Spatio-temporal Variability of Wildfires and Their Climate Drivers from Continental to Global Scale

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Authorization to Submit Dissertation

This dissertation of Maria Zubkova, submitted for the degree of Doctor of Philosophy with a Major in Natural Resources and titled "Spatio-temporal variability of wildfires and their climate drivers from continental to global scale," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Fire is a natural component of most ecosystems, and it has effects on vegetation, soil, water, atmospheric composition, and human well-being. Despite increasing interest in interdisciplinary approaches to analyze global fire activity, and the growing body of wildfire research, there are still many gaps and uncertainties in our knowledge. Our understanding of the complex relationships between fire and climate is still limited, especially when the strong influence of human activity on fire is also considered.

This dissertation evaluates the role of the environmental context in determining the spatial and temporal patterns of fire activity at continental to global scale. First, the fire-climate relationship was analyzed by considering the amount of burned area, which is the most studied and understood fire metric. Globally, the area burned has changed significantly in the last two decades; the largest observed change being the decrease of fire activity in Africa, where the amount of burned area declined by 18.5% between 2002 and 2016. Although fire activity in Africa has been modified by humans throughout history, this research found that climate factors directly related to biomass productivity and aridity explained about 70% of the changes in burned area in natural land covers, providing evidence that increased terrestrial moisture during the 2002-2016 study period contributed to the decline in fire activity in Africa. These results illustrate the strong influence of climate on fire activity, and that climate variables are an effective proxy for fuel productivity and fuel dryness.

Based on these findings, a novel framework was proposed for identifying fire regions, defined as climate niches, based on key drivers of fire, and subsequently characterized by summary metrics derived from satellite-based fire products. This framework was based on the assumption that fuel productivity and desiccation are the two fundamental processes that limit fire activity, and their combination sets important boundary conditions for key fire regime metrics on a large scale. By testing this approach in Africa and Australia, it was evident that while the amount of rainfall is an important driver of fire through controlling fuel productivity, the variation of rainfall within and between years drives fuel dryness and fire activity especially in Australia, a continent with a strong precipitation gradient.

These results informed an additional global analysis, where 26 distinct fire regions were identified, excluding areas where fire activity is highly modified by human activity. This approach not only discriminates between regions with significantly different fire activity across a number of biomes but also identified how fire attributes vary under different conditions and what factors constrain modern fire regimes. These findings improve our understanding of fire complexity and its interaction and feedbacks with climate which is essential to assess the potential effect of global climate change on fire regimes.

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Dedication

This work is dedicated to the four most important people in my life. My parents for their endless support through all my degrees. I will be forever grateful for all the time and resources they spent on my education and personal growth. My best friend, Tatyana. She might not understand a word in English and have no idea what I was doing in the other part of the world for the past 5 years, but she and her husband had always believed in me and my success more than I will even believe in myself. And last but not least, Mike, who could have got an honorary doctorate for the hours he spent discussing my study if he was not receiving his own doctoral degree at the same time. The last few years of my doctoral studies would be impossible not only without his help with coding, editing, and brainstorming ideas but also without his patient, kind words and loving support.

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M.Z., L.B., and J.A. conceived the overall approach of the paper. M.Z. refined the methods, performed the analysis, structured and wrote the paper with assistance from L.B. J.A. provided technical assistance, and comments while drafting and finalizing the manuscript.

Chapter 1: Introduction

Fire is a global phenomenon whose relationship with vegetation developed soon after the appearance of terrestrial plants more than 400 m.y.a. (Bowman et al., 2009; Glasspool et al., 2004). Fire has strong evolutionary and ecological consequences for biota (Pausas and Keeley, 2009): it influences the structure, function, and composition of ecosystems, especially affecting the vegetation (by stimulating the regeneration of some species and suppressing others), soil (by removing organic matter and recycling minerals) and atmosphere (by emitting carbon monoxide and dioxide, methane, nitrous oxides, trace gases and aerosols) (Bowman et al., 2009; Certini, 2005; DeBano et al., 1998; Morgan et al., 2001; Sedano and Randerson, 2014). Fire contributes to the global carbon cycle through the emission of greenhouse gases and aerosols from biomass burning, with approximately 6–8 Gt CO2eq yr^{-1} emitted globally by fires (Rossi et al., 2016), which is very significant relative to the 30 ±8% Gt CO2 yr^{-1} total carbon equivalent resulting from the combustion of fossil fuels (Andres et al., 2012; Le Quéré et al., 2018). Moreover, there is a growing awareness of the adverse effects of fire on human health and the economy (Lohman et al., 2007; Bowman et al., 2017). There are many examples of catastrophic fires in ecosystems prone to high fire activity that also support high population density like California, U.S, most Mediterranean countries in Europe, and Australia (Bowman et al., 2011; Cameron et al., 2009; Mann et al., 2016) that cause billions of dollars in damage and loss of life and ecosystem services (Cameron et al., 2009; Johnston, 2009; San-Miguel-Ayanz et al., 2013). While the negative effects of fire on humans increase the attention of public and scientist to fire research, our knowledge of fire as an integral Earth system process remains incomplete (Bowman et al., 2009).

There is an established body of peer reviewed literature on fire as a physical process. Three dominant factors constrain fire: fuel, heat, and oxygen on a microscale; and vegetation, ignitions, and climate on a regional scale (Parisien and Moritz, 2009). However, a theoretical framework that describes the limits of fire activity at the global scale is still lacking (Boer et al., 2016; Parisien and Moritz, 2009). Krebs et al. (2010) wrote: "[…] in a complex process like fire, that involves temporal cascades, interactions, and feedbacks, every cause is also an effect, every effect may be a causal variable, and no variable is truly independent." Spatial and temporal patterns of fire are usually studied together with climate data because climate controls fuel loads, fuel flammability and extreme weather events (Bowman et al., 2009; Bradstock, 2010). Temperature is considered by many authors as the main driver of fire activity (Aldersley et al., 2011; Gillett et al., 2004; Krawchuk and Moritz, 2011) which induces plants growth, i.e. fuel accumulation, and reduces atmospheric and fuel moisture which creates favorable conditions for fire ignition and propagation (Daniau et al., 2012; Flannigan et al., 2009). Numerous studies have found a strong positive correlation between temperature and several fire characteristics and therefore predicted an increase in fire activity in the future due to warming of the planet (Daniau et al., 2012; Krawchuk and Moritz, 2011).

The relationship between fire and precipitation, on the other hand, is less ubiquitous (Abatzoglou et al., 2018; Williams and Abatzoglou, 2016). Precipitation can promote or suppress fire depending on the ecosystem, amount and seasonal pattern of rainfall. In fuel-limited systems such as grasslands, where the amount of precipitation drives fuel accumulation, years with above-average rainfall are usually followed by years with high fire activity (Bird et al., 2012; Daniau et al., 2012; Higgins et al., 2000). In contrast, in energy-limited systems such as forests where the climate is moist, fuel is always sufficient to carry fire and a lack of precipitation during warm season promotes curing of fuel leading to increased flammability (Bradstock, 2010; Trouet et al., 2006; Williams and Abatzoglou, 2016). Ecosystems whose average annual precipitation falls in the middle of the moisture gradient are usually less sensitive to the amount of rainfall and more to its seasonal cycle (Bedia et al., 2015; Lehmann et al., 2011; Russell-Smith et al., 2007). In addition, not all ecosystems belong to one of the above categories, since more than one factor (i.e. fuel or energy considered alone) can limit fire activity (Batllori et al., 2013; Bradstock, 2010). For example, Littell et al. (2009) have shown that forested mountain ecosystems in the western U.S. required warm and dry conditions for moisture depletion right before the beginning of the fire season, but also had a positive relationship with antecedent rainfall which promotes fuel accumulation. This interplay between factors that control fire activity at a range of temporal scales adds to the challenge of understanding fire-vegetation-climate relationships and incorporating their links and feedbacks within vegetation and fire models to get accurate predictions (Sedano and Randerson, 2014; Syphard et al., 2017).

The influence of human activities makes those interactions even more complex. Humans have been using fires for millennia during many stages of their evolution and have had a profound impact on fire regimes (Bowman et al., 2009; Pausas and Keeley, 2009). Fire was first used as a tool for cooking and heat, and later for "fire-stick farming" (Bird et al., 2008) where it started to influence vegetation and biodiversity. There is evidence that humans have altered fire regimes through changes in socio-economic factors, population growth, and land management (Balch et al., 2017; Marlon et al., 2008; Parks et al., 2016; Pausas, 2004). Anthropogenic activity can change the number and time of ignitions, which can lead to a shift and/or expansion in fire seasonality (Balch et al., 2017; Bowman et al., 2011; Calef et al., 2017). Humans traditionally ignite fires earlier in the season in arid ecosystems to prevent large, hot, and hard to control late-season fires (Archibald, 2016; Elliott et al., 2009), therefore manipulating fire size and intensity. Expanding population into the wildland-urban interface is usually followed by fire suppression (Radeloff et al., 2005). In areas such as western U.S. forests, fire suppression in 20th century has led to fuel build-up that changed fire regimes from moderate-frequency low-intensity surface fires to much hotter and more severe crown fires that are hard to control and are more devastating for biodiversity and humans themselves (Collins et al., 2013; Westerling, 2006). Humans also manipulate fire activity through land cover conversion. Increases in the number of agricultural fields, grazing pressure or infrastructure reduce the amount of biomass and increase landscape fragmentation which leads to smaller, less intense fires (Archibald et al., 2012, 2009; Hantson et al., 2015; Le Page et al., 2010). On the other hand, increasing industrialization can lead to land abundance which increases the build-up of biomass and can promote large, hot fires that are not controlled in the absence of humans (Martínez-Fernández et al., 2013; Moreira et al., 2001; Pausas and Fernández-Muñoz, 2012; Viedma et al., 2015). Additionally, humans can introduce fire in places that are not naturally fire-prone like the rainforests (Bowman et al., 2011; Flannigan et al., 2009). High levels of moisture usually prevent fire ignition and propagation in tropical forests, but deforestation opens tree canopies which allows fuel to dry (Brando et al., 2014; Cochrane, 2003). Fires in the cleared rainforest are then started during extremely dry conditions in South America and Southeast Asia, which further increases the negative impacts for biodiversity and the carbon budget (Cochrane, 2003; van der Werf et al., 2008). These manipulations of fire characteristics can change vegetation structure by creating conditions lead to the removal of native species (Elliott et al., 2009; Miller et al., 2010), resulting in changes to soil, watershed stability, and biodiversity (Cochrane, 2003). Furthermore, some argue that anthropogenic factors can diminish the influence of changing climate (Archibald, 2016; Syphard et al., 2017) making fire behavior predictions even more uncertain (Archibald et al., 2012; Balch et al., 2017; Bowman et al., 2011).

Taking into consideration the complex relationship between climate, vegetation, humans, and fire and the lack of information about different aspects of fire activity on a continental to a global scale, current research has often characterized fire activity in terms of the amount of total burned area and its relationship with climate (Parks et al., 2016; Whitman et al., 2015). This fire metric was chosen due to calculation simplicity (Archibald et al., 2013), and since variations in global pyrogenic atmospheric emission are directly related to yearly variability in the amount of burned area (van der Werf et al., 2010) and in many ecosystems, potential changes due to variations in fire activity beyond the level of resilience are a growing concern (Buma and Wessman, 2013). Although climate change-induced warming was predicted to increase fire activity (Balshi et al., 2009; Flannigan et al., 2013, 2009; Westerling, 2006), recent studies based on remotely sensed data have revealed a decline in the global amount of burned area (Andela et al., 2017; Earl and Simmonds, 2018). This is a somewhat counterintuitive and unexpected result because higher temperatures increase the flammability of fuel, but closer analysis of continental fire statistics clearly shows decreasing trends in burned area are not uniform across all regions (Earl and Simmonds, 2018). In fact, regional trends show a great difference in the direction and the amplitude of changes in annual burned area. At higher latitudes, where higher temperatures promote drying of fuel and therefore higher fire potential (Abatzoglou and Williams, 2016; Dennison et al., 2014; Moritz et al., 2012), the fire trend was increasing (e.g. Westerling et al., (2006) in the western U.S., Andela et al. (2017) in North America, Earl and Simmonds (2018) in Canada). However, fires in higher latitudes contribute little to the global fire activity (Giglio et al., 2018), albeit with a greater relative impact on fire emissions due to the high biomass consumption in boreal forests and peatlands (van der Werf et al., 2017). A larger portion of the global amount of burned area comes from the tropics, particularly tropical savannas which are characterized by warm climate with very seasonal precipitation that promote fuel accumulation and desiccation (Daniau et al., 2013; Saha et al., 2019; van der Werf et al., 2008). These fire-prone ecosystems are located on several continents, but they are predominant in Africa where tropical savannas cover most of the continent. Consequently, Africa alone contributes more than half of the global burned area and over half of the global carbon emissions from fire (Giglio et al., 2018; Rabin et al., 2015; van der Werf et al., 2017). Interestingly, it is also the only continent with a significant (and negative) change in the amount of burned area (Andela et al., 2017) which makes it even more important to understand what mechanisms drive fire activity in this very fire-prone continent (Andela and van der Werf, 2014). Being able to evaluate the importance of different climate drivers and anthropogenic activity in Africa, a continent where regional weather statistics are not reliable, historical fire records do not exist, and human population grow in accelerating rate (Akinsanola et al., 2017; Andela and van der Werf, 2014; Archibald, 2016; Beck et al., 2017) is a pressing issue. However, it is also a challenging task, which is why there is no agreement in the published studies on the nature of current trends in the amount of burned area.

Answering questions about the drivers of inter-annual variability and recent changes in burned area on a continental and global scale will bring some clarity to the complex interaction among fire, climate and modern human activity. However, burned area alone cannot provide enough information to characterize fire activity within the context of the multivariate environment (Krawchuk et al., 2009; Liu and Wimberly, 2015). Other fire characteristics like the timing and duration of the fire season, fire intensity, and reoccurrence intervals have a variety of implications on biodiversity, ecosystem services, and human society (Aldersley et al., 2011; Lavorel et al., 2007).

To characterize fire activity and its impact on ecosystems, the term "fire regimes" was introduced in 1975 by Gill (1975), yet there is neither a universal definition nor an agreement on which fire characteristics have to be included and how to define them (Krebs et al., 2010; Morgan et al., 2001). Whitlock et al. (2010) referred to fire regimes as "the full range of variability in fire activity within a given vegetation type" while Archibald et al. (2013) also added that this repeated pattern of fire should be "at a certain location in space". The list of fire characteristics that are generally accepted to describe fire regimes includes the extent of the burned area, fire frequency, intensity, severity, seasonality, type, and size (Morgan et al., 2001) but this list is not explicit. It was suggested that every user must choose and define each parameter according to the purpose of the study and provide a clear description to avoid misunderstanding and confusion (Krebs et al., 2010).

