forest, deciduous forest, mixed forest, grasslands, shrub, pasture/crops, wetland and others (infrastructure, water, barren land).

The study area is gridded into a 0.5° resolution raster. The fractions of the land cover classes as well as the fractions of the burned area per year are calculated for each 0.5° cell. This execution requests the information of the exact cell area of each cell in the raster as well as the information about the area covered by each land cover class and the fires size per cell. Because the grid resolution is given in degrees, the cell areas vary by latitude and are not equally in size over the study area. With the "area" function in R, the cell sizes are calculated by using the longitudinal span of the center of each cell. To determine the land cover fractions, the 30x30m resolution land cover raster with the reduced classes is taken and a count is performed to assess how many pixels per class occur in each cell. To divide the fires into cells, the identity function in ArcGIS is used. By applying the dissolve function, the fires in each cell per year are aggregated together and the area burned per cell can be calculated. To add the data together, a join based on the latitude and longitude of the data is performed.

To obtain insight into which land cover classes wildfire mainly occurs, an overlay with the fire data and the land cover data set is done. By gridding the data, the exact location of the fires within the cells is lost. To still be able to identify which land cover classes are affected the most by fire, the dominating land cover fraction of every cell is marked as the responsible class for causing a fire. A count is performed to see how often fires occurred /did not occur in each cell with the dominant land cover class.

6.2 FIRE PARAMETERS

Based on the WATCH data set, the precipitation (in mm/day), the GDD and the Nesterov Index are calculated for each year and cell in the 0.5° grid. These variables are then pooled together with the elevation, land cover and area burned per cell.

To identify whether a relationship exists between the fire parameters and the burned area, a linear correlation is performed in R. The following formula is applied: $y = mx + b$, whereby m is the slope, b is the intercept, x is the independent variable (climate and land cover) and y is the dependent variable (fraction of area burned per grid cell) (see appendix B). The Pearson correlation assumes the data to be in interval and ratio scale, linear and normal distributed.

6.2.1 ENVELOPES

For each variable (fire parameters, land cover and elevation), an envelope is created. The envelope indicates the value range for which fire occurrences can be observed. The value range of each factor is constricted by a maximum and minimum value for where fire events are most likely to occur. Outside the envelope, no fire events occur. The minimum and maximum values are dependent on the calculated fractions of the area burned. To minimize possible uncertainties in these calculations, all cells with an area burned up to 5% are set to zero and are treated as cells without fire events.

As a corollary, a very small number of fire occurrences (equivalent to a large fraction of unburned area) are expected for observations outside of this envelope. This task is performed in Matlab.

6.3 GENERALIZED LINEAR MODEL

The logistic regression is a type of generalized linear model (GLM). It is used to analyze the relationship between independent variables and a binary dependent variable. It is a convenient tool to assess the impact of a number of factors (GDD, precipitation, Nesterov Index, Elevation, land cover) on the probability that a fire will ignite (Lehsten et al. 2010). In other words the GLM is used to see if the size of a fire (dependent variable) can be predicted by climate and land cover (independent variables). Instead of using a binary variable (cell with fire - cell without fire), the fractions of the area burned per cell are taken to estimate the probability of a fire to ignite to obtain a weighted result. The logarithm of the variable is used when the relation between the fraction of area burned and the independent variable appears to be skewed. A unimodal response is used for all variables. Before including all independent factors in the regression, it is first performed for each factor separately. This task is performed in Matlab.

6.3.1 MODEL SELECTION

Because not all factors are good fire predictors, a model selection with the sequential feature selection function is performed in Matlab. The best predictor subset is chosen and parameters which do not help to explain the occurrence of wildfires are excluded from the final model. The sequential feature selection selects stepwise (forward) all factors that help minimize the mean squared error (MSE). To eliminate the influence of chance, only parameters that reduce the deviance significantly (p-value <0.05) are taken into the end model. A 10-fold cross-validation without stratification is applied to test how accurate the model is. Ten test runs are carried out whereby the grid cells automatically are separated into ten equal sized subsamples (Mathwork does not state how big those samples are). In each run, one subsample is used as validation data whereas the remaining samples are used as training data. The MSE is calculated as the average from each run (Mathworks (a)).

Because the sequential feature selection did not select factors to help predict the fire occurrence, it is assumed that the model penalizes the factors too strongly. Instead of the 10-fold cross validation, a bootstrapping procedure is applied to see if factors get selected. The grid cells (including the fire parameters, elevation, land cover) were resampled 359 times. Because the procedure runs very slowly, a random number between 300 and 400 is chosen - a range that does not exceed the capacity. For each grid cell-observation, a random number between 0 - 1 is created. If the number is below the threshold of 0.8, the observation is chosen to be in the training data set. In each run, the best predictor subset is determined. The predictors that are selected in more than 50% of the runs used because they are helpful in explaining fire occurrences.

7 RESULTS

The results derived from the analysis presented in the methodology section are stated in this chapter.

7.1 DATA INVESTIGATION

According to Bailey's eco-division data set, the conterminous United States consists of 7,957,445 km^2 land, excluding the area of the great lakes.

7.1.1 NUMBER OF FIRES, CHARACTERISTIC FIRE SIZE AND AREA BURNED

From 1999 - 2010, a total of 15,081 wildfire events were recorded, burning an area of 124,660 km^2. (1.5% of the total area of the conterminous U.S.). It cannot be excluded that some areas burned on multiple occasions.

The bar plot (figure 8) shows an overview of the number of fires and the total area burned per year (see also table 2).