The choice of a sufficient time frame to capture "repeated pattern" and appropriate "certain location" (spatial unit of the analysis) is as important as the selection of fire characteristics because fire behavior and its effect on vegetation depend on vegetation structure, topography, and microclimate which vary according to the spatial scale (Mckenzie et al., 1996); also ecosystem disturbances such as fire and recovery dynamics further increase landscape heterogeneity (Turner et al., 1994). For example, when estimating fire intervals from individual tree cores collected in the field, fire frequency will change drastically by moving from the tree cluster scale to the forest ecoregion scale (Arno and Petersen, 1983). Since fires burn only a small portion of the landscape, increasing the size of the study area and the number of sample trees will result in a shorter fire return interval (Finney, 1995). At the same time, as we decrease the spatial scale there is a higher likelihood that the area will represent more than one habitat with one particular fire regime (Arno and Petersen, 1983; Lertzman et al., 1998). The choice of the temporal and spatial scale of the analysis depends also on data source: while local or regional studies can be based on forest service or other agencies data with several decades of records (e.g. Moreno and Chuvieco (2013) in Spain, Parisien et al. (2006) in Canada, Faivre et al. (2011) in Mediterranean, Malamud et al. (2005) in the U.S., Drobyshev et al. (2012) in Sweden), this data is not spatially explicit, not always freely accessible, complete, or accurate (Fornacca et al., 2017).

An alternative data source is satellite-derived data that provides coherent multi-temporal spatial information (Benali et al., 2017). Close to two decades of freely available data from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Terra (launched 1999) and Aqua (launched 2002) polar-orbiting satellites, that has specific features for fire monitoring (Justice et al., 2002b, 2002a; Roy et al., 2005), made it possible to analyze recent trends and fire activity pattern from local to global scale (Giglio et al., 2013). Two global MODIS derived products, active fire and burned area products, provide information about the spatial extent of fire, approximate day of burning, and thermal signature of fire with high temporal (1day) at coarse spatial resolution (500-1000m). While remotely sensed data is the only source for global analysis to capture spatial and temporal patterns of fire activity (Benali et al., 2017), those studies are constrained by the length of the archive of available data (Archibald et al., 2013) and there is an open debate if observation record available to date is sufficiently long to conduct meaningful fire regimes analysis especially in places with moderate to low-frequency fire return interval (Bowman et al., 2009; Daniau et al., 2012; Krawchuk and Moritz, 2014).

Regarding spatial units for analysis, previous studies attempting a global fire classification were based on grid cells (Archibald et al., 2013; Chuvieco et al., 2008; Le Page et al., 2008). However, the uniform arbitrary spatial scale might not be appropriate for several reasons: grids might not be homogeneous from the biophysical point of view (Pausas and Fernández-Muñoz, 2012), the arbitrary size of the cell has an impact on fire metrics since fire characteristics are scale-dependent (Morgan et al., 2001), and 0.5° grid cells might be too small to ensure the adequate number of fire detections for statistical analysis, especially in areas with infrequent fires (Malamud et al., 2005). An alternative method for spatial disaggregation of data is the use of homogeneous ecological units (ecoregions) (Pausas and Fernández-Muñoz, 2012). Several studies in the U.S. found consistency in fire characteristics within ecoregions (Littell et al., 2009; Malamud et al., 2005; Westerling et al., 2003), as Abatzoglou and Kolden (2013) pointed out, the use of ecoregions relies on the assumption that fuel loads and fuel types are homogeneous within each ecoregion, which might not be always the case.

Despite the uncertainties and limitations mentioned above, there is a broad need for capturing spatio-temporal variability in fire activity (Bowman et al., 2009): this information is required to estimate the departure from historical conditions (Morgan et al., 2001; Murphy et al., 2013), to improve our understanding of the global trends in fire activity (Bowman et al., 2009), to evaluate the skill of process-based models for predicting variations in fire regimes (Murphy et al., 2011), and to quantify the consequences of fire on biodiversity, ecosystem services and human society (Aldersley et al., 2011; Lavorel et al., 2007). A detailed description of fire regimes is needed to better understand the complex factors that are involved in wildfire activity (Jiménez-Ruano et al., 2017; Moreno and Chuvieco, 2013) and to determine what processes have a dominant effect on variability in fire regimes since variation in one fire characteristics in a region can modify fire regime which can lead to changes in carbon emission and post-fire vegetation regeneration (Kasichke et al., 2010; van der Werf 2010). Additionally, we need a better understanding what causes changing in fire regimes to predict future ecological problems that we can face due to the changing climate, increase in global human population and land transformation (Aldersley et al., 2011; Moreno and Chuvieco, 2013; Syphard et al., 2017) and to develop more realistic projections of different climate change scenarios (Sedano and Randerson, 2014). Information about future fire activity is important for qunatify ecosystem vulnerability and for assessing management options accordingly (Heward et al., 2013; Sedano and Randerson, 2014; Trouet et al., 2006; Turco et al., 2016). Lastly, a better understanding of the climate-vegetation-fire-human interaction can help with one of the biggest challenges we faced on the edge of the environmental crisis: how to create a balance between human needs and the sustainability of natural ecosystems (Pausas and Keeley, 2009).

This work evaluates the fire-vegetation-climate relationship for large spatial areas to improve our understanding of how environmental context determines different aspects of fire regimes across biomes. The dissertation is divided into three main chapters that further develop the three main goals of the research: (1) to investigate the drivers of trends and inter-annual variability in fire activity by systematically analyzing the relationship between climate and the amount of burned area; (2) to propose a new framework for defining continental fire regimes by delineating climate niches based on key drivers of fire, and characterizing them using several fire regime metrics; and (3) to apply the proposed framework worldwide to identify global fire regimes and understand the major drivers of fire activity.

In each chapter the extent of the study area is expanded. Chapter 2 analyzes climatic controls on burned area in Africa, the most fire-prone and the only continent with significant recent trend in the amount of burned area. Chapter 3 defines fire regimes in Africa and Australia, two most fire-prone continents with a similar list of biomes yet substantially different in terms of main fire regime characteristics. Chapter 4 applies the framework developed for Africa and Australia to ecoregions globally in order to define modern fire regimes and understand what shapes fire regimes at the global scale. These results are summarized and discussed in Chapter 5. The results of this research provide a source of information which is useful to guide current fire research at broad spatial scales and a foundation for evaluating how projected changes in climate and land use may modify fire regimes in the future.

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Introduction

Several recent studies have reported a global decline in burned area, prominently observed in Africa (Andela et al., 2017; Earl and Simmonds, 2018). Africa is the most fire prone continent, responsible for over half of the global area burned and for more than half of the global pyrogenic greenhouse gas emissions (Rabin et al., 2015; van der Werf et al., 2017). According to satellite-derived estimates, over 80% of burned area (BA) in Africa occurs in savanna with the remainder occurring in forests and croplands (Giglio et al., 2013). Fire seasonality in Africa follows the respective dry seasons occurring primarily from October to March with a peak of the season in December-January for Northern Hemisphere (NH), and April to October with a peak in August for Southern Hemisphere (SH) (Boschetti and Roy, 2008). Savanna fires in Africa are generally surface fires, burning as frequently as every 1-6 years (Archibald et al., 2013, 2010c). The long dry season of African savannas and the high rate of fuel accumulation have been identified as the main contributors of such an extensive amount of burning (Archibald et al., 2009); grasses can regrow quickly after the fire, which makes the ecosystem prone to frequent fires (Archibald et al., 2009; Van Wilgen, 1997).

Three components must be present for fire ignition: sufficient biomass to burn, fuel flammability, and an ignition source (Bradstock, 2010; Moritz et al., 2012). Both climate and humans can modify biomass abundance, the number of ignitions, and potential fire spread. It is challenging to decouple the effect of these drivers, especially in Africa, a continent where humans have influenced the fire regime for millennia and where up to 90% of fires might be anthropogenic (Andela et al., 2017; Archibald Sally, 2016; Knowles et al., 2016). Precipitation has a strong impact on the amount of BA in Africa (Andela and van der Werf, 2014; Archibald et al., 2010a), but the relationship between fire activity and moisture availability is highly variable and ecosystem-dependent (Abatzoglou et al., 2018; Williams and Abatzoglou, 2016). In fuel-limited ecosystems, precipitation promotes fuel load accumulation and subsequent fires, while in energy-limited ecosystems, precipitation enhances fuel moisture and limits flammability and fire spread (Daniau et al., 2012; Murphy et al., 2011). Additionally, several studies have confirmed that climatic variables related to water balance specific to vegetation demands, and therefore fuel moisture, have stronger and more direct relationships with fire activity compared to precipitation (Barbero et al., 2015; Daniau et al., 2012; Riley et al., 2013). The impact of human activities on fire is inherently complex, with direct and indirect effects. Increased population can directly result in increased ignitions, fire suppression, as well as altered fire seasonality (Balch et al., 2017). Indirectly, human activities lead to reductions of fuel amount and fuel connectivity due to livestock pressure, cropland expansion, and road density (Archibald Sally, 2016). Anthropic influences on fire also vary geographically. For example, fire has long been used as a land management tool in much of Africa; fire is widely used for preparing agricultural fields, preventing bush encroachment, improving quality and quantity of forage, maintaining biodiversity, hunting, and reducing future fire risk (Knowles et al., 2016; Le Page et al., 2010).

Previous studies have used empirical climate-fire models (Andela et al., 2017; Andela and van der Werf, 2014; Earl and Simmonds, 2018) to elucidate drivers of recent changes in fire activity in Africa. While the BA inter-annual variability in SH was partly explained by rainfall variability (Andela and van der Werf, 2014), the nature of the strong BA decline in NH is still not well understood. Earl and Simmonds (2018) proposed that it is linked to the observed increase of net primary productivity (NPP). This increase in NPP in Africa was attributed to decrease in vapor pressure deficit (Zhao and Running, 2010) and increase in rainfall (Hoscilo et al., 2014). We hypothesize that increased fuel moisture reduced flammability and BA. Andela and van der Werf (2014) pointed at socio-economical changes as a main factor of reduction in BA NH Africa; however, their statistical models showed that only a quarter of the decline was attributed to cropland expansion and another quarter to changes in precipitation, leaving the remaining half of the reduction unexplained.

In the present study we reanalyzed the recent changes in fire activity in Africa using the MODIS MCD64A1 Burned Area product over a 15-year study period (2002-2016). Previous studies have typically calculated trends and variability in fire activity using high spatial resolution grids, possibly at a scale too fine for appropriately describe top-down climate-fire relationships on inter-annual time scales. Furthermore, they did not distinguish the influence of climate on fuel abundance and flammability for different vegetation types (Littell et al., 2016).We analyzed trends at the ecoregion scale and further examined changes within cropland and natural lands. Further, we expand on previous work by systematically exploring a simple relationship between the amount of burned area and climate, considering not only precipitation but also variables that are more mechanistically related to plant-available water and flammability. The overarching goal of this study is to investigate the drivers of trends and inter-annual variability in fire activity in Africa which will be useful for fire policies and management, and statistical fire and vegetation models.

Methods and Materials

Datasets

Burned area: the most recent Collection 6 MODIS Global Burned Area Product (MCD64A1) provides daily global 500m resolution BA maps (Giglio et al., 2018). The MCD64A1 data record from April 2002 to March 2017 was used to derive a monthly BA time series. Although the MODIS fire products are available from April 2000 onward, their use prior to November 2000 and during June 2001 is deprecated because of extended outages (Giglio et al., 2016).

Climate variables: the choice of an appropriate climate dataset is vital but challenging, particularly in Africa where the lack of a dense weather station network severely affects data reliability (Dinku et al., 2014; Tadesse et al., 2014; Tote et al., 2015) especially for precipitation (Beck et al., 2017). We chose the Famine Early Warning Systems Network Land Data Assimilation System (FLDAS) since it was produced specifically for drought monitoring in Africa (McNally et al., 2017), and incorporates precipitation data from infrared satellite observations, atmospheric models, and stations. We used simulation run “C” that used Noah Land Surface Model and outputs from MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications) at 0.5° resolution (Rienecker et al., 2011) and CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) at 0.1° resolution

(Funk et al., 2015) which has been extensively used in Africa (Dembélé and Zwart, 2016; Funk et al., 2015; Tote et al., 2015). Additionally, overall trends in precipitation and surface soil moisture derived from FLDAS agree with independent satellite-derived trends from GRACE 2002-2016 that depicts increased terrestrial water storage across much of Africa (Rodell et al., 2018), thus further supporting our choice of precipitation dataset. From FLDAS we considered precipitation (P) and soil moisture content at 0-10 cm depth (SM). Penman-Monteith reference evapotranspiration data (ETo) was derived from MERRA-2 for consistency, being one of the FLDAS inputs. Effective Rainfall (ER) was calculated as P minus ETo. Monthly P, ER and SM time series were generated from January 2001 to March 2017.

Global ecoregions: the Terrestrial Ecoregions Of the World (TEOW) (Olson et al., 2001) were used as the spatial analysis unit, because of commonalities in vegetation which mediates climate-fire relationships as in previous studies (Abatzoglou et al., 2018).

Land cover: the Land Cover Climate Change Initiative (LC-CCI) v.1.6.1 Annual Global Land Cover (2002-2015) was used to mask unburnable surfaces and to define land cover types within ecoregions. The LC-CCI 300m resolution maps are generated from MERIS, PROBA-V, SPOT-VGT, and AVHRR data (CCI-LC-PUGV2, 2017).

Livestock density: Gridded Livestock of the World (GLW 3) global subnational livestock distribution data for 2010 at 0.083333° (Gilbert et al., 2018). Densities of different livestock species were combined into Actual Carrying Capacity (ACC) defined in equivalent Tropical Livestock Units (TLU), applying the conversion factors for cattle (0.70), sheep and goats (0.10) proposed by Pica-Ciamarra et al., 2007.

Road density: Global Roads Inventory Project (GRIP) global gridded road density dataset at 8 km resolution (Meijer et al., 2018).

Analysis

For the purpose of the analysis, TEOW and LC-CCI were used to create a two-level stratification, separating ecoregions by broad land cover types (forests, non-forest, and cropland). In this study, savannas, shrublands and grasslands were aggregated into the non-forest class; croplands include all LC-CCI cropland and cropland-natural vegetation mosaic classes.

Burned Area Seasonality and Trends

Total BA was summarized using the April-to-March optimal fire year (FY) proposed by Boschetti and Roy (2008). This resulted in a 15-year annual BA time series stratified by land cover and ecoregion. Ecoregions where a land cover is not significantly present (i.e. less than 5% of the ecoregion area) and/or with negligible fire activity (less than 0.5% of the ecoregion burned on average) were excluded from the analysis. For each ecoregion, the fire season (FS) was determined as the minimum number of consecutive months in which 80% of the total average annual BA occurs (Abatzoglou et al., 2018).

In order to determine spatial patterns and rates of change, BA trends were calculated for each ecoregion by fitting a simple linear regression to the 15-year BA time series; trends were thus represented by the slope of the regression line.

Analysis of potential anthropogenic drivers

Human activity has both the potential of increasing fire activity, through accidental and intentional ignitions, and decreasing it by transforming natural land into croplands, reducing fuel load through grazing, and due to landscape fragmentation (Archibald Sally, 2016; Knowles et al., 2016). The lack of gridded, multi-temporal datasets of variables directly linked to human pressure limits the possibility of including anthropogenic drivers in a continental fire model. As an alternative, we created spatial masks of (a) croplands, (b) grazing pressure, and (c) road density, and analyzed separately the BA trends inside and outside the areas affected by significant human activity.

In order to fully account for cropland expansion during the study period, we aggregated the annual landcover maps to define a single cropland mask encompassing any pixel mapped as cropland or cropland/natural vegetation mosaic during 2002-2016. This choice ensures that the burned area trends observed inside the cropland mask fully capture both cropland expansion and any changes in agricultural practices, whereas the trends observed outside of the mask reflect only areas that remain natural lands for the entire time period.

Grazing negatively influences fire activity, since livestock reduces available fuel (Anderson et al., 2007; Archibald et al., 2009; Archibald and Hempson, 2016). Spatial analyses have observed that BA in SH Africa is drastically reduced when ACC is greater than 6 TLU, but relationships between grazing pressure and area burned are non-linear since more grazers are required to reduce fuel loads in more productive ecosystems (Archibald et al., 2009; Archibald and Hempson, 2016). To account for the different agro-ecological conditions across Africa, we followed the methods proposed by Pica-Ciamarra et al. (2007), using reference Maximum Carrying Capacity (MCC) values provided for different levels of annual rainfall, and defining four grazing pressure classes based on the ratio between the ACC from the GLW3 dataset and MCC (Table 2.1).

We defined a map of high/low road density by applying to the GRIP dataset the threshold value of 33.3 m/km2 after which BA significantly decreases, proposed by Archibald et al. (2009).

Table 2.1. Actual Carrying Capacity, expressed in Tropical Livestock Units, for the four levels of grazing pressure. The four grazing levels are defined based on the ratio between Actual Carrying Capacity (ACC) and Maximum Carrying Capacity (MCC). MCC is defined for four levels of total annual rainfall (Pica-Chamarra et al., 2007).

Level of livestock pressure	Arid < 500 mm	Semi-arid 500-1000 mm	Sub-humid 1000-1500 mm
None (ACC/MCC ≤ 0.5)	< 5	< 12.5	< 16.5
Low (0.5 < ACC/MCC < 0.74)	5 - 7.4	12.5 - 18.5	16.5 - 24.5
Medium (0.75 < ACC/MCC < 0.99)	7.5 - 10	18.6 - 25	24.5 - 33
High (ACC/MCC ≥ 1)	> 10	> 25	> 33

Fire-climate relationship

We investigated the relationship between fire and climate on natural lands (i.e. excluding all croplands as defined above) using ecoregion-level linear models that predict BA as a function of climate variables, temporally integrated over meaningful intervals that represent conditions prior to and during the FS.

Three climate variables (P, ER and SM) were considered because previous studies found them to be strong predictors of fire activity and drought in forest and savanna (Daniau et al., 2012; Higuera et al., 2015; Lehmann et al., 2014; McNally et al., 2017). Previous studies showed that the relationship between fire and climate can be sensitive to the seasonal windows examined (Littell et al., 2016); we therefore considered distinct temporal accumulation intervals that capture the conditions both antecedent to the FS and concurrent with the FS which encompass the influence of climate variability on fuel loading and flammability, respectively. The average monthly value of each variable was calculated for each ecoregion, and integrated for each year over two temporal intervals: the FS, and the water year preceding the fire season (1WY), defined as the 12-month period ending 2 months before the FS (Abatzoglou et al., 2018).

The relative importance of antecedent and concurrent conditions changes across ecosystems. For example, in fuel-limited ecosystems, like SH non-forest, antecedent moisture is the main driver of fire activity, because it promotes biomass accumulation and therefore increase the amount of available fuel to support subsequent fires (Archibald et al., 2010b; Balfour and Howison, 2002; Van Wilgen et al., 2004). In energy-limited systems, like tropical forests, unusually dry conditions during the FS promote fire activity because of increased flammability (Cochrane, 2003; Higuera et al., 2015; Littell et al., 2016).

Expanding on the approach by Abatzoglou et al. (2018), for each ecoregion the relationship between BA and climate time series was explored through a simple linear model. BA was log-transformed to satisfy the assumption of normality as BA data are often right skewed (Abatzoglou et al., 2018; Higuera et al., 2015). Thus, the base-10 logarithm of the annual BA (BA_{LC}) in each land cover type (forest, non-forest) of each ecoregion is predicted as the linear combination of antecedent (C1) and concurrent (C2) climate conditions, plus an error term ε:

$$\log(BA_{LC}) = \beta0 + \beta1 \times C1 + \beta2 \times C2 + \varepsilon \qquad (1)$$

The model (1) was built separately for the three climate variables to evaluate the robustness of relationships and test whether measures of surface moisture that are more mechanistically related to plant-available moisture improve upon those which only consider precipitation; in each case, β0, β1 and β2 were estimated through ordinary least squares, and the time series of predicted BA (BApred) was computed. The ratio =t(BApred)/t(BA) , between the slope t [Mha yr-1] of the linear interpolation of the predicted and observed BA time series is the fraction of BA trend that can be explained by the climate variables, and represents the degree to which climate variables have driven BA changes in our model framework.

To verify the assumption of independence of covariance of the predictor variables, we computed the variance inflation factor (VIF), that quantifies the severity of multicollinearity of C1 and C2, with VIF>5 being a common cutoff value for high collinearity (James et al., 2017).

We computed the Durbin-Watson statistic to assess the temporal autocorrelation (Durbin and Watson, 1950). Because in several ecoregions the test confirmed temporal autocorrelation at one year lags, we also explored a modified version of (1) using the first-order differencing procedure which is one of the most common remedies for temporal autocorrelation (Chatfield, 2003; Wooldridge, 2012).

Given the relatively short time interval of the study, we verified the robustness of the analysis by testing the use of simplified versions of (1), using for each ecoregion the single time interval that resulted in the largest adjusted coefficient of determination. Additionally, we repeated the analysis by using de-trended climate and BA time series to fit the model, and then applying the model to the original time series.

Results and discussion

Burned Area Trends

During the study period, the annual average BA in Africa was 280.6 Mha, 45.7% of which was in NH. Of the 112 ecoregions, 81 had significant fire activity; the ecoregions excluded from the analysis are prevalently located around the Sahara Desert. Non-forest fires were predominant (204.7 Mha yr-1, 72.9% of the total), followed by forest fires (41.1 Mha yr-1, 14.7% of the total) and cropland fires (34.8 Mha yr-1, 12.4% of the total) (Figure 1).

Overall, BA in Africa declined by 51.9 Mha (18.5%) during 2002-2016 with 80.3% of the decline (41.7 Mha) occurring in NH. Negative trends were statistically significant ($p < 0.05$) in 21 of the 81 ecoregions, 14 of which were in NH. Although several ecoregions showed a positive trend, none were statistically significant.

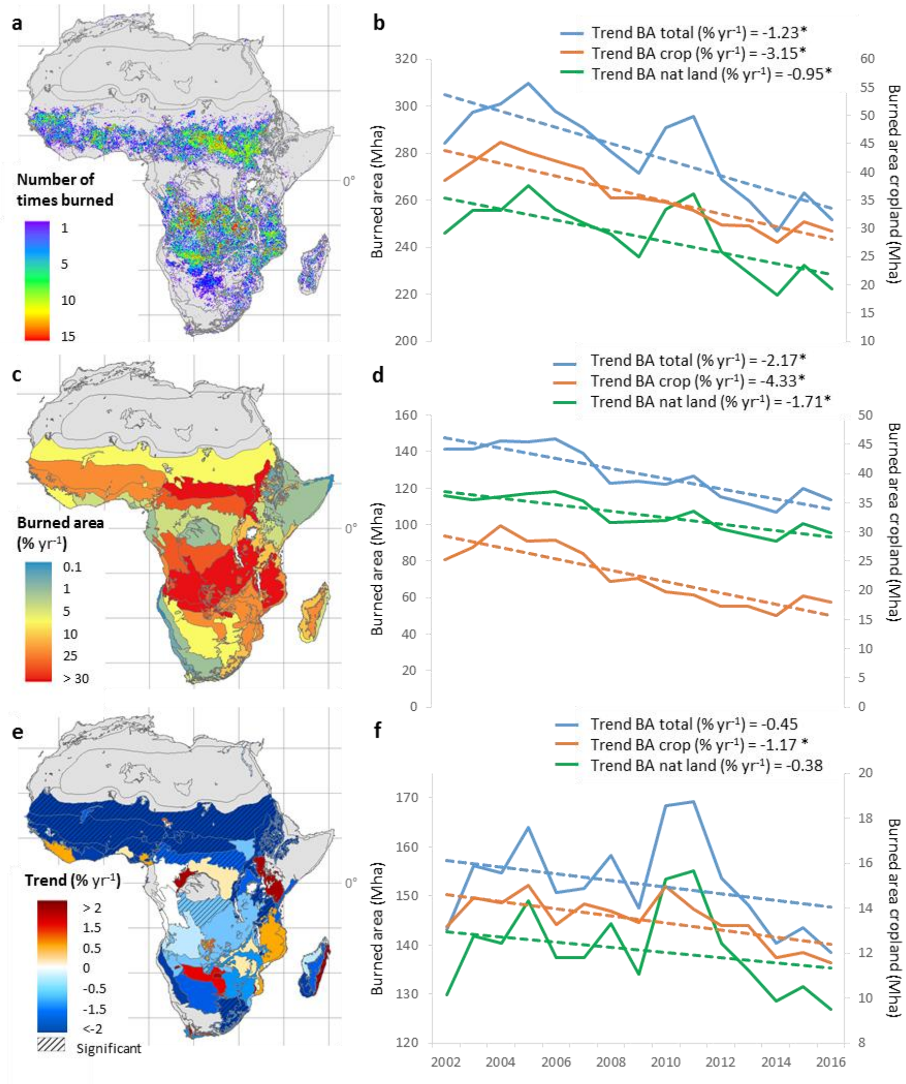

Figure 2.1. Left column: (a) Number of times burned during in the 2002-2016 study period (at MODIS 500m resolution) (c) Average ecoregion burned area fraction per year; (e) Linear trends in burned area. Grey color represents ecoregions with negligible fire activity (less than 0.5% of the ecoregion burned on average). Graticule lines are every 10°. Right column: Burned area time series observed by MCD64A1 for: (b) Whole continent; (d) Northern Hemisphere; (f) Southern Hemisphere. In all three cases, the plots report the total burned area (blue lines), the burned area detected in croplands (orange lines) and the burned area detected in natural lands (green lines), with the respective trends represented by the dashed lines. Asterisk indicates significant trends.

Impact of human factors on BA trends

The cropland mask derived from the aggregation of the 2002-2015 LC-CCI annual maps encompassed a total of 491 Mha, with only a modest expansion (1.06 Mha) observed in the study period. The inter-annual variability within natural lands and croplands is very similar (Figure 2.1 right column); since it is well established that climate explains most of fire inter-annual variability (Andela et al., 2017), this may imply that climate is responsible for years with high or low fire activity even in croplands. BA trends have the same direction but vary in magnitude, with cropland burning experiencing a steeper negative trend than natural landcovers in both hemispheres. Overall, croplands account for 31.7% of the total BA decline (31.6% in NH, 32.0% in SH).

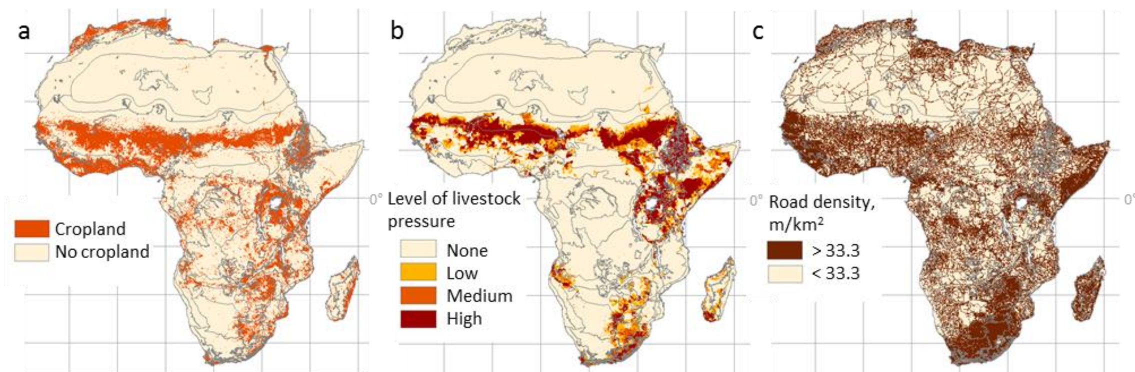

Figure 2.2. (a) Cropland mask; (b) Level of livestock pressure; (c) Road density. All maps are created at native resolution. Graticule lines are every 10°.

Livestock pressure (Figure 2.2b) highly correlates spatially with croplands (Figure 2.2a), with over 50% of the high livestock pressure areas falling within the cropland mask. We separately computed BA trends for each livestock pressure class on croplands and on natural lands (Table 2.2). Considering the whole continent, the negative trend is higher with some grazing pressure (-1.7% to -1.9% on natural lands, -4.6% to -4.7 % on croplands) than no grazing pressure (-0.8% on natural lands, -2.4% on croplands). The two hemispheres however exhibit a very different behavior, with a strong connection between livestock pressure and BA trends in SH both in croplands and natural lands, and a negligible connection in NH. In particular, about 75% of BA in NH, and the strongest negative trend (-1.9% yr^{-1} which accounts for 78% of the BA decline), occurred in areas with no livestock pressure. Higher level of livestock pressure showed a very similar, albeit slightly lower trend (-1.6% yr^{-1}, -1.3% yr^{-1} and -1.6% yr^{-1} for low, medium and high pressure respectively). These results suggest that part of the observed BA reduction in croplands could be attributed to grazing, but the decline of BA on natural lands in NH does not appear to be related to livestock pressure.

Table 2.2. Impact of livestock pressure on trends in burned area. Refer to Table 2.1 for definitions of level of livestock pressure.

Level of livestock pressure	Trend in burned area in natural land (km^2/year)			Trend in burned area in cropland (km^2/year)		
	NH	SH	Total	NH	SH	Total
None	-14789 (-1.9%)	-2495 (-0.2%)	-17287 (-0.8%)	-5087 (-4.1%)	-808 (-0.68%)	-5895 (-2.4%)
Low	-2009 (-1.6%)	-1056 (-2.9%)	-3065 (-1.9%)	-1466 (-4.7%)	-314 (-4.32%)	-1780 (-4.6%)
Medium	-785 (-1.3%)	-540 (-3.73%)	-1325 (-1.7 %)	-1165 (-4.6%)	-187 (-4.8%)	1352 (-4.6%)
High	-1423 (-1.6%)	-526 (-4.1%)	-1949 (-1.9%)	-1987 (-4.5%)	-268 (-6.9%)	-2255 (-4.7%)

BA trends stratified by road density and landcover are reported in Table 2.3. At the continental level, high road density corresponds to a slightly more pronounced BA trend (-0.9 and -1.1% for low and high road density in natural lands, -3.0% and -3.3 in croplands), with a stronger relationship in SH than NH. In natural lands in particular, the trend is -0.2 % and -0.5% for low and high density in SH, while -1.7% and -1.9 % in NH. These results suggest that in NH road density is not a likely driver of BA decline in natural lands.

Table 2.3. Impact of road density on trends in burned area.