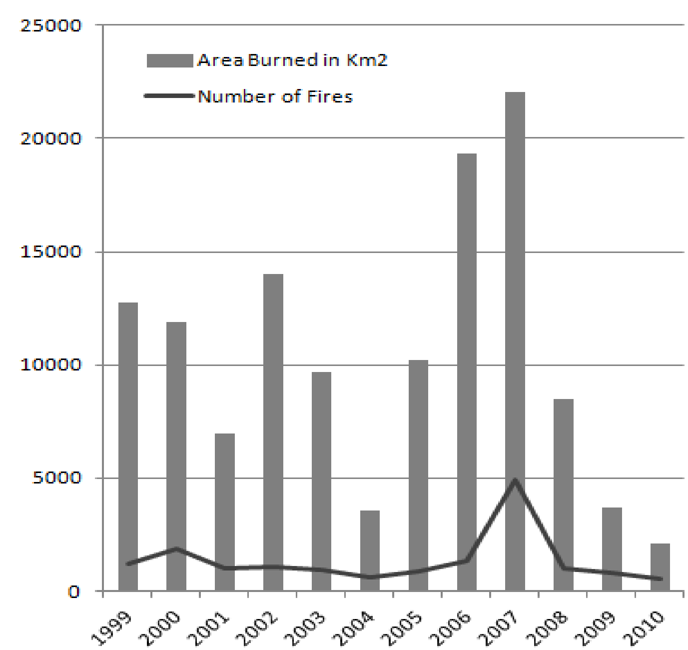


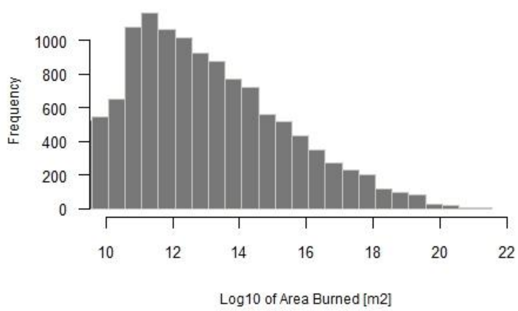
Figure 8: Area Burned and Number of Fires per Year

On average, 1256 fires burned 10,388 km^2 per year. An anomaly in the years 2006 and 2007 is detected, causing the data to become skewed. In 2006, 1309 fires burned up to 19,347 km^2 and in 2007, 4062 fires burned up to 22,030 km^2. Excluding these years gives a mean of 971 fires and a burned area of 8328 km^2 per year. However, these years are within the range of a normal distribution. With $R^2 = 0.569$ (including the years 2006/2007) and a p-value < 0.05, a strong linear correlation exists between the number of fires and the total area burned per year.

The logarithmic frequency histogram (figure 9) shows that the fire sizes are not normally distributed. Small fire events occur more frequently than larger events with an (almost) exponential decrease.

The characteristic fire size (CFS) over the whole decade equals to 0.08km^2 (or in other terms around 12 soccer fields) (table 2), meaning that smaller to medium sized fires contribute the most to the area burned.

No distinct trend is revealed when assessing the CFS over the decade (figure 10). However, a 10 year time span is a too short period to obtain a useful result for a time series analysis.



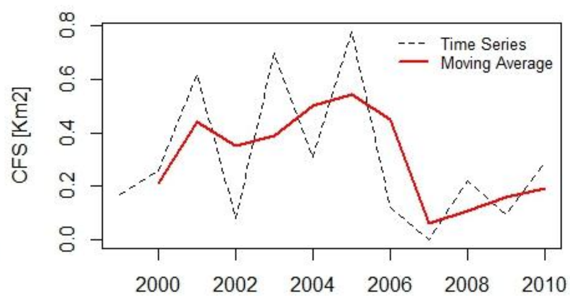


Figure 9 (left): Frequency Histogram of Area Burned 1999 - 2010
Figure 10 (right): Time Series and Moving Average

Table 2: Nr. of Fires and Area Burned per Year

* Instead of taking the mean (0.3), the CFS is calculated over all years directly, resulting in a CFS of 0.08km^2
-- No calculation is pefromed forthe year 1999

Year	Nr. of fires	Area burned [km^2]	CFS [km^2]
2010	539	2083	0.292
2009	805	3682	0.096
2008	959	8476	0.219
2007	4062	22029	0.0009
2006	1309	19347	0.123
2005	869	10200	0.777
2004	580	3564	0.307
2003	896	9688	0.695
2002	1004	14023	0.08
2001	987	6954	0.619
2000	1890	11877	0.258
1999	1181	12738	--
Total	**15,064**	**124,660**	**0.3***

Table 2 gives an overview of the area burned and the characteristic fire size (CFS) per year (1999 - 2010). The numbers are rounded.

7.1.2 ECO-DIVISION

The overlay analysis (table 3) shows that most fire events occurred in the Temperate Steppe Mountain (Mnt) division (7412 fires over all years), the Temperate Desert division (4745) and the Mediterranean Mnt division (4695). However, proportionally to the area of the eco-division, the most extensive burned area is found in the Mediterranean Mnt division (11% of the division), the Temperate Desert division (6%), the Tropical/Subtropical Desert Mnt

Table 3: Nr. of Fires and Area Burned per Eco-division 1999 - 2010

Area [km2] and Area [%] show the area of the eco-division and its size in percentage compared to the U.S.
Nr. of Fires shows the amount of fires per division
Area burned [km2] and Area burned [%] show the area burned of the eco-division and its size in percentage compared to the division
CFS: Characteristic Fire Size per division
-- Area burned [%]: Sum of proportions of area burned per division does not provide a meaningful result
-- CFS [km²]: Division with less than 100 fire events

Eco-division	Area [km²]	Area [%]	Nr. of fires	Area burned [km²]	Area burned [%]	CFS [km²]
Mediterranean Mnt	241610	3.04	4695	27649	11.44	0.255
Temperate Desert	696942	8.78	4745	44659	6.4	0.462
Trop./Subtrop. Desert Mnt.	130238	1.64	864	6680	5.12	0.050
Mediterranean	89213	1.12	937	3272	3.66	0.129
Savannah	20875	0.26	207	663	3.17	0.911
Temperate Steppe Mnt	585601	7.37	7412	16013	2.73	0.0008
Temperate Desert Mnt	113099	1.42	270	2754	2.43	0.693
Subtropical Mnt	22841	0.29	24	37	1.62	--
Marine Mnt	306341	3.9	269	4091	1.33	1.062
Trop./Subtrop. Steppe	658809	8.3	459	5956	0.9	0.198
Trop./Subtrop. Desert	449103	5.66	467	3363	0.74	0.27
Subtropical	1069621	13.47	715	6715	0.62	8.862
Temperate Steppe	1101346	13.88	475	1648	0.14	0.075
Warm Continental	382569	4.82	233	368	0.10	0.064
Hot Continental Mnt	193102	2.54	283	133	0.07	0.021
Hot Continental	970603	12.23	809	264	0.03	0.078
Prairie	773446	9.74	27	131	0.02	--
Warm Continental Mnt	113391	1.43	0	0	0	--
Marine	38695	0.49	0	0	0	--
Total	**7,957,445**	**100**	**22,891**	**124,396**	**--**	**0.08**

division (5%) the Mediterranean division (4%) and the Savannah division (3%).
Because some fire events are located on border regions of the eco-divisions and therefore are present in more than one division, the total number of fires is higher in table 3 than table 2. The intersect function in ArcGIS splits these "boarder fires" in two parts and when looking at the individual count of all eco-divisions, some fires are listed twice. The total area burned is not affected by double counts since the geometry calculation only takes the area in the eco-division into account. The difference for the total area burned in the tables is very small. When calculating with the total number of fires, the value from table 2 is taken.