Road density (m/km2)	Trend in burned area in natural land (km^2/year)			Trend in burned area in cropland (km^2/year)		
	NH	SH	Total	NH	SH	Total
< 33.3	-11199 (-1.7%)	-1395 (-0.2%)	-12594 (-0.9%)	-3607 (-4.1%)	-623 (-1.2%)	-4225 (-3.0%)
> 33.3	-7847 (-1.9%)	-3179 (-0.5%)	-11026 (-1.1%)	-6119 (-4.5%)	-956 (-1.2%)	-7074 (-3.3%)

Climate and BA trends in natural lands

Increased ER and surface SM due to a combination of increased rainfall and decreased ETo have been observed across much of Africa in the last 15 years (Figure 2.3i-l). BA in non-forest (Figure 2.4) negatively correlates with all three climate variables at concurrent (FS) and antecedent (1WY) timescales in Northern and Central Africa, and positively in Southern Africa but only at antecedent timescales. Noticeably, P has a weaker correlation with BA than ER and SM in all ecoregions. Considering forests instead (Figure

2.5), most of the ecoregions did not have a strong relationship between BA and either concurrent or antecedent climate conditions, and this relationship was predominantly negative.

The linear models (1) were estimated for each ecoregion and landcover, separately for each climate variable. Only two ecoregions had VIF > 5, indicating that the use of C1 and C2 in (1) is not redundant.

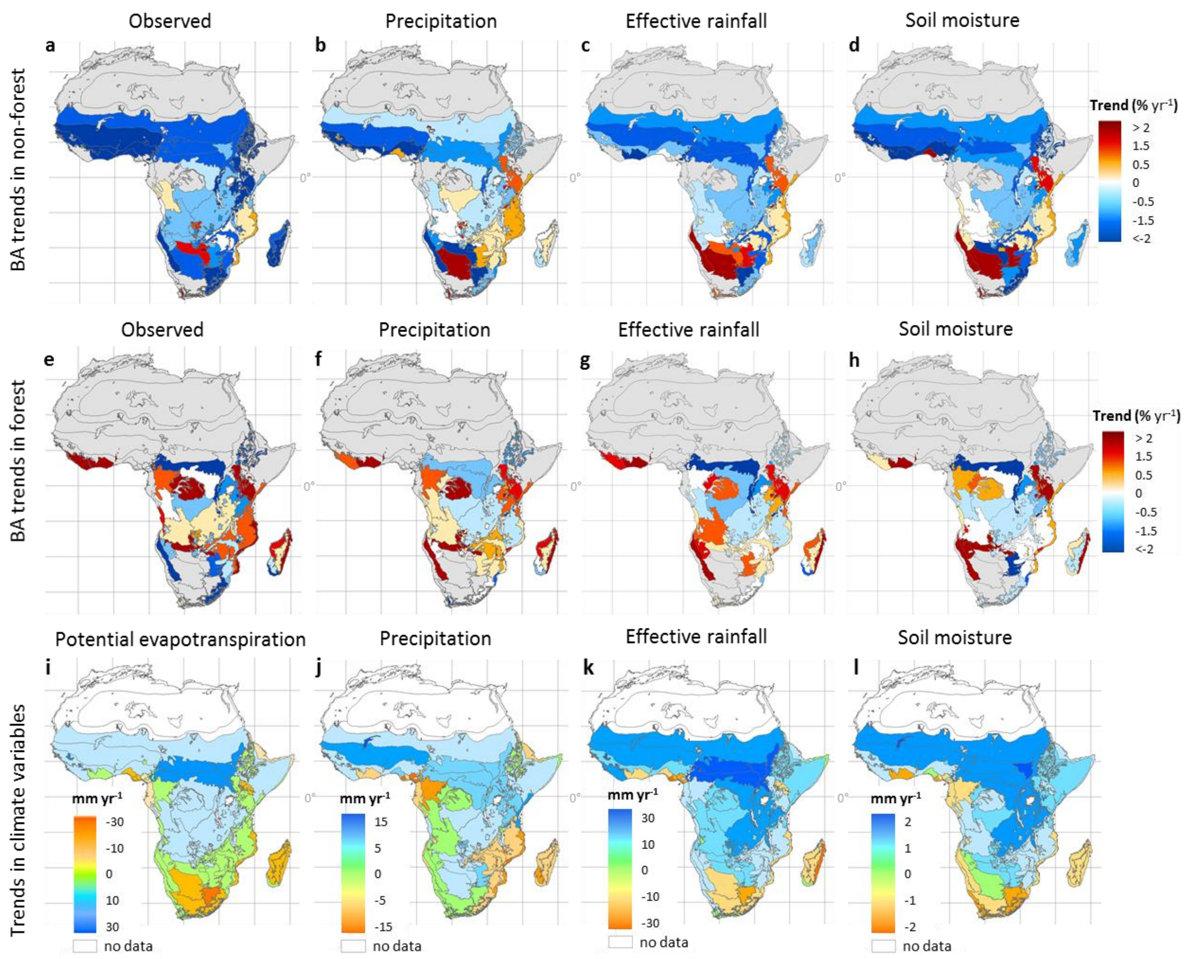

Figure 2.3. Linear trends in burned area and climate data. Top row (a-d): BA trends in non-forest; middle row (e-h): BA trend in forest; bottom row (i-l): trends of climate variables. (a, e) Observed linear trend in burned area; (b, f) modeled linear trends using precipitation as a predictor; (c, g) modeled linear trends using effective rainfall as a predictor; (d, h) modeled linear trends using soil moisture as a predictor. Grey color represents ecoregions with negligible fire activity in each landcover. Graticule lines are every 10°.

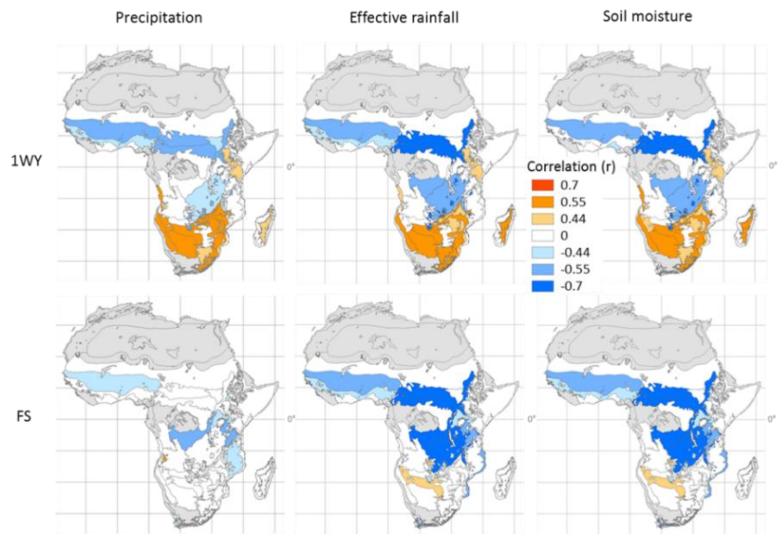

Figure 2.4. Linear Pearson's correlation coefficients between the base-10 logarithm of fire year burned area for non-forest land cover type and climate variables calculated over two time intervals: 12-month accumulated precipitation ending 2-months prior to the fire season (1WY, top row), and over the fire season (FS, bottom row) using the MCD64A1 burned area for the period 2002-2016. Only statistically significant correlations (|r|>0.44, p-value<0.5) are reported. Ecoregions with less than 5% land cover for each vegetation class are shaded gray. Graticule lines are every 10°.

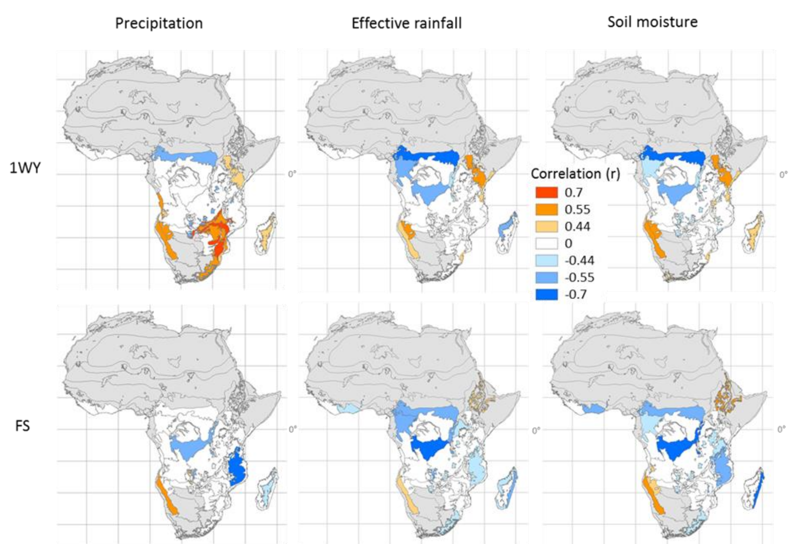

Figure 2.5. Linear Pearson's correlation coefficients between the base-10 logarithm of fire year burned area for forest land cover type and climate variables calculated over two time intervals: 12-month accumulated precipitation ending 2-months prior to the fire season (1WY, top row), and over the fire season (FS, bottom row) using the MCD64A1 burned area for the period 2002-2016. Only statistically significant correlations (|r|>0.44, p-value<0.5) are colored. Ecoregions with less than 5% land cover for each vegetation class are shaded gray. Graticule lines are every 10°.

ER was the best predictor of the overall BA decline, explaining 73.2% of the observed trend, followed by SM (60.8 %) and P (30.1 %). SM, however, better reconstructed the inter-annual variability, resulting in slightly lower residuals (MAE = 2.7%) than ER (MAE = 3.0%); P had instead significantly higher residuals (MAE = 4.2%). Considering separately the two hemispheres and the two landcovers, in NH ER was the best predictor in non-forest, with SM performing only marginally worse. While in NH in forest, SM was a better predictor. In SH there is no clear pattern, with all three variables performing similarly both in terms of trend, and inter-annual variability. To summarize the results, Figure 2.6f reports the prediction obtained using the best variable for each ecoregion; Figure 2.7 shows the spatial distribution of the best climate predictor for each ecoregion. Temporal autocorrelation was significant only in few ecoregions, and the results of the transformed models are consistent with the original models. The simplified version of the models confirmed that ER is the best predictor (69.1% explained), followed by SM (52.6 %) and P (26.8 %). The more conservative models based on de-trended time series further indicates that ER is the best of the three predictors, especially in NH Africa. However, the predictive power of the simplified models decreased substantially, arguably due to the low inter-annual BA variability in NH Africa, which is problematic when fitting the model to de-trended data.

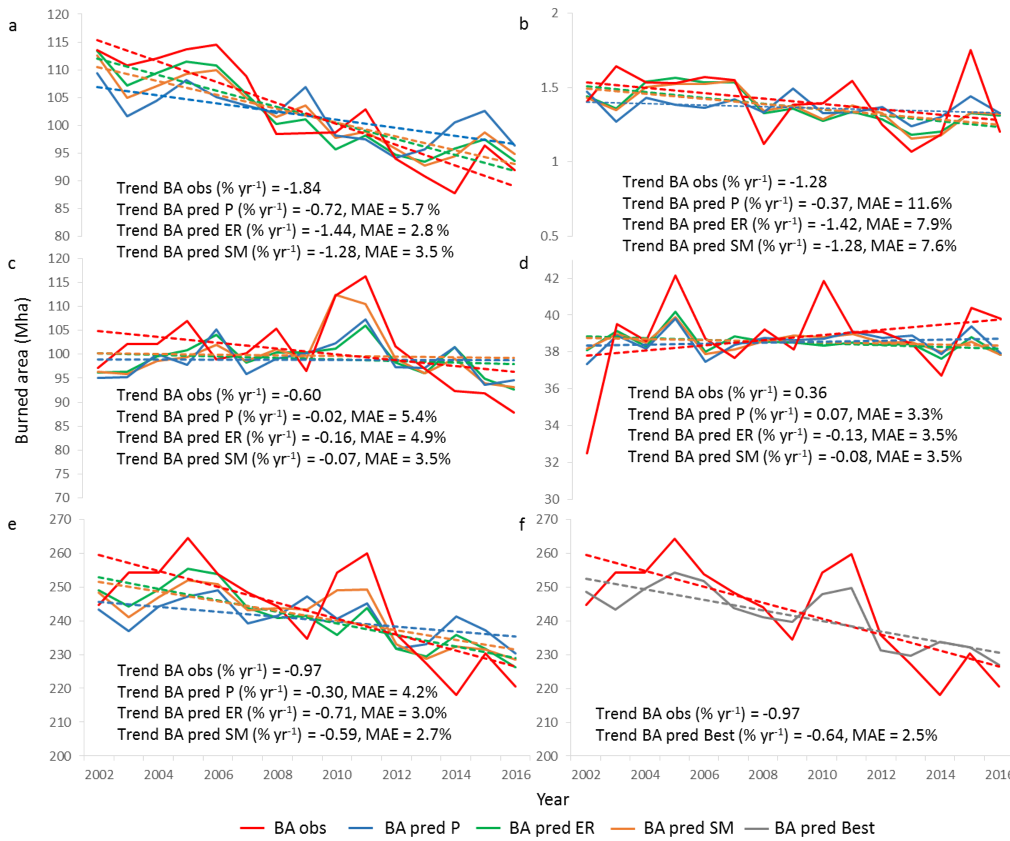

Figure 2.6. Observed and predicted BA in natural lands. Linear trends in (a) NH non-forest; (b) NH forest; (c) SH non-forest; (d) SH forest; (e) the whole continent; (f) the whole continent, selecting in each ecoregion the model with the highest adjusted R2 (Figure 2.7). (BA obs – burned area observed from MODIS MCD64A1; BA pred – burned area predicted by linear models; P – model was computed with precipitation as predictor; ER – effective rainfall; SM – soil moisture; MAE – mean absolute error as a percent of the average BA obs).

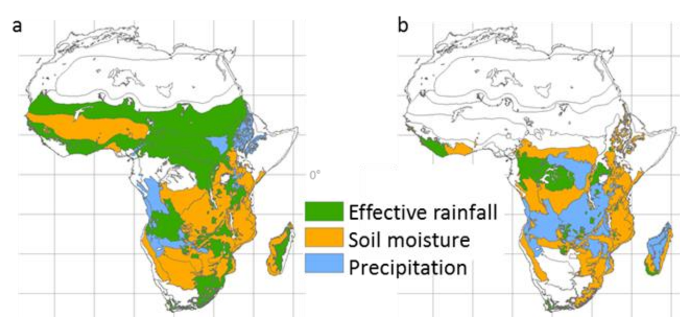

Figure 2.7. Climate variable resulting in the model with the best prediction of the BA time series (i.e. highest adjusted R2) in each ecoregion for (a) non-forest, (b) forest. Graticule lines are every 10°.