Figure 11 visualizes what is stated in table 3 (CFS). It can be seen that the fire events align well within the eco-divisions. The area burned per eco-division is not normally distributed but exponentially, meaning that some divisions (for instance the Mediterranean Mnt, the Temperate Desert and the Tropical / Subtropical Desert Mnt division) are significantly ($P < 0.005$) more severely affected by wildfire than others (e.g. Warm Continental Mnt or Marine division). The $R^2 = 0.611$ ($P < 0.005$) implies that there is a strong correlation between the area burned and the number of fires in the eco-divisions.

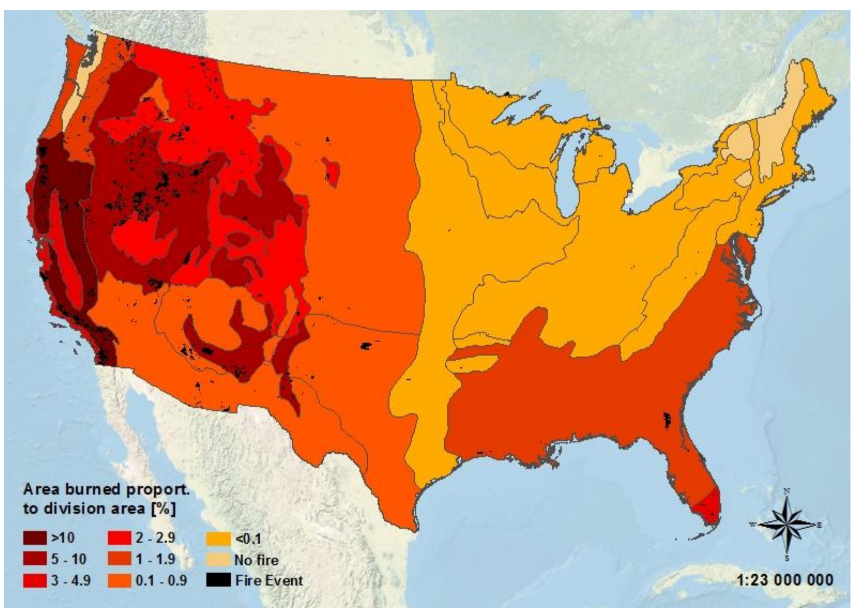


Figure 11: Area burned in proportion to area of eco-divisions

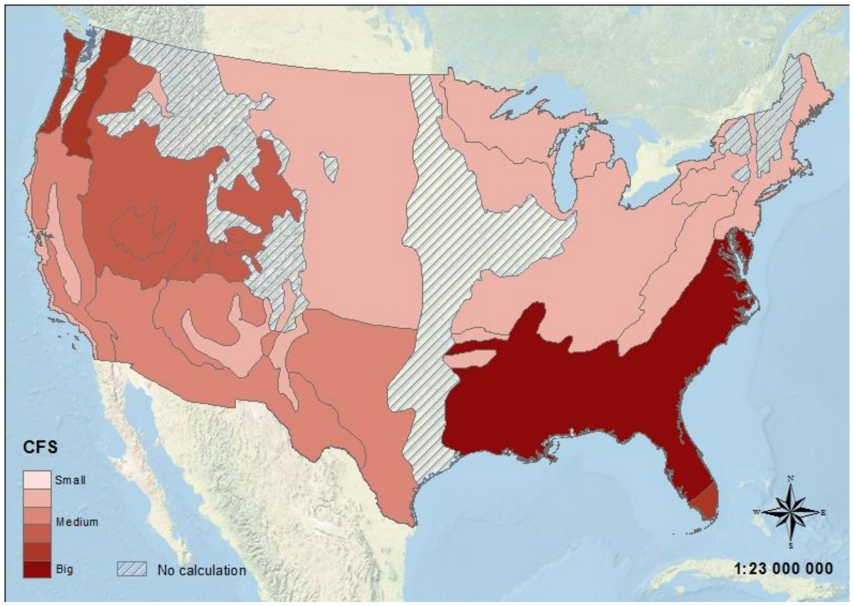


Figure 12: CFS per Eco-Division

It can be seen that the CFSs in eco-divisions located in the South East and the West of the country are larger (but still rather small than large) than the CFSs in other parts (figure 12). The subtropical division in the East has an eight times bigger CFS than the division ranked second.

No significant correlation could be found between the CFSs and the area burned per eco-division. Also no correlations are found between CFSs and the mean of the fire parameters per division over the past decade nor between the mean fire parameters and the area burned per eco-division.

7.1.3 LAND COVER

The calculated fractions of the land cover classes across the U.S. are in agreement with the statistics from MRLC (chapter 3.2).

When drawing a comparison between the biggest land cover fraction and the presence or absence of fires per cells, it can be assessed that more than one quarter of all cells with evergreen forest or shrub land as the dominating land cover class experienced fires over the past decade. Fires occurred in 11% of all cells (table 4). It is possible that the same cell burned several times. No fire burns more than 50% of the grid cell. The distribution of the burned areas seems to be in accordance with the description in chapter 3.

Table 4: Occurrence of fire in Land Cover Classes

Land Cover	Cells without Fire	Cells with Fire	[%]
Evergreen	3585	1013	28.3
Shrub	6189	1599	25.8
Grassland	4769	335	7
Wetland	771	32	4.2
Deciduous	4759	180	3.8
Other	1549	57	3.7
Planted	8787	222	2.5
Mixed	231	0	0
Total	**30640**	**3438**	**11.2**

7.2 Fire Parameters

Table 5 gives an overview over all correlation coefficients. With a p-value smaller than 0.001, all correlations reach statistical significance. No correlation is found between the GDD and Nesterov Index and between the fire size and the fire parameters. The very weak negative relationship between the area burned and the GDD can be explained by the fact that an unimodal rather than a linear relationship exits. A moderate negative correlation is found between the precipitation and the Nesterov Fire Index, meaning that it is more likely for the index to increase when the yearly precipitation is low (29% of the variation can be explained (R^2=0.29)). With a shared variance of 15%, a moderate positive correlation between precipitation and GDD exists. Sufficient precipitation leads to an increase in GDD. A moderate negative correlation exists between the

Table 5: Correlation Coeff. (Pearson) & Coeff. of Determination between Parameters