These results point to increased fuel-moisture in humid area as an alternative explanation of the recent decline in BA in Africa. Increased moisture during the FS reduces fuel flammability thereby limiting ignitions and fire spread, particularly in wet savannas (mean annual precipitation >900 mm yr^{-1}) where moisture is not a limiting factor for vegetation productivity and fuel for fire propagation (Herrmann et al., 2005; N'Datchoh et al., 2015). In the drier savanna of Southern Africa, instead, a positive rainfall-fire relationship is observed: increased moisture in the years before the FS promotes biomass productivity, and hence more dry flammable fuels in the following year (Archibald et al., 2009; Daniau et al., 2012). These results are consistent with previous findings by Andela and van der Werf (2014). Forests in Africa are located within humid and moist sub-humid zones that are not fuel-limited, and therefore the negative correlation with climate variables is supported by other studies that found these ecosystems to be sensitive to fire weather and drought (Bedia et al., 2015; van der Werf et al., 2008).

Conclusions

We analyzed recent changes in fire activity in Africa using the 2002-2016 Collection 6 MODIS MCD64A1 Burned Area Product. We observed a strong BA decline in both hemispheres, although trends were only statistically significant in NH. Reductions in cropland BA accounted for approximately one third of the continent-wide decline, but BA declines in natural lands were predominantly associated with climatic conditions which yielded increased near surface moisture during 2002-2016. Climate variables that account for near-surface moisture availability antecedent and concurrent to the fire season were the strongest BA predictors. We found that ER explained both the most inter-annual variability and trend in BA of the three moisture variables considered. Overall, these results show that climate variables can explain a larger portion of the BA decline in Africa compared to previous studies (Andela and van der Werf, 2014). This outcome may be due to the use of more complex climate variables (EM, SM), to the improved empirical models that use physically meaningful accumulation time intervals, and to the adoption of ecologically relevant spatial analysis units rather than a lattice of square cells (Abatzoglou et al., 2018).

Recent trends in terrestrial moisture may be result of internal climate variability including El Niño–Southern Oscillation and sea-surface temperatures in the tropical Pacific and Indian Oceans (Andela and van der Werf, 2014; Earl and Simmonds, 2017; Rocha and Simmonds, 1997a, 1997b). However, looking at the regional scale, Hulme et al. (2001) established strong forcing of ENSO only in southeastern and eastern equatorial Africa. While Western Africa region with the strongest decline in BA showed little or no rainfall sensitivity to ENSO. Climate model simulations predicted further increase in SM and decrease in drought risk in NH Africa in the second half of the century due to increase in precipitation and/or decrease in evaporative demand (Beck et al., 2017; Lehner et al., 2017). This may imply that current increased fuel-moisture is not due to the current cycle of large-scale atmospheric processes and additional research is needed to attribute the origins of such trends.

We acknowledge several limitations of this study. All input datasets are inherently affected by uncertainties: (i) the accuracy of our cropland mask depends on the LC dataset, whose spatial resolution might be too coarse, especially in very fragmented landscapes; (ii) while MCD64A1 better detects small fires than previous global BA datasets (Giglio et al., 2018) it still underestimates BA in croplands and tropical forests, therefore affecting the confidence of our analysis in these landcovers; (iii) despite selecting climate datasets specifically designed and/or validated in Africa, it is well documented the scarcity of direct observations might cause biases (Akinsanola et al., 2017; Beck et al., 2017). While the 15-year study period is relatively short for assessing trends, particularly for fire metrics (Parks et al., 2014), the very short fire return intervals in Africa and spatial extents of the ecoregions mitigates the risk of finding spurious correlations. Finally, we note that not in all ecoregions we were able to adequately model BA trends and inter-annual variability using climate variables alone. This is not unexpected given the numerous other environmental and societal factors influencing fire activity, especially in ecoregions where the majority of BA occurs in croplands, and where it is likely that human activity is the main driver of long-term BA trends. We believe that this research places a high priority on the development of continental scale BA models that assess the impact of both human and climate drivers.

Limitations notwithstanding, our finding of a strong relationship between ER, SM and BA in most fire-prone ecoregions in Africa provides new insights into the fire-climate relationship in savannas. Although precipitation promotes fuel build up prior to the fire season, climate variables that incorporate additional meteorological inputs arguably better reflect plant available moisture, resulting in better predictive ability in a simple linear model.

We believe that this paper work contributes to a growing body of research aimed at better understanding the relationship between anthropogenic pressure, climate and fire. Our findings suggest that, regardless of the magnitude of human contributions, the role of climate in the changing fire regimes of Africa should not be ignored.

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Chapter 3: A Tale of Two Fire Continents: Fire and Climate Drivers in Africa and Australia

Introduction

Fire activity is often characterized in terms of 'fire regime', generally defined as a particular combination of fire characteristics such as fire frequency, size, intensity, severity, seasonality, and type (Gill, 1975). Despite the abundance of published studies focused on fire regimes (Archibald et al., 2013; Chuvieco et al., 2008; Faivre et al., 2011; Jiménez-Ruano et al., 2017; Le Page et al., 2008), there is neither a consensus on the definition of fire regime, nor on what fire characteristics need to be included and how to define them (Krebs et al., 2010). The most commonly adopted approach for the identification of fire regimes is empirical: several metrics derived from remotely sensed datasets of active fire or burned area detections are used as an input for an unsupervised classifier, and explanatory factors are only subsequently associated to the resulting classification (Archibald et al., 2013; Conedera et al., 2018; Faivre et al., 2011; Le Page et al., 2008; Riaño et al., 2007). This type of approach does not take into consideration any of the underlying biophysical processes that lead to a particular fire regime, which makes future predictions based on changing environmental factors challenging. Neither has it provided a sensitivity analysis to understand how a particular choice of fire metrics affects the final output.

In this study, we explored a new framework for defining "fire regions", meaning regions homogeneous in terms of fire activity rather than "fire regimes" since our analysis was constrained by the data span of the available 2002-2019 record of fire activity from MODIS satellite observations, which might be too short for fire regime definition; also due to the lack of data some vital fire metrics were absence from our analysis such as fire severity and fire type. The fire regions were defined as climate niches, based on key drivers of fire, and subsequently characterized in terms of summary metrics derived from satellite-based fire products. Similar to biomes (Olson et al, 2001), those climate niches were identified by analyzing the spatial pattern of few variables that roughly describe the conditions relevant to fire activity. We applied a conceptual model of the main drivers of fire regimes proposed by Bradstock (2010) such as biomass (amount of fuel), availability to burn (fuel moisture), fire spread (fire weather). Ignitions were not considered since it was suggested that it is not a limiting factor if humans are present (Archibald et al., 2009).

We applied this method to investigate the biogeography of fire across Sub-Saharan Africa and Australia two most fire-prone continents that are responsible for more than half of total global emissions from biomass burning, and where savanna is the dominant landcover affected by fire (van der Werf et al., 2017). This new framework allowed us to analyze whether, despite the similar vegetation composition, fire activity is significantly different between two continents.

Savanna ecosystems are unique in terms of vegetation composition, due to the coexistence of grasses and woody species which make them highly valuable for biodiversity and ecosystem services (Ratnam et al., 2011; Scholes and Archer, 1997). Savannas are the most fire-prone ecosystem globally due to defined wet and dry seasons, where the first promotes fuel accumulation and the second causes fuel desiccation and flammability (Bond and Keeley, 2005; Hoffmann et al., 2012). Frequent fire limits tree encroachment and promotes a continuous grass layer that rapidly regrows and becomes flammable; fire thereby acts as a regulator of vegetation structure (Staver et al., 2011). Although savannas cover 20% of the global land surface (Hutley and Setterfield, 2008), savanna fires account for more than 85% of the global area burned and 65% of the total carbon emission (Giglio et al., 2013; van der Werf et al., 2017), placing a high priority understanding the drivers of fire activity in these ecosystems. Improving our knowledge of the interactions between fire, climate and vegetation is necessary for managing savannas, quantifying ecosystem vulnerability, calibrating global fire and vegetation models, and projecting the response to future climate change (Beringer et al., 2015; Lehmann et al., 2014; Stevens et al., 2017). Changes in fire activity may result in a shift in the tree-grass ration in savanna which can have severe effects on biodiversity, ecosystem services, carbon, nutrient and hydrological cycles (Higgins and Scheiter, 2012; Sankaran et al., 2005; Scheiter et al., 2015).

Fuel accumulation is restricted by the amount of precipitation; therefore, grassland productivity is the main limitation for fire in arid and semi-arid savannas (Bradstock, 2010; Nemani et al., 2003). In dry regions like central Australia and southern Africa previous research has shown accumulated rainfall over more than one growing season to be a strong predictor of burned area in the following year (Abatzoglou et al., 2018; Archibald et al., 2010). When precipitation reaches a certain threshold, not the amount of fuel but its moisture content becomes critical. Prolong dry season that desiccates fuel has the potential to drive high fire occurrence which is a well-known characteristic for mesic savannas (Leys et al., 2018; van der Werf et al., 2008). Aseasonal rainfall is the main driver of high tree cover in wet environments, where an increase in rainfall seasonality reduces tree cover and increases chances of fire occurrence (Staver et al., 2011). Other than within year fluctuation in rainfall, an unusual dry or wet year can create more favorable conditions for fire activity. For example, drought increases the amount of dry litter in forested regions while above-average rainfall promotes the build-up of grassland biomass that increases fire spread (Bradstock, 2010). These several moisture-related variables constrain fire in different ways which can result in fundamentally different fire regimes.

Methods and Materials

Climate and fire metrics

Five climate metrics related to moisture variability were used to define potential climate niches for fire regions:

- Mean annual precipitation (MAP) defined as the annual precipitation average over 17 years (March 2002 - February 2019) using the fire year proposed by (Boschetti and Roy, 2008).
- Year-to-year variability in precipitation (variability) was calculated as the inter-annual coefficient of variation in precipitation that was defined as the ratio of the standard deviation by the MAP.
- Intra-annual variability in precipitation using approach proposed by Saha et al. (2019) that partitioned a year cycle into two seasons: with high rainfall accumulation and low by calculating within season residual sum of square. Since calculating precipitation seasonality was not a trivial task due to various aspects of seasonality that were found to be important for fire studies and lack of a strict definition (Saha et al., 2019), we defined it using three parameters:
    - Amplitude (mm), the difference in average precipitation between wet and dry season;

- Amplitude (%), a ratio of Amplitude to MAP;
- Seasonality index (SI), a measure of how this partitioning approach was appropriate for a particular region. SI approached 1 if the region had two distinct seasons in precipitation, SI approached 0 if the region had more than one dry and one wet season within a year.

All variables were calculated within 0.5-degree cells using data from FLDAS (the Famine Early Warning Systems Network Land Data Assimilation System) (McNally et al., 2017) that used CHIRPS (The Climate Hazards group InfaRed Precipitation with Stations) as precipitation input for simulations.

Three main fire characteristics, commonly used by the previous literature in the definition of fire regimes, were calculated retrieving data from two global monthly remote sensed products: MODIS Global Burned Area Product Collection 6 (MDC64A1) and MODIS Active Fire Product Collection 6 (MCD14ML):

- Percent mean annual burned area within natural land (BA) calculated from MDC64A1;
- Fire size calculated from MDC64A1 using an algorithm proposed by Humber (personal communication, 2019) according to which individual fires were identified using flood-fill algorithm but instead of identifying one specific temporal window, uncertainty layer from MDC64A1 was used to adjust the temporal threshold for each cell individually. Due to reduced accuracy of small fire detection, fires less than 5 pixels (1.07km^2) were excluded from the analysis.
- Fire radiative power (FRP) as a proxy for fire intensity (Archibald et al., 2013) calculated from MCD14ML. Only fire points with a confidence level higher than 50% that were detected within natural land were included in the analysis. Since the area of a MODIS pixel changes depending on the distance from nadir, we estimated approximate pixel area by calculating the along-scan and along-track pixel dimensions using formulas provided by Giglio (2013).

The 95th quantiles rather than maximum were used for fire size and FRP to avoid the influence of the outliers (Archibald et al., 2013). Natural land was restricted by areas outside of croplands, urban, and unburnable surfaces defined by the annual Global Land Cover product from 2002 to 2015 (CCI-LC-PUGV2, 2017).

Statistical analysis

Principal component analysis (PCA) and clustering are the most common approaches for identifying regions with similar climate or fire characteristics. PCA is used to identify patterns in the data which might not be straightforward when a dataset contains a large number of variables that are not statistically independent (Le Page et al., 2008) which is common in ecological studies (e.g. Archibald et al., 2013; Faivre et al., 2011, Abatzoglou et al., 2009, Whitman et al., 2015). PCA is especially useful for fire regime studies since a user can include numerous parameters that might reflect fire activity without prior analysis. Delineation of fire regimes requires some sort of segmentation that produces regions with a maximum internal similarity and with maximum differences from other regions. For that task, we chose hierarchical clustering, commonly used in fire regime studies since it does not require the number of target clusters be previously defined and biogeographic regions are hierarchically arranged (Conedera et al., 2018; Faivre et al., 2011; Le Page et al., 2008; Riaño et al., 2007). Clustering was based on a Euclidean distance matrix computed using the first several PCs that had eigenvalue>1 (Girden, 2010). Grid cells were incrementally merged into clusters using Ward's linkage method, according to which the distance between two classes equivalent to an increase of the sum of squares when they are being merged. The number of classes was defined by inspecting a dendrogram which according to Wilks (2005) the merging process can be stopped right before the distance between merged clusters jumps.

PCA and clustering were performed separately for Africa and Australia since we did not want to assume that tradeoff between climate variables were similar in both continents. Prior to the analysis, to ensure that all variables have equal weights, all data were rescaled between 0 and 1 and centered (Mardia et al., 1979). To test if our data is suitable for PCA, we performed the Kaiser-Meyer-Olkin test (KMO) that measures sampling adequacy and Bartlett's test of sphericity that tests if correlation matrix that is used for PCA is an identity matrix. KMO > 0.5 and the significance level of the Bartlett test < 0.05 indicate that the sampling is adequate for factor analysis and we can proceed with PCA (Bartlett, 1951; Kaiser, 1974).

While we expected climate variables to change gradually throughout the continents, mapping regions using grid cells would create a noisy output map, with neighboring cells falling to different clusters which makes this type of map difficult to read or use for ecological applications. For that reason, once few distinct climate domains were estimated, we overlapped 0.5° grid cells with the Terrestrial Ecoregions of the World (Olson et al., 2001) that were used in several studies instead of grid cells to define regions with homogeneous fire activity (Abatzoglou et al., 2018; Pausas and Fernández-Muñoz, 2012). To avoid assigning a fire region to areas that do not experience fire activity, ecoregions that burn less than 0.1% on average within natural land were excluded from the analysis. To test our hypothesis that areas in different climate domains experience divergent fire activity, we compared fire metrics within each region for the statistical difference using Welch student t-test. To understand similarities and differences in relationships between fire and climate in Africa and Australia, we visualized how each fire metric varies with climate variables within each continent.