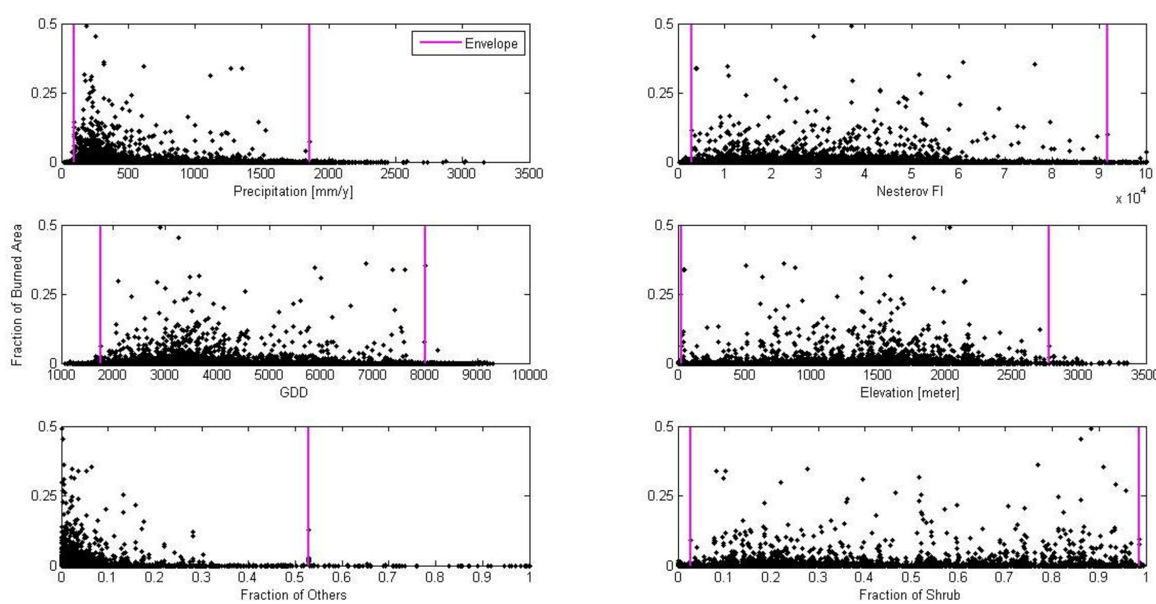
Nr: Number of Fires; Area: Area Burned; GDD: Growing Degree Days; Pre: Precipitation; Nest: Nesterov Index; Elev: Elevation
** Nr. of fires not available per cell
* Taken from table "Fire Number and Area Burned per Year"

	Nr	Area	GDD	Pre	Nest	Elev
Nr		*0.754	**	**	**	**
		0.568				
Area	< 0.001		-0.027	-0.069	0.108	0.078
			0	0.004	0.011	0.006
GDD	< 0.001	< 0.001		0.391	0.182	-0.53
				0.152	0.033	0.258
Pre	< 0.001	< 0.001	< 0.001		-0.544	-0.69
					0.297	0.484
Nest	< 0.001	< 0.001	< 0.001	< 0.001		0.366
						0.134
Elev	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	

Correlation	
Neglectable	0.0 +/- 0.19
Weak	0.2 +/- 0.39
Moderate	0.4 +/- 0.59
Strong	0.6 +/- 0.79
Very Strong	0.8 +/- 1
P-Value	
R^2	

GDD and the elevation. The GDD depends on temperature. Lower temperatures in higher altitudes lead to limited growth. A strong negative correlation is found between the elevation and the precipitation (48% of the variance is shared). The higher the elevation, the less precipitation is present. In reality, the relationship is inverted and more precipitation is present in higher altitudes (Pyne et al. 1996). This result appears unexpected and more work needs to be done to figure out why a negative relationship is persistent. A weak correlation is present between the elevation and the Nesterov Fire Index, inferring that the conditions for a fire to ignite are slightly better in lower altitudes. The correlation between number of fires and area burned is explained in section 7.1.1.

Figure 13 shows the fire parameters and the land cover classes plotted against the fraction of area burned. The red lines indicate the envelope limit before and after which a fire event is no longer detected. Each dot corresponds to a grid cell.
All plots can be read as "No fires occur below the minimum value and above the maximum value". For instance are no fires detected in cells experiencing less than 90mm and more than 1800mm precipitation per year. In between this threshold fires may or may not occur. No cell covered with more than 20% of deciduous forest experienced a fire in the time span 2000 to 2010. No minimum cover is needed to hinder a fire.
Unfortunately, the certainty of the minimum and maximum values of the envelopes can not be determined.



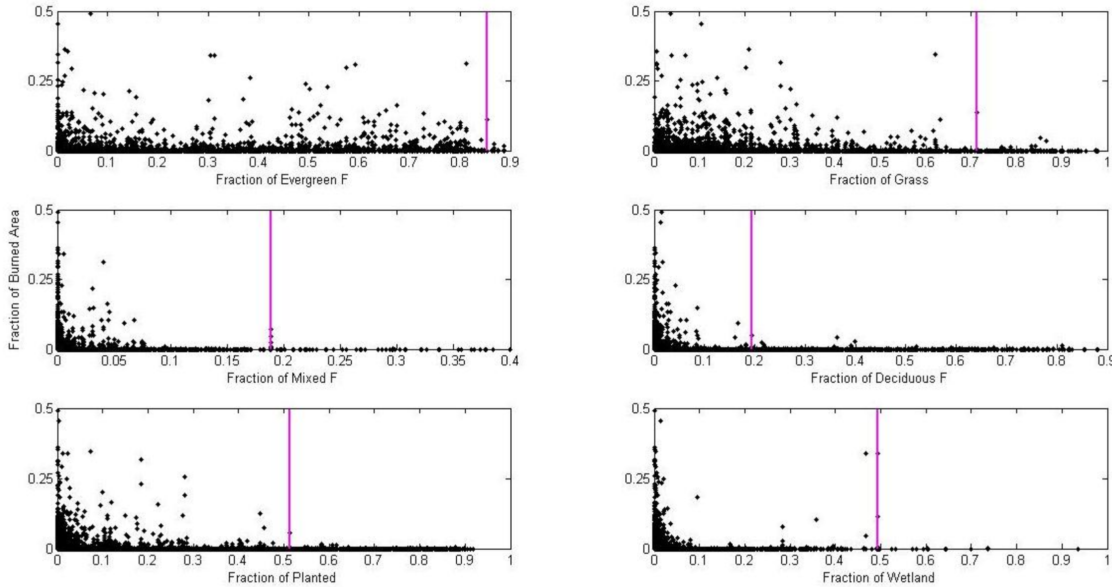


Figure 13: Fraction of Area Burned per Factor with Envelope

7.3 GENERALIZED LINEAR MODEL

Table 6 shows the correlation between each factor and the fraction of area burned. The relationships are extremely weak and only a minimal improvement to the linear model is made (see table 5). Almost no influence of the controlling factors on the area burned exists. The Nesterov Index is the climatic parameter which best predicts the fire size, "others" is the land cover class which explains the area burned best, followed by shrub land. Elevation as a topographic influence ranks third place. No relationship is found between the area burned and the mixed forest, deciduous forest, wetland and agricultural areas. The results are significant (p-value < 0.05).

Table 6: GLM Output of Single Model

NA: No Answer. The relationship is too weak and no R^2 could be calculated

Variable	R^2.
Nesterov	0.0168
Others	0.0131
Elevation	0.0094
Shrub	0.0082
Precipitation	0.0070
Evergreen	0.0058
Grass	0.0031
GDD	0.0012
Mixed	NA
Deciduous	NA
Wetland	NA
Planted	NA

Figure 14 shows the response of the burned area to the controlling factors. The red line is the model response. No red line is plotted where no relationship exists. The coefficients of the GLM and an explanation of their use are listed in appendix B

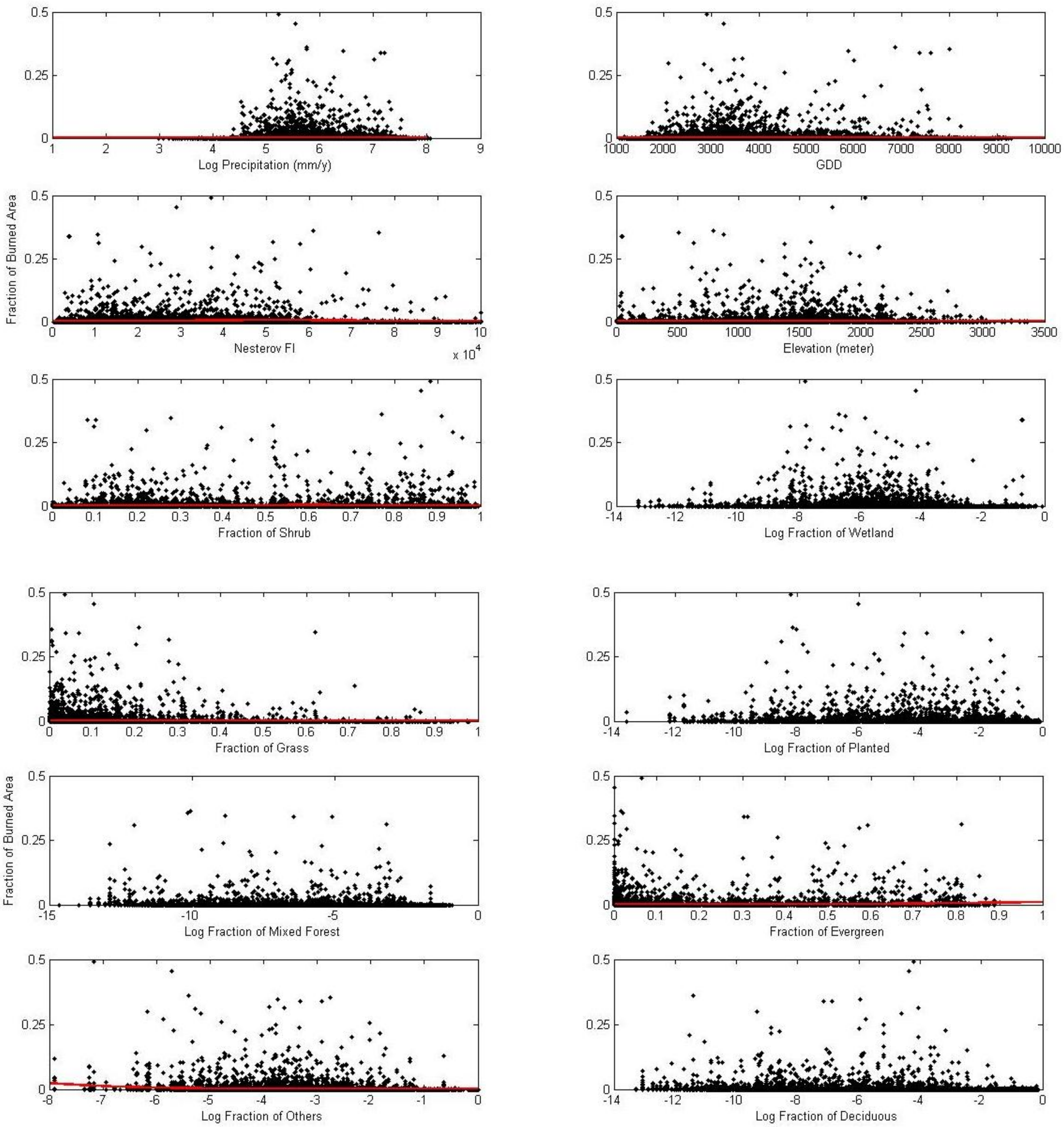


Figure 14: Response of burned area to the controlling factors

The red line is the model response. No red line is plotted where no relationship exists.

7.3.1 MODEL SELECTION

When running a 10-fold cross-validation, none of the factors are selected as a good predictor for the occurrence of fire.

When applying the bootstrapping technique, the Nesterov Index, the "others" land cover class (includes infrastructure, water and barren land), the evergreen forest and the GDD are included in the end model. These factors improve the model significantly and are best at predicting fire occurrences. The results are significant (p-values < 0.05). Table 7 gives an overview over the end-model with the factors selected to improve the fire prediction (the number of runs is 359). Depending on the run, between 10-20% of the variance is explained by the end-model.

Table 7: Model Selection: Bootstrapping

Improving Factors	Selected in Runs	[%]
Nesterov Index	359	100
Others	315	87.7
Evergreen Forest	269	74.9
GDD	200	55.7

8 DISCUSSION

In this chapter the results are discussed and the sub-questions are answered in order to approve or reject the hypothesis.

8.1 DATA INVESTIGATION

Bigger CFSs are found in the South East as well as in the North West, thus eco-divisions with dry, hot summers, evergreen trees, shrub vegetation and less fragmented landscapes. The different CFSs evolve from the different climate, land cover types and topography, which are present in each division (Malamud et al. 2005). No ascending fire gradient from East to West is detected as Malamud et al. (2005) describe it in their paper. Instead of calculating the CFSs by taking the maximum value of the normal distribution in log-space as suggested by Lehsten et al. (2014), Malamud et al. (2005) used a different approach (power law-based linear fire area relationship). Johansson (2011), who calculated the CFSs in boreal regions by using a similar approach as in this thesis, found that CFSs are rather small than large, while Archibald et al. (2009) state that a minor number of large fires cause the majority of the area burned in African regions. For the eco-divisions in the United States, several small to medium sized fires are found to contribute more to the total area burned than a few large fires.