The effect of anthropogenic activity

While in this paper we emphasize natural fire activity, people have profoundly altered fire regimes for a long time and in places with strong anthropogenic activity it is important to consider human influence on current fire regime (Archibald et al., 2013; Guyette et al., 2002; Sanderson et al., 2002; Syphard et al., 2017). Based on previous literature we applied several thresholds to exclude areas with strong anthropogenic activity and tested if fire regime metrics within the fire region changed significantly using Welch student t-test. Three main human impacts were considered:

- Fire suppression. While human presence increases ignition events, a high level of population density has a direct negative effect on BA due to fire suppression (Archibald, 2016). This threshold in population density might vary depending on fire metric and location and was found in Africa to be somewhere between 10-50people/km2 (Archibald et al., 2009; Kahiu and Hanan, 2018). Here, we excluded grid cells with more than 30people/km2 which was a suitable threshold for global-scale analysis (Aldersley et al., 2011) using data from Gridded Population of the World (GPWv4) 2010 at 30 arc-second resolution (CIESIN, 2016)

- Fuel connectivity. Indirectly human can affect fire activity by fragmenting landscape building settlements, roads or changing the proportion of cultivated and natural land. Archibald et al. (2012) found that fire spread significantly decreased when the proportion of flammable area went below 0.6. Here, cells with a proportion of cropland, urban, and unburnable surfaces higher than 0.4 were removed.
- Fuel abundance. Grazers can compete with fire for fuel and a high level of livestock can reduce fuel loads and increase fuel fragmentation, therefore, have a negative effect on BA and fire size (Archibald, 2016; Archibald et al., 2009). Here, we applied the method from Zubkova et al. (2019) retrieving data from Gridded Livestock of the World (GLW3) 2010 at 0.083333° (Gilbert et al., 2018) and removed all cells with high livestock density.

Results

Results of the KMO and Bartlett test showed that climate variables were suitable for PCA (KMO = 0.53 for Australia and 0.57 for Africa, Bartlett's test p-value<0.0001 for both continents). The first two components of PCA that had eigenvalue>1.0 explained a large proportion of the original variance (82.0% for Australia and 80.3% for Africa) and only those two components were used in following hierarchical clustering.

As can be noted from Figure 3.2(a) that presents the components loading after the rotation, the first two PCs were associated with different climate variables in two continents. While in Australia the primary climate gradient was related to amplitude and the second to variability, in Africa, MAP was a primary gradient that split the continent into dry and wet regions while the second gradient, SI, highlighted areas without two pronounced precipitation seasons. Variation of fire metrics across the climate space showed some striking differences between continents (Figure 3.2b-d). In Africa, the most frequent fires could be found in areas with an intermediate level of MAP and seasonality index above the mean, while in Australia, a high level of MAP was not a constraint for frequent fires as long as this precipitation fall within highly defined wet season. Relationships between climate variables and fire size and FRP were not as clear as with BA. In Africa fires varied from small to larger than 1000km^2 as long as seasonality was at least moderate. A high level of MAP seemed to have a negative effect on fire size together with low precipitation variability. FRP was low at both end of MAP gradient but seasonality was not an important driver of fire intensity. In Australia, while both precipitation variability and seasonality had a tendency to limit fire size, fires bigger than $1000km^2$ were observed almost anywhere on the continent. In terms of fire intensity, high level of MAP and highly defined seasonality seems to restrict fire intensity in Australia.

The cluster analysis identified 4 climatic domains in Australia and 5 in Africa (Figure 3.3). Further, we gave a description of each cluster according to climate gradients (Table 3.1) and provided suggested names based on either with which biome they overlap the most or their geographical location. In Australia, cluster 1 was associated with high precipitation amplitude, high MAP and low variability and located in the northern part of the continent which is represented by mesic savanna. Moving to cluster 2, amplitude and MAP were decreasing while variability reached its peak – arid savanna. Cluster 3 had the lowest level of amplitude and MAP – xeric shrublands and desserts while cluster 4 could be described by the lowest variability and high MAP – temperate and Mediterranean forests. In Africa, cluster 1 had high MAP and amplitude with two highly distinct precipitation season – mesic savanna, while cluster 2 was the wettest region with the smallest difference between wet and dry season compare to MAP – tropical forest. The rest three clusters had a low level of MAP and high variability and they were separated according to SI. Consequently, cluster 3 had a strong seasonality pattern – the Sahel region. This seasonality was decreasing moving to cluster 4 – dry SH (Southern Hemisphere) and 5 – Horn, with the latest being a region where wet season being frequently interrupted by dry periods.

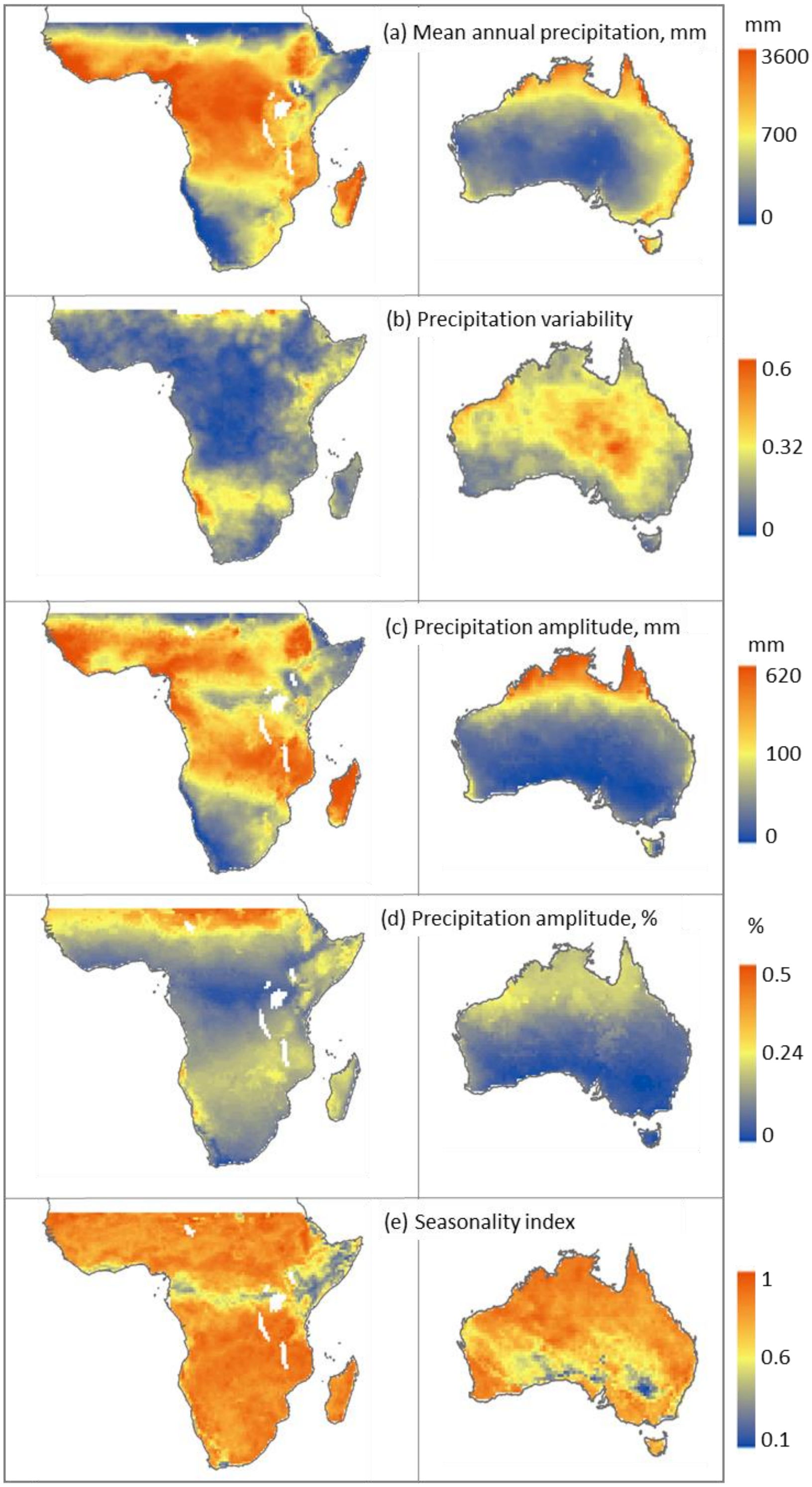

Figure 3.1. Five 0.5º gridded climate variables used as inputs for PCA. (a) Mean annual precipitation in mm, (b) Precipitation variability, (c) Precipitation amplitude in mm, (d) Precipitation amplitude as a percentage of mean annual precipitation, (e) Precipitation seasonality index.

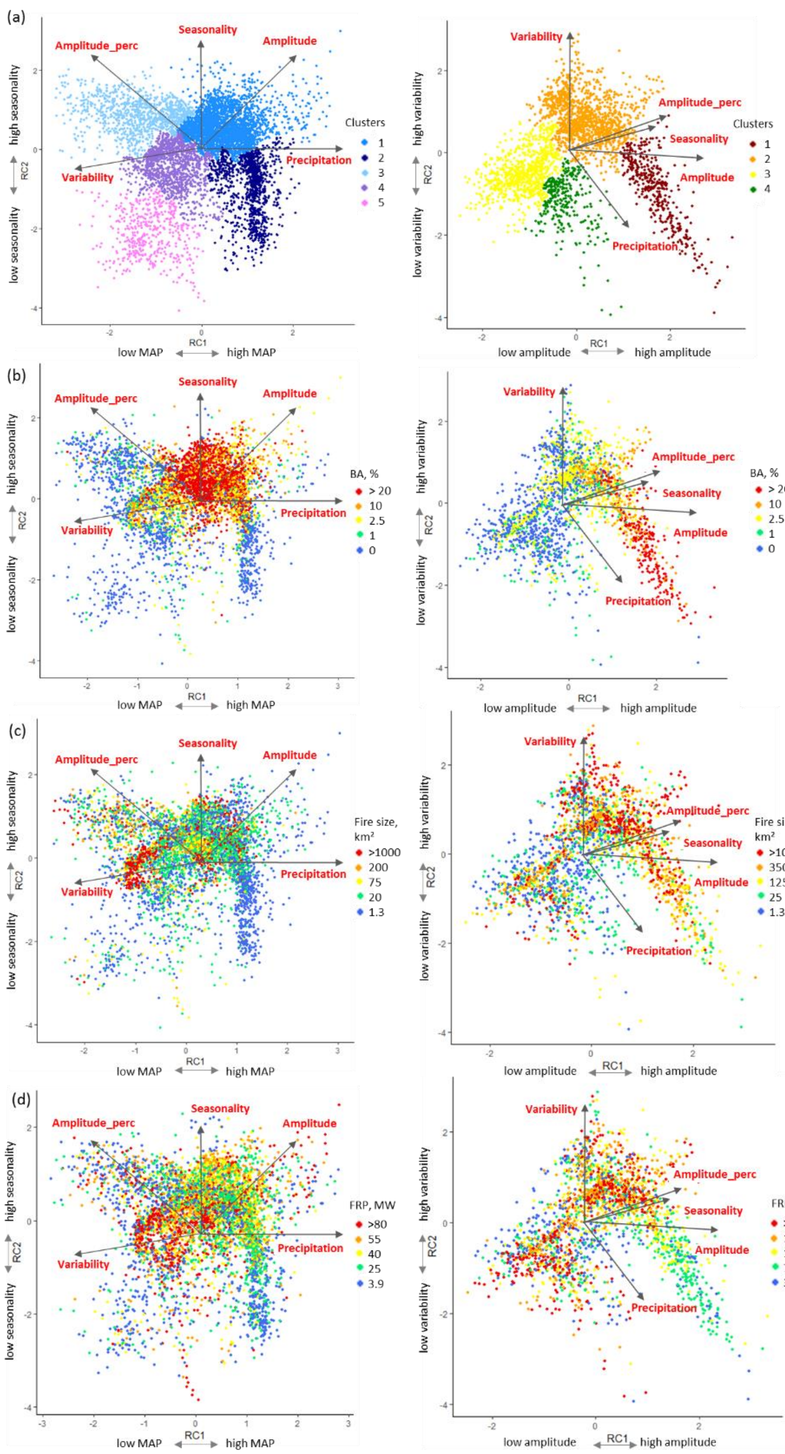

Figure 3.2. Climate domains of the fire regions and fire metrics in Africa (left) and Australia (right): (a) 9 fire regions; (b) percent mean annual burned area; (c) 95th percentile of fire size; (d) 95th percentile of fire radiative power. Biplots showing the ordination of 0.5° cells along the first two principal axes, the five climate variables are presented by arrows overlaid on rotated components of PCA using Varimax to improve the interpretation of the results.

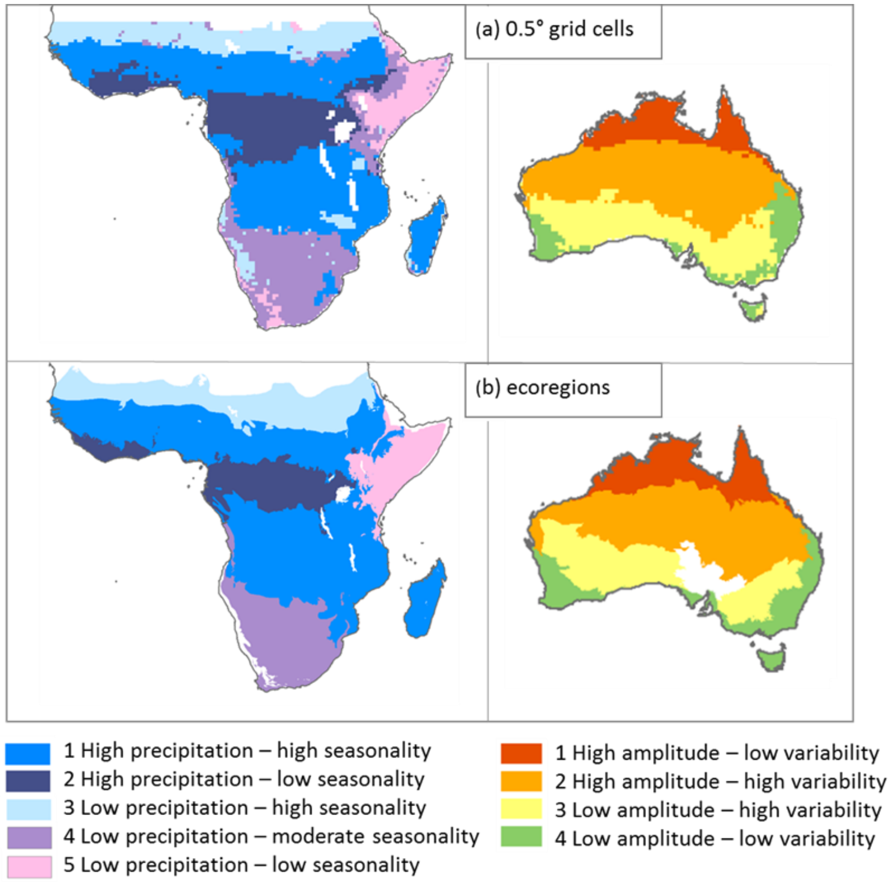

Figure 3.3. Spatial distribution of major fire regions in Africa and Australia. (a) The output of hierarchical clustering; (b) Final map of fire regions using ecoregions as a spatial unit. Ecoregions that burn less than 0.1% on average within natural land were not included.