The size a fire can reach is not only dependent on environmental factors but also on fire suppression measures. Fire suppression is not equal in all states. Applying an optimized suppression method might lower the CFS and minimize the total area burned. It cannot be said if favorable climate and vegetation or less suppression actions lead to the outstanding big CFS in the Subtropical and the Savanna division. It could also be that sufficient fire suppression is present. This enables the vegetation to grow continuously and densely and once a fire breaks out, the area burned will be even larger (Dennison et al. 2014). The high CFS could also be considered as an outlier since only few fires occur compared to the division size (see table 3).

The largest wildfires are detected in the western states, Georgia and Florida (Sommers et al. 2011), thus in states with bigger CFSs. The CFS seems to increase when numerous large fires are present, even if smaller fires contribute most to the total area burned. However, no statement can be made concerning the relationship between CFSs and the area burned since the correlations are not significant (p-values > 0.05). Lehsten et al. (2014) state that different mechanisms are behind each feature and that the CFSs depend distinctly on the eco-division.

No statements can be made when looking at the relationship between the CFSs and the averaged GDD, precipitation and Nesterov Index per eco-divisions. Again, the results are not significant (p-values > 0.05). Nevertheless, taking the averaged fire parameters over a whole division does not represent a good picture, since the divisions are quite big and even though divisions are characterized by similar climates, variability exists. Furthermore, the average over the whole decade is taken to compare the CFS with the fire parameters per division, which excludes important variables and only provides a very coarse picture of the reality.

A great variety of CFSs exist among the years. The year 2007, which is characterized as a moderate La Niña year (CPC 2014), has a notably higher number of fire events and the largest area burned out of all years with the smallest CFS of only $900m^2$. The years 1999 and 2000 are weak la Niña years (CPC 2014) and also show an outranging number of fire events with a rather small CFS. Other years have almost a 1000 times bigger CFS. It therefore seems that significantly more small fires occur when La Niña conditions are present, leading to a smaller CFS. This is however only an assumption and no statistical analysis is carried out on this point.

Since a time frame of only one decade does not contain long enough data to draw conclusions about the impact of climate change on fire regimes in the United States, no statement concerning the time series can be made. Even though no trend is found, it can be reasoned that the process of global warming is in full swing and an increase in wildfire activity can be expected. However it cannot be said if human induced climate change (anthropogenic climate change) or natural climatic variability acts as the main force (IPCC 2007).

8.2 Fire Parameters

When creating envelopes for each factor to assess where fires most likely do not occur (figure 13), different patterns are recognizable. A high index value of any fire supporting factor (or a low index value of a fire preventing factor) does not necessarily mean that a maximum fire size is reached. The size is likely to be small, depending on other conditions such as fire suppression, land use, fuel availability, fragmented landscapes or fire barriers (Johansson 2011; Archibald et al. 2009; Lehsten et al. 2010). Fire patterns can occur randomly within the envelope. A minimum limit however indicates that for most fires a certain threshold of the index value must be reached before a fire can burn (Johansson 2011; Archibald et al. 2009; Lehsten et al. 2010).

Too much precipitation hampers fire development, as can be seen when looking at the Marine division, a division characterized by the absence of fires and abundant rainfall (see table 3; appendix A). Also lower temperatures are dominant in this division and it cannot be said weather precipitation or temperature is the main limiting factor. No precipitation hinders vegetation growth and thus fuels development. A minimum of 90mm/year is found to be the limit below which fires most likely do not occur. This threshold is very low when considering that even deserts can receive up to 250mm/year. It therefore can be said that no minimum precipitation is required to produce fuel so a fire can start burning in the United States. It seems that enough fuel is available in dry areas.

Cells with a Nesterov Index higher than 90,000 are not affected by fires either. Even though a high Index value indicates better preconditions for a fire to start burning (high temperature, low dew point and low precipitation), a too high value limits the vegetation growth and without fuel, no fire inflames. Such regions are found in the South Western U.S. (parts of the Mojave desert, Great Basin or Sonoran desert). The range where fires might occur is quite large. Most likely other factors penalize the occurrence stronger than the Nesterov Index does.

Above a GDD value of 8000, the chances for fires to ignite are very small. At this threshold as well as below 1800, plant growth and survival is limited and not enough burning material is present. Most parts of the USA are in between that range. Southern Florida, southern Texas and parts of the Sonoran desert (GDD too high) and the temperate steppe regime Mnt division (GDD too low) are outside that range. Even though deserts are characterized by a high GDD (GDD is a temperature based indicator), the conditions for vegetation to profilate are not optimal and deserts therefore only are sparely vegetated.

Above 2700m altitude no fires which cover more than 5% of the cell are found in the data set. The vegetation growth is limited due to alpine conditions (too cold temperatures, too much precipitation (or too less after a certain height)), thus no fuel is available to burn (Pyne et al. 1996). The minimum boundary is at sea level.

Shrub land and evergreen forests seem to be very combustible (Krawchuk et al. 2009) with nearly no minimum limit and a maximum limit at almost 100%. Needle trees for instance have a particular sap in their branches which boosts wildfires (Pynes et al. 1996). Also grass land with a maximum threshold of 70% per grid cell is quite combustible. The combustibility must be seen in context with other factors. Shrub land, grass land and evergreen forests are vegetation types which survive well in arid areas. They are found to large extent in the West (Gebhardt et al. 2007). An interplay between several factors therefore makes these classes particularly flammable (Malamud et al. 2005). This is in accordance with the determination of the dominant land cover classes calculated via count, where the same land cover classes are identified to be very combustible (see table 4).

Cells with a cover of more than 50% of wetlands and agricultural surfaces do not burn any more. When looking at the plots it can be seen that most cells burn when there is less than 10% of wetland cover. The "others" land cover class contains water bodies, barren land and infrastructure, thus elements which are nearly incombustible. The limit is as well set at 50%, however, this limit seems to be caused through an outlier and the actual limit is already at a lower value. Mixed and deciduous forests are not particularly combustible either. A dense tree cover is linked to a moist environment, partly because of the higher moisture content in the leaves and stems (Lehsten et a. 2010).

8.3 Generalized Linear Model

Only slightly better (ergo no) correlation exists between the area burned and the fire parameters on a large geographic scale when working with the GLM instead of the linear regression. For both the linear regression and the GLM, the coefficient are very low estimates (see appendix B). This could be because most cells are not affected by fire and therefore have a value of zero. The correlation would most likely increase if the fire parameters were available in a finer spatial resolution since they vary below a 0.5° resolution (Lehsten et al. 2010). The correlation might also result in a better fit when distinguishing the fires and the fire parameters into two seasons instead of taking the annual mean since the fire season in the United States takes place during the summer months (see section 8.4).

Lehsten et al. (2010) found a stronger relationship in Africa when correlating the area burned with the precipitation means of preceding seasons, since vegetation needs time to grow and to produce fuel. Unfortunately, the date of too many fires is not stated in the data set and such a division is not possible.

Enough precipitation and fuel is often available in cooler environments and accumulated temperature therefore plays an additional important role in fire prediction (Crevoisier et al. 2007). The end model includes the GDD and Nesterov Index to significantly enhance the fire prediction but exclude the precipitation. Both the Nesterov Index and the GDD are measurements based on temperature (although the Nesterov Index also includes precipitation in its measurement). Together with the fact that almost no minimum precipitation value has to be exceeded for a fire to occur, accumulated temperature indeed seems to play a bigger role in the United States.

The Nesterov Index, which is designed to rate fire danger, scores as the best predictor. The index is selected in every run. The reason for such a high score is the embedding of precipitation, dew point and temperature in the index, elements which fires sensitively react to. The "others" land cover class (infrastructure, water, barren land) is included as the second best predictor. This factor is included in 88% of the runs to significantly improve the fire prediction. Several researchers (Levine et al. 1995; Archibald et al. 2009; Lehsten et al. 2010) state that population density is a good indicator to predict fire events, since zones around populated areas burn regularly, caused through human caused ignition. The "others" land cover class does not contain information about population density but about infrastructure, thus cities and roads where people linger. As stated in previous chapters (see figure 13), cities and roads are not very combustible and can act as fire barriers. However, they still explain fire events occurring in close distances. Also barren land and water bodies are included in this class but it can be expected that they rather act as fire blockers, although people might also remain around water bodies (Pyne et al. 1996). The correlation coefficient might be better when separating the "others" class into "Infrastructure" and "Water and Barren land".

Evergreen forest is included in 75% of all runs to be a good predictor. The GDD is included in 56% of the runs. Both factors score low in the single model but are included in the end model. The inclusion can be explained by the correlation of these factors with other factors. The GDD for instance correlates with precipitation and elevations (see table 5) but also with vegetation. Evergreen forest, shrub and grass land scored higher than the GDD in the single

model and put the score of the GDD up. The factor scores strong enough in the bootstrapping procedure to be included in the end model.
Even though shrub and grass land are identified as being very combustible, it is not said that they also acts as good predictors. More than 20% of the U.S. is covered by grass or shrub land and of course not all of this land burned. Combustible land cover alone is not enough for a fire to ignite. A combination of different factors is needed. Precipitation, the Nesterov Index and elevation, factors that are correlated with each other, determine how combustible the grass and shrub land is. Heterogenic, mixed and moist deciduous forest are less combustible (Evans et al. 2011) and no correlation is detected at all (neither in the single model nor when applying the bootstrap procedure).

Even though the Nesterov Index scores best, it still does not score well enough to state that a relationship between climate and the occurrence of wildfires can be found. Neither climate nor land cover are therefore the dominating factor influencing the occurrence of wildfires. Climate sets boundaries on where it is possible for fires to occur and where they certainly do not occur but other factors codetermine the incidences. Hence more significant factors are needed to explain wildfire patterns. Wind for instance affects fire development and varies strongly at a local scale. It should not be averaged over a grid cell since it is even influenced by the fires themselves. Also slope should not be averaged over a 0.5° grid cell. The high spatial variability gets lost at larger scale and should only be included when doing a small scale analysis (Lehsten et al. 2010).

Other research papers conducted over a longer time period found evidence that the fire weather elements and the resulting fire parameters are the decisive factor determining the occurrence of fires (Pierce et al. 2004; Malamud et al. 2005; Flannigan et al. 2006). Dennison et al. (2014) for instance found that the increasing number of larger fires in the western United States is linked with global warming. The impact is notable in southern and mountain regions, thus areas that also experienced severe droughts in the past years. Dennison et al. (2014) state that the trend towards larger fires is unlikely to be due to random variation alone. Even though this thesis could not detect any evidence for climate to be the dominating factor leading to wildfires, climate still affects the fire regimes. A changing climate affects the ecosystem and has an impact on the spread of evergreen forests and shrub land as well as on droughts and earlier snow melt which will affect the spread of fires (Sommers et al. 2011).

8.4 UNCERTAINTIES

Several uncertainties are present in this thesis. First of all, a temporal scale of only 10 years is used which is not enough time to observe a significant change in climate and fire regimes. The set up of this thesis requires an advanced statistical background and therefore mistakes in both the methodology as well as the analysis cannot be excluded.

Uncertainties exist in the data sets themselves. The data used stems from different sources and first had to be converted into the format needed. The fire data provided by Landfire for instance is a compilation of different sources, using different techniques and therefore does not deliver results of the same quality. The Landfire data differentiates various fire types but no information about the certainty that all fires are classified correctly is given.

It was not possible to bring the climate data and the wildfire data set into the exact same projection. The data is slightly shifted (50-100km^2 westwards) and when assigning each fire to a grid cell, not the actual GDD, precipitation and Nesterov Index is given but the shifted value. The fire parameters are continuous and do not change abruptly from one cell to the other but uncertainties are present in further calculations. No statistical measure was applied on this inaccuracy. When assessing the total area burned in both the original wildfire shapefile as well as in the dissolved and gridded shapefile, it becomes clear that due to the shifted projection almost one third of the fires got lost, which of course deteriorates the results. The use of shifted data and the loss of one third of the fire data cannot be justified and a solution to bring the data sets into the same projection must be found when repeating this study.

The same land cover map is used for the whole decade, neglecting possible changes. In a time span of 10 years the changes are not too extensive however uncertainties remain. The "others" land cover class is especially affected by uncertainties since urban areas expand and the population grows on a yearly base. An increase from 9.7% from the year 2000 to the year 2010 is measured and the South and West of the country are particularly affected by growth. Forest, agricultural and barren land are hereby used as building land (USCB 2011).