We characterized fire regions based on BA, fire size and FRP (Table 3.2). The overall pattern was similar for both continents: mesic savannas were the most fire-prone regions, moving to wetter regions with low seasonality BA significantly decreased and moving to drier regions while BA decreased, fire size and FRP substantially increased. However, the amplitude of each fire metric varies drastically between continents. Not only in Africa much bigger areas were represented by mesic savanna, BA there was significantly higher compared to Australia especially when area highly affected by anthropogenic activity was removed. In contrast in Australia, a much smaller area was prone to highly frequent fires, but fires tend to be larger and more intense. In particular, in Australia fires were more than six times bigger compared to Africa considering both mesic and dry regions. Accounting for human pressures, the difference in arid regions was drastically reduced but was still significant. FRP did not vary quite that much but still in Australia fires were twice hotter comparing arid regions.

Table 3.1. Characteristics of 9 fire regions in Africa and Australia. The median and 25th to 75th quantiles of each climate variable are reported (parentheses).

Africa					
Region	Precipitation, mm	Amplitude, mm	Amplitude, %	SI	Variability
1	1114 (884-1349)	166 (145-199)	15.7 (12.8-18.6)	0.86 (0.83-0.89)	0.11 (0.09-0.15)
2	1627 (1441-1759)	118 (94-139)	7.8 (6.2-9.2)	0.75 (0.63-0.79)	0.08 (0.06-0.1)
3	275 (163-439)	86 (54-118)	29.1 (25.7-35.1)	0.87 (0.84-0.90)	0.24 (0.19-0.3)
4	266 (171-411)	44 (21-66)	15.9 (11.4-19.4)	0.46 (0.39-0.54)	0.31 (0.22-0.41)
5	440 (326-612)	66 (44-87)	14.7 (11.9-17.5)	0.82 (0.78-0.85)	0.22 (0.18-0.28)
Australia					
Region	Precipitation	Amplitude, mm	Amplitude, %	SI	Variability
1	889 (718-1114)	178 (142-217)	20.7 (19.8-21.3)	0.87 (0.84-0.89)	0.26 (0.23-0.30)
2	256 (205-383)	21 (17-32)	12.8 (9.4-17.3)	0.80 (0.75-0.84)	0.36 (0.32-0.41)
3	234 (200-328)	20 (17-27)	4.9 (3.4-6.2)	0.64 (0.53-0.71)	0.24 (0.29-0.28)
4	622 (453-803)	52 (38-67)	6.5 (5.6-8.3)	0.80 (0.76-0.84)	0.18 (0.16-0.22)

Table 3.2. Three fire metrics estimated for each fire region in Africa and Australia. BA – percent mean annual burned area, FSize – 95th percentile of fire size, FRP – 95th percentile of fire radiative power. All variables were estimated using 0.5° degree cells with more than 25% of the natural land. Fire metrics that are statistically different compared to other regions within the continent are denoted by an asterisk, and between the continents are in bold, p-value<0.01. Fire metrics that were estimated only within areas without major anthropogenic activity are reported in parenthesis and in bold are values that are significantly different compared to the whole region.

Africa			
Region	BA,%	FSize, sq.km	FRP, MW
1	**26.16*** (**33.67**)	33.92 (**45.51**)	68.07 (**71.77**)
2	**2.74*** (**1.29**)	22.97 (23.83)	**46.92*** (45.15)
3	6.31* (**11.84**)	**67.19**** (**94.45**)	74.58 (75.92)
4	4.72* (4.46)	**49.16**** (**350.97**)	**99.65*** (**127.49**)
5	1.09* (1.11)	**45.48**** (**77.06**)	72.15 (70.43)
Australia			
Region	BA,%	FSize, sq.km	FRP, MW
1	**22.18*** (22.67)	**227.98*** (333.17)	**92.37*** (96.48)
2	4.89* (5.13)	**669.62*** (717.39)	**170.21*** (172.58)
3	1.06 (1.10)	**267.47*** (**576.57**)	**179.40*** (**198.51**)
4	1.15 (**1.69**)	30.27* (**120.47**)	**121.23*** (157.83)

Discussion

Previous work on fire regimes either analyzed the climate-gradient of one fire characteristic (e.g. fire frequency (Boer et al., 2016), fire size (Hantson et al., 2017)) as a function of climatic water balance and precipitation respectively or summarized several fire metrics in a purely statistical framework that did not explicitly include climate variables (Archibald et al., 2013). These methods might lead to inconsistent results. The first approach is difficult to transfer across scales, or to different regions, as one single metric cannot fully represent fire activity continentally or globally. Moreover, existing studies used a limited number of climatic variables for defining the fire-climate gradient, which might be overly simplistic considering the complexity of fire phenomenon and the multiple processes that drive fire (Bradstock, 2010). The second approach can result in attributing the same "fire regime" label to regions with similar fire activity, but very different environmental conditions. For example, small infrequent fires can be observed in the tropical forests due to the high moisture content of fuel that prevents fire ignition and very dry regions where lack of fuel limits fire propagation (Pausas and Ribeiro, 2013). This can lead to misinterpretation of processes that drives present fire activity and misunderstanding how fire might change in the future.

The present study represents a significant advance in the understanding of fire-climate relationships on a continental scale for the following reasons. First, we delineated fire regions using the number of climate variables that was proved to play an important role in determining the large-scale distribution of fuel and fire favorable weather conditions (Archibald et al., 2009; Hempson et al., 2018; Lehmann et al., 2011; Murphy et al., 2013; Russell-Smith et al., 2007). Second, we characterized each fire region in terms of environmental conditions and fire metrics that were commonly used in the fire regimes literature. While three fire-regime characteristics calculated using 17 years of data cannot be considered as a comprehensive list using strict fire regime definition, in this approach we delineated fire regions based on biogeographic variation of environmental factors that limit fire activity and having longer time series or additional fire metric will not change spatial distribution of fire region but will only expand our understanding of fire activity there. Third, in the opposite of several previous studies (Archibald et al., 2013; Hantson et al., 2017), we did not assume that the same biomes in different continents experience identical fire activity.

In fact, similar to Lehmann et al., (2014) we found that different environmental factors drive fire activity in Africa and Australia, and that fire regime characteristics significantly vary between continents.

Our analysis of fire metrics within climate space illustrated that fire activity is influenced by both fuel load and fuel moisture. While rainfall during wet season promotes biomass accumulation and fuel connectivity, sufficiently long dry season is needed for drying potential fuel and creating conditions for fire ignition (Bradstock, 2010). Our results showed the evidence of a unimodal relationship between MAP and fire occurrence in Africa where BA at both extremes of rainfall gradient was the lowest (Pausas and Ribeiro, 2013; van der Werf et al., 2008), while in Australia that was not the case. Not the amount of rainfall that vegetation receives annually but how evenly it's distributed throughout the year was the main driver of fire occurrence. We delineated two dramatically different fire regimes in areas with high MAP: mesic savanna with very high fire occurrence due to sufficient MAP for fuel abundance and long dry season that desiccated fuel making it susceptible for fire, and temperate and Mediterranean forests where not having pronounced dry season made fire ignition and propagation less frequent (Bradstock, 2010). This difference between two continents can be explained by their geography, high precipitation seasonality in Africa overlapped with places that received an intermediate level of precipitation (high fire occurrence) while in Australia areas with rainfall were uncommon.

Our results indicate that the relationship between fire size and climate is comparable in the two continents. In general, fire size tends to increase with precipitation variability at the lower end of precipitation gradient which can be explained by low accumulation rate of biomass in dry regions and infrequent years with higher than usual rainfall can promote large area burnt in the following year (Bradstock, 2010). However, the tradeoff between FRP and climate varied between continents. In Australia, a negative relationship between FRP and BA could be identified where very intense fires were associated with any climate conditions except high MAP and seasonality where the most amount of burned area was observed, while in Africa this relationship was not distinguished. Intense fires could be found there in any region other than tropical forest where fuel is not dry enough to promote hot fires or Horn where not having a distinctive long dry season might prevent not only high BA but also large intense fires.

It should be noted that high and low values of fire metrics were relative to each continent. The astonishing difference between FRP and fire size in two continents were explained in the previous literature by different level of anthropogenic activity (Archibald, 2016; Hantson et al., 2017). On one side, highly impacted savannas in Africa (Archibald, 2016) with small, low intensity fires that reoccur every few years creating heterogeneous landscape that further prevents fires to spread and, on the other side, one of the most intact savannas in Australia (Hutley et al., 2011) with more rare hot mega-fires that can spread for hundred kilometers due to less landscape fragmentation. Taking human pressure in consideration show expected results, in Africa BA in natural land was significantly higher in mesic savannas and Sahel both places highly transformed by human (Dwomoh and Wimberly, 2017; Rishmawi and Prince, 2016) while in tropical forest BA in natural land was significantly lower than can be explained by human using fire for deforestation and forest degradation (Hoffmann et al., 2003). Fire size also significantly increased everywhere except tropical forest when areas highly affected by a human were not considered especially in dry SH region where fire size increased by the magnitude of seven. Our findings align with previous studies that have found that anthropogenic activity reduces fire size due to landscape fragmentation, suppression, and fuel reduction (Archibald, 2016). The difference was less noticeable in Australia due to the lower level of anthropogenic activity. However, even after accounting for human pressure significant differences between fire activities in two continents were still present. It can be explained either by setting up thresholds not high enough to remove all anthropogenic influence or by having other factors that have an effect on fire activity. Those continents vary also in terms of vegetation cover and soil properties. Savannas in these two continents are dominated by different woody plant traits (Lehmann et al., 2014; Stevens et al., 2017), insensitive to variation in fire regimes eucalypt trees in Australia diverge from savanna tree in Africa (Moncrieff et al., 2016; Scheiter et al., 2015), and intermediate level of MAP and SI supports higher percent of tree cover in Africa which can be due to low nutrient soils in Australia (Lehmann et al., 2014; Staver et al., 2011; Stevens et al., 2017).

The present analysis shows that differences in climate conditions drive fire occurrence in Africa and Australia. This can have important consequences under future climate change scenarios, as climate-related changes in fire regimes could also drive long-term changes of vegetation composition since fire is one of the main controls of grass-forest coexistence in the tropics (Lehmann et al., 2014; Sankaran et al., 2005). Considering that mesic savanna in Africa is not a fuel-limited region, it is sensitive to an increase of the length of wet season or MAP and a recent decrease in fire activity there was already documented (Zubkova et al., 2019). Those changes in MAP and increase in human pressure like fire suppression, increase of livestock, and reduction of mega-herbivore fauna all can lead to woody encroachment (Dantas et al., 2016; Stevens et al., 2017) and after tree cover reaches a certain threshold fire propagation becomes challenging (Hennenberg et al., 2006; Sankaran et al., 2005) which further increases tree cover that can force savannas to transition into an alternative state (Bond 2008). The opposite is possible too when a decrease in MAP promotes more frequent fires which can lead savanna to shift to a treeless state with a negative impact on carbon stock (Cochrane, 2003; Scheiter et al., 2015). Previous studies conducted in Australia found strong positive relationship between MAP during antecedent conditions and BA (Abatzoglou et al., 2018; van der Werf et al., 2008), therefore increase in MAP and in SI promotes fires especially in the southern part of the continent due to high rate of fuel accumulation (Scheiter et al., 2015). A decrease in moisture availability can change fire patterns to infrequent fires which will have an effect on vegetation cover by promoting less fire resilient species (Dantas et al., 2016). Consequently, different fire regions in Africa and Australia can be highly sensitive to various changes in precipitation pattern which can lead to the disruption from a present fire regime (Hantson et al., 2017) which together with human environmental impacts might have detrimental effects on biodiversity and ecosystem services.

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Chapter 4: A Framework for Delineating Global Fire Regions Based on Key Drivers of Fire Activity

Introduction

Fire is a natural component of most ecosystems, and it has effects on vegetation, soil, water and atmospheric composition (Bowman et al., 2009; Certini, 2005). Fire contributes to the global carbon cycle through the emission of greenhouse gases and aerosols from biomass burning, releasing the equivalent of around 20% of fossil fuel emissions (van der Werf et al., 2006, 2010), and as an agent of ecological change influencing global vegetation dynamics (Bond et al., 2005; Goetz et al., 2012; Thonicke et al., 2001) and the surface energy budget (Jin, 2005; Randerson et al., 2006). The impacts of fire on ecosystems depend on various aspects of fire; to characterize this variation of fire activity, the term “fire regimes” was introduced (Gill, 1975) which broadly describes fire frequency, intensity, severity, seasonality, type, and size (Morgan et al., 2001). While the extent of burned areas has been often used by previous literature as the sole input to characterize fire regimes (Bradstock, 2010; Krawchuk and Moritz, 2011; Parisien and Moritz, 2009; Pechony and Shindell, 2009), a single fire characteristic cannot fully explain such a complex phenomenon, which involves multiple loops and feedbacks between vegetation status, landscape characteristics, climatic variables, human activity, and fire itself (Barros and Pereira, 2014, Krawchuk 2009). For instance, fire reoccurrence affects vegetation composition, structure and life cycles and changes in the fire-free period can transform an ecosystem (Morgan et al., 2001; Staver et al., 2011), whereas fire size can provide insight into the rate of fuel regrowth and the barriers to fire spread (Archibald and Roy, 2009; Whitman et al., 2015). The intensity and severity of fire are linked to fire behavior and drive changes induced by fire such as biomass consumption, tree mortality, and soil heating (Morgan et al., 2001). While some correlation between fire metrics can be expected, e.g. high intensity can be attributed to large fires with fast fire spread rates and long burning durations (Archibald et al., 2013), it is important to consider and ensemble of fire regime characteristics to understand the full range of variability in fire activity and its effect on ecosystems (Whitman et al., 2015).

Despite the topical relevance of fire research, our understanding of the global spatial pattern of fire regimes and what processes drive its variability is limited (Hantson et al., 2015; Krawchuk et al., 2009; Murphy et al., 2013). Several techniques have been used to characterize fire regimes from local to global scales, each with strengths and weaknesses. Rule-based methods are based on knowledge gained from case studies, previously published literature, and expert opinions and their accuracy depends on the quality of regional historical data. These methods are not applicable for continental to global scale (Murphy et al., 2013). Empirical approaches that determine leading dimensions of fire activity using unsupervised classifiers are easy to implement at different scales and are unbiased, unlike the rule-based approaches (Archibald et al., 2013; Conedera et al., 2018; Faivre et al., 2011; Le Page et al., 2008; Riaño et al., 2007). However, these methods depend strongly on the set of fire metrics that were used for classification (Krebs et al., 2010) and do not take into account linked and feedback processes with climate and vegetation. Process-based modeling approaches that simulate fire regimes using global fire, land-surface, and vegetation models (Krawchuk et al., 2009; Lasslop and Kloster, 2017; Pechony and Shindell, 2009) do not always accurately represent current fire activity and the model's complexity can prevent useful generalization (Archibald et al., 2013; Kloster et al., 2010; Prentice et al., 2011).