The calculated GDD is valid for the whole year. Fire events might happen early in the year and using the GDD as an approximation for burnable material therefore leads to uncertainties since the GDD also might accumulate after the fire event takes place. To ensure a correct implementation, the GDD should only be calculated up to the date of the fire. Unfortunately, the exact fire dates are not stated in the metadata for all fire events and a correct implementation therefore is not possible. However, the GDD values of the whole year still can be used since most fires in the United States take place during the summer months. No appreciable growth is detected with temperatures lower than 5°C and therefore not as much growth is accumulated in the fall and winter. The yearly GDD value therefore still can be used to estimate vegetation growth and the approximation for burnable material.

Even if similar climatic conditions and vegetation are present, a fire might occur in one place but not in the other. This can be explained by different fire policy actions in different parts of the United States. The Federal Government as well as individual state governments determine how fire suppression takes place. Fire suppressing actions are not taken into account in this study but might have an impact since regions with no or only few fires might not be dependent on climate and vegetation only, but also on effective suppression actions.

9 CONCLUSION

The fire system is complex and several aspects must be taken into account to predict fires. Time, space and scales must be considered to make accurate propositions on the occurrence of fire.

How strong and in what way do land cover and climate affect the occurrence of wildfire in the United States?

On a large geographic scale with a 0.5° spatial resolution, only very weak correlations are found between the fire occurrence, the fire parameters, topography and land covers.

The Nesterov Index and the "others" land cover class score best. However, no factor is identified to be good enough to actually predict wildfire events. Climate sets the frame on where fires might occur and determines where fires do not occur. Once the minimum envelope-threshold of any factor is reached, fires act randomly and independent of climate and land use. It cannot be said how climate and land cover affect the fire occurrence.

The hypothesis **"Climate is the dominant factor in the interannual variation which leads to wildfires in the United States"** cannot be supported. Fires are also dependent on other factors. Local components such as the soil moisture, wind, fire barriers or the fire suppression policy must be considered. Smaller fires are found to contribute most to the total area burned. No statements concerning the relationship between climate and the CFS could be made.

Which climate zones and land cover types are affected the most by wildfires?

Generally climate zones with a period of sufficient rainfall followed by several dry days with a humidity below 30% are the most severe affected by wildfires. The Mediterranean Mnt, Temperate Desert and Tropical /Subtropical Desert Mnt division (all located in the western and south western United States) are the eco-divisions with the most area burned in proportion to their surface area.

The maximum threshold of fires in shrub land and evergreen forest is at almost 100%, indicating that these two land cover classes are extremely combustible.

9.1 OUTLOOK

To get more accurate results, a smaller area could be investigated in more detail, including additional factors such as vegetation density, slope, wind speed or soil moisture. Such data is not available or should not be used on a large scale as is the case in this thesis. Landfire offers diverse free data sets, which can be taken into account in further research.

To actually get an overview regarding which land cover classes are affected by wildfires, a shapefile data set should be used to conduct overlays. The 30x30 raster data set is too big in size to handle and an overlay with a lower resolution raster delivers too coarse results. To see the influence of "infrastructure and people" more clearly, the "other" land cover class can be divided into two parts, including information about the population density.

In further analysis, fires could be divided into two seasons to make conclusions about the temporal variety and a data set over a longer time period should be taken to actually see how climate and fire regimes changed.

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11 APPENDICES

A: BACKGROUND

Descriptions of Bailey Eco-province Sections in the United States

B: RESULT

Fire Parameters and Generalized Linear Model

C: SCRIPT

Matlab and R-Script

A: DESCRIPTIONS OF BAILEY ECO-DIVISION SECTIONS IN THE UNITED STATES

A list of Bailey's eco-divisions with geomorphic characteristics and potential natural vegetation for the United States is provided by the US Forest Service and accessible under following URL:

http://www.fs.fed.us/land/ecosysmgmt/colorimagemap/ecoreg1_divisions.html (Update: 2008; Access: January 2014)

B: FIRE PARAMETERS AND GENERALIZED LINEAR MODEL

Table 8 gives the slope (m) and intercept (b) values for the linear regression (y = mx + b) performed in section 6.2. (The table can be read as follows: Fraction of area burned = 0*GDD + 0.0021). The slope and intercept are very small for all factors since most grid cells are not affected by fire but all cells have a value for climate and land cover.

Table 8: Slope and Intercept of Variables

*The "others" land cover class includes infrastructure, water and barren land

Independent variable (x)	Slope (m)	Intercept (b)
GDD	0	0.0021
Precipitation	0	0.0023
Nesterov	0.0001	0.1272
Elevation	0.0122	0.8925
Others*	-0.0030	0.0014
Deciduous	-0.0034	0.0015
Evergreen	0.0043	0.0006
Mix	-0.0068	0.0012
Grass	-0.0004	0.0011
Shrub	0.0034	0.0003
Planted	-0.0030	0.0018
Wetland	-0.0036	0.0012

The code [logitCoef, dev, stats] = glmfit (independent variable X, fraction of area burned Y, binomial distribution) returns three coefficient estimates (in form of a vector) for a generalized linear regression of the responses in Y on the predictors in X (Mathworks (b)). The first coefficient is the absolute coefficient, the two other coefficients are placed before the corresponding variable. The GLM equation for a variable looks as follows: yfit = $\frac{\exp(\mathrm{Coef}(1)+\mathrm{Coef}(2)*\mathrm{variable}+\mathrm{Coef}(3)*\mathrm{variable}^2)}{(1+\exp(\mathrm{Coef}(1)+\mathrm{Coef}(2)+\mathrm{Coef}(3)*\mathrm{variable}^2))}$. This equation leads to the model response as showed in figure 14. The coefficienct estimates of the GLM's of each variable are presented in table 9. A vector of zero indicates that no relationship is found between the area burned and the independent variable (climate and land cover).

Table 9: GLM Coefficient estimates for each variable

*The "others" land cover class includes infrastructure, water and barren land

Variable	Coefficient estimates (vector)		
	(1)	(2)	(3)
Precipitation	-16.3543	4.4080	-0.4622
GDD	-5.1852	-0.0005	0
Nesterov	-8.8085	0.0001	0
Elevation	-9.3424	0.0041	0
Shrub	-8.3650	8.9651	-7.2321
Wetland	0	0	0
Grass	-7.2148	8.6704	-16.5622
Planted	0	0	0
Mixed	0	0	0
Evergreen	-7.2700	2.1427	0.6033
Others*	-16.3543	4.4080	-0.4622
Deciduous	0	0	0

C: SCRIPT

The R-Script and the Matlab script can be found together with the thesis in LUP, under the master thesis series number 322 with the title The Influence of Climate and Land Cover on Wildfire Patterns in the Conterminous United States.

12 List of previous published master thesis reports

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