Some studies have examined fire regime components with respect to climate at the local- to continental-scales (Russell-Smith et al., 2007; Whitman et al., 2015), recognizing that environmental controls on fire activity (e.g. fuel load, fuel flammability) are the result of climatic factors (Krawchuk et al., 2009; Whitman et al., 2015). Climate-focused approaches have not been implemented on a global scale because, while the main drivers of fire regimes are reasonably well characterized, the multiple loops and feedbacks between vegetation, climate, and fire activity are not fully understood (Krebs et al., 2010; Murphy et al., 2013). Bradstock (2010) proposed a conceptual model of the key drivers of fire activity that included biomass, availability to burn, fire spread and ignitions and used them to characterize fire regimes across Australia. The results presented in Chapter 3 of this dissertation, that were broadly based on this model, confirmed that systematic variations in these key processes can be used to predict spatial variation in fire regimes on a continental scale. Additionally, while the fundamental components of this model are universal, fire can be constrained in different ways depending on what limits fire in a particular ecosystem and that identification of these limiting factors is crucial to understand global diversity of fire regimes (Bradstock, 2010). For example, while dry weather conditions are usually favorable for fuel desiccation and fire propagation, in arid ecosystems fire is limited by low productivity meaning above-average rainfall can increase biomass build-up which can lead to mega-fires that will not reoccur until enough biomass will be accumulated again (Murphy et al., 2013; Russell-Smith et al., 2007). Forested ecosystems, instead, have high productivity but experience infrequent fires; unusually warm and dry conditions trigger large intense fires (Littell et al., 2009). Tropical savannas stand somewhere in the middle of productivity gradient and are characterized by very frequent, low-intensity fires (Murphy et al., 2013; van der Werf et al., 2008), while tropical forests and deserts, environmental extremes of productivity, experienced very low fire activity (Bedia et al., 2015; Hennenberg et al., 2006).

In this study, we build on the results from the previous chapter, by characterizing global fire regimes through the definition of global fire regions, in order to improve our understanding of fire-climate-vegetation interactions at the global scale. The delineation of global fire regions entails three major stages: (i) the selection of the relevant climate and environmental variables; (ii) the extraction of the main climate gradients using principal component analysis and their stratification using statistical clustering; and (iii) the characterization of each region in terms of main fire-regime attributes. This information about spatial and temporal variability in fire activity can be used for fire regime model validation, understanding global trends of fire activity, estimating departure from historical conditions and improving fire management strategies and environmental policies (Abatzoglou and Kolden, 2013; Bowman et al., 2009; Dee et al., 2011; Murphy et al., 2011). The results of this study can also give inputs for statistical fire and vegetation models (van der Werf et al., 2008; Whitman et al., 2015). While the current data span of satellite observations is arguably short compared to the data record of other climate variables (Daniau et al., 2012; Giglio et al., 2013; Murphy et al., 2011), the main principles that drive spatial variability of fire regimes can be applied to estimate changes in fire activity in response to temporal changes in climate and land-use despite the fact that observing the effects of these processes requires a longer record than satellite data provides as stated (Williams and Abatzoglou, 2016).

Methods and Materials

Preliminary analysis

Similar to Chapter 2, we defined fire regions using as spatial analysis unit the Terrestrial Ecoregions of the World (henceforth, ecoregions) proposed by Olson et al. (2001), based on the assumption that fire activity shows a strong association with vegetation structure (Murphy et al., 2013; Whitman et al., 2015). Ecoregions with insufficient fire activity (average annual burned area is less than 0.05% of the ecoregion's area) were not included in this study. We also excluded areas intensely modified by anthropogenic activity where no natural 'fire regime' can be observed, since it is well established that human can alter natural fire regimes by changing fire seasonality, reducing fire size and intensity, and by increasing or decreasing amount of burned area based on the amount and type of human pressure (Archibald, 2016; Bowman et al., 2011; Daniau et al., 2012; Syphard et al., 2007). High population density and high cropland fraction were both found to have a strong effect on fire activity globally (Lasslop and Kloster, 2017). Previous studies agree that the relationship between burned area and human population is not linear, with the increase of human population density and fire activity until the certain point after which burned area drastically decreases, though this threshold varies depending on region and on the study (Aldersley et al., 2011; Archibald et al., 2009; Kahiu and Hanan, 2018, Syphard 2007). In this analysis, the goal was not to exclude all ecoregions where fire activity could be altered by humans but to avoid assigning natural fire regimes to regions certainly highly modified by human activity where climatic conditions or vegetation type were not primary drivers of fire activity. We therefore excluded ecoregions with population density higher than 140 people/km2 using data from the Gridded Population of the World (GPWv4) 2010 at 30 arc-second resolution (CIESIN, 2016). Several studies found that above 100 people/km2 fire frequency rapidly drops (Archibald et al., 2010b; Syphard et al., 2009), and in Africa in locations with a population density above 140 people/km2 natural fire activity was not observed c. A total of 119 regions were excluded from the analysis because population density exceeded this threshold (Figure 4.1).

Land fragmentation and transformation should also be considered as an indication of anthropogenic pressure, relevant for the study of fire regimes. It has been suggested that for fire to spread the proportion of flammable area need to be above 30% of an ecoregion

(Hargrove et al., 2000). Since cropland fraction was found to be a good proxy for landscape fragmentation (Pfeiffer et al., 2013), in this study, we also excluded ecoregions where (a) croplands represented more than 70% of the ecoregion area or (b) more than 70% of the area burned was detected in croplands. The proportion of cropland was calculated from the LC-CCI v.1.6.1 Annual Global Land Cover time series at 300m resolution (CCI-LC-PUGV2, 2017), derived from MERIS, PROBA-V, and SPOT-VGT satellite data and had high class-specific accuracies for agriculture classes (Tsendbazar et al., 2016). The ecoregions excluded from the analysis because of these criteria were mainly located in Eurasia and Asia. It should be noted that these ecoregions are potentially prone to fire when considering only a productivity gradient, but due to high population density, land fragmentation and limited fuel availability likely experienced far less fire activity than they would have in the absence of human population. It is reasonable to assume that their fire regimes are driven by economy, agricultural habits, culture and traditions rather than biophysical processes (Aldersley et al., 2011; Bistinas et al., 2013).

The results of Chapter 3 confirmed previous research, indicating that the climate-vegetation-fire relationship varies between continents even within the same biome, as Lehmann et al. (2014) explained in terms of evolutionary history. Therefore, in addition to ecoregionss, we used the biogeographic realms of the world (Olson et al., 2001), since boundaries between realms represent barriers to historical and current gene flow (Moncrieff et al., 2016). From the 8 realms, Antarctic and Oceanic realms did not experience significant fire activity (as defined above) and were not considered in the analysis. It should be noted that – to align the realm definition with the standard geographic definition of continents used for fire activity reporting – Papua New Guinea and part of Indonesia were merged in this study with the Indo-Malay realm (Figure 4.2).

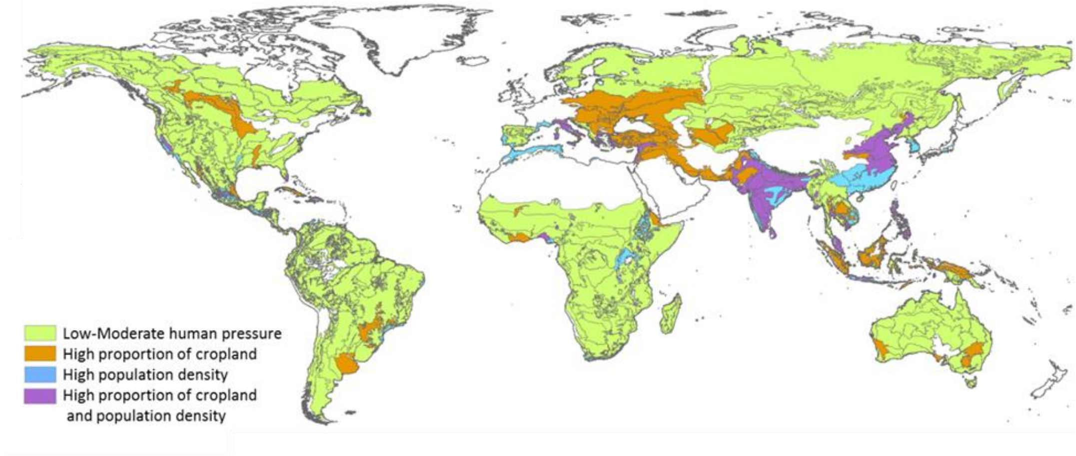

Figure 4.1. Spatial distribution of ecoregions with different levels of human pressure. We assume that regions with low to moderate human pressure represent current natural fire activity (light green) while regions with high population density and/or high proportion of cropland have an intensely modified fire regime. Ecoregions that burn less than 0.05% on average were not included (white).

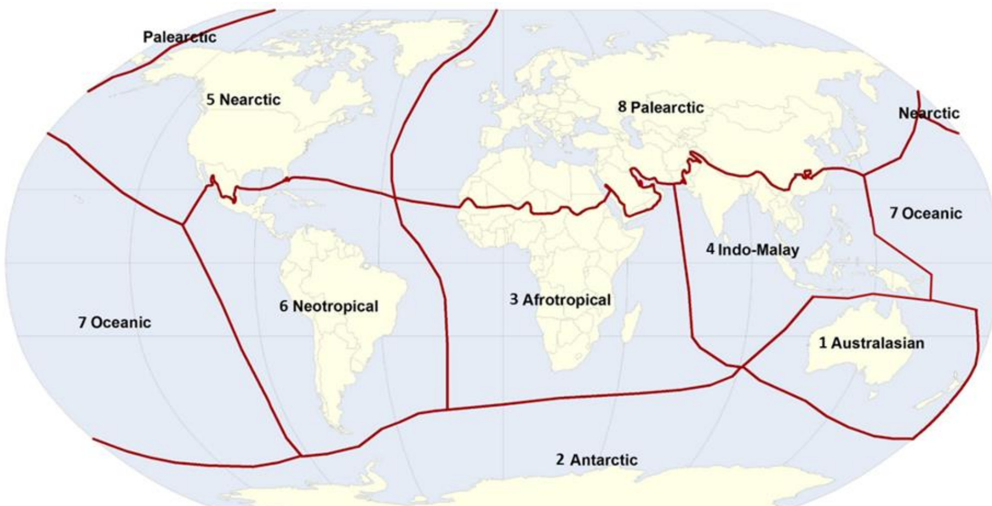

Figure 4.2. Biogeographic realms of the world, modified from Olson et al. (2001).

Key drivers of fire regimes

Our approach for characterizing global fire regimes was based on a conceptual model of key drivers of pyrogeography proposed by Bradstock (2010), where fire activity is restricted by four "switches": biomass, availability to burn, fire spread, and ignition. Based on previous studies, the environmental factors that potentially influence each of these "switches" in different ecosystems are defined as follows:

- Biomass accumulation is controlled by environmental conditions prior to the fire season, from a few months to a few years. The amount of biomass (i.e. the potential fuel), is driven by the available moisture and temperature because of their strong link with the physiology and growth of plant species (Gerten et al., 2004; Hawkins et al., 2003; Krawchuk and Moritz, 2011). While in arid regions amount of rainfall during the wet season and its variability are the main limitations for production of high fine-fuel continuity (Archibald et al., 2010a; Russell-Smith et al., 2007), high-latitude forests are not water-limited and the warm season temperature is what limits biomass production (Parisien and Moritz, 2009; Saha et al., 2019).
- Availability to burn is controlled by dry and warm conditions in the season leading up to and including the fire season (Littell et al., 2009) since low precipitation and high evapotranspiration reduce fuel moisture. Regions with prolonged dry seasons have ideal conditions for fuel desiccation, while drought is required for wetter ecosystems to deplete the level of moisture for soil, foliage and fine dead surface fuel (Krawchuk and Moritz, 2011).
- Fire spread is controlled by atmospheric conditions during the fire season that promote flame length and depth, such as high temperature, low humidity and strong winds (Bradstock, 2010). Unfortunately, these conditions exist during a small temporal window which makes them hard to incorporate into continental or global analysis (Aldersley et al., 2011; Parisien and Moritz, 2009). Bradstock (2010) suggested that this fire weather can be analyzed as a function of the amount of rainfall and latitude, the latter can be accounted for by temperature gradient.
- Ignition is usually not considered as a limitation of fire activity in fire regimes studies due to the stochastic nature of lightning presents (Abatzoglou et al., 2016) and evidence suggesting that even very low population density is enough for a sufficient number of ignitions (Archibald, 2017) and if humans are not present, lightning strikes can fill the void (Knorr et al., 2014). However, an abundance of fuel and favorable weather conditions cannot guarantee fire if the ignition source is absent.

Climatic variables

For each realm, we selected five climate variables that represented potential environmental conditions controlling fire (Table 4.1).

For the Afrotropical, Australasian and Indo-Malay realms we used the same five variables that were proposed in Chapter 3. These variables were found best to describe precipitation patterns in tropical and arid regions where the intensity and duration of the rainy season limit fire activity (Russell-Smith et al., 2007).

Compared to the above realms, the Neotropical realm encompasses similar biomes, but different climatic domains (Lehmann et al., 2014). The Neotropical realm had a stronger latitude gradient and more complex topography, which can have an effect on biomass and fire spread (Hantson et al., 2016; Hawkins et al., 2003). To take this into account, we also included in the analysis the mean temperature of the coldest month as one of the climate variables.

The two remaining realms, Nearctic and Palearctic, have unique characteristics, due to a more pronounced temperature gradient, and differences in fire-climate relationships latitudinally and altitudinally (Westerling et al., 2003); we therefore used a different set of climate variables. Mean annual temperature, total annual precipitation and temperature seasonality or annual temperature range were found to be main drivers in these domains, especially in higher latitude (Batllori et al., 2013; Krawchuk et al., 2009; Whitman et al., 2015) since they affect fuel accumulation, atmospheric and fuel moisture, number of lightning ignitions, pest outbreaks, and tree mortality (Daniau et al., 2012; Flannigan et al., 2009; Thuiller et al., 2005). To account for the amount of rainfall during the growing season, we included in the analysis the accumulate precipitation during three winter months (Littell et al., 2009; Syphard et al., 2017; Whitman et al., 2015) and as a proxy for precipitation seasonality we used a ration between accumulated precipitation during the driest month and the wettest month since both of these climate variables were used in the previous studies (Batllori et al., 2013; Krawchuk et al., 2009; Parisien and Moritz, 2009).

All variables were calculated within 0.5-degree cells using data from FLDAS (the Famine Early Warning Systems Network Land Data Assimilation System) (McNally et al., 2017) at 0.1-degree resolution using CHIRPS (The Climate Hazards group InfraRed

Precipitation with Stations) as precipitation input for simulations. We excluded small oceanic islands and coastal grid cells with <70% land area.

Table 4.1. Climate variables used to analyze climate space for each realm. The name of realms based on the index can be found in Figure 4.2.

Variable	Abbreviation and Units	Description	Realm
Mean annual precipitation	MAP (mm)	Annual precipitation average over 17 years (Mar 2002 - Feb 2019)	1,3,4,5,6, 8
Year-to-year variability in precipitation	Variability	The inter-annual coefficient of variation in precipitation that was defined as the ratio of the standard deviation by the MAP	1,3,4
Precipitation Amplitude	P_amplitude (mm)	The difference in average precipitation between wet and dry season. Calculated using Saha et al. (2019) approach.	1,3,4,6
Precipitation Amplitude in relation to MAP	P_amplitude_perc (%)	A ratio of Amplitude to MAP	1,3,4,6
Seasonality index	SI	A measure of precipitation seasonality. SI varies between 0 (no defined dry and wet season) to one (highly distinct one wet and one dry season within 12 months) using Saha et al. (2019) approach.	1,3,4,6
Winter precipitation	P_winter	Precipitation accumulated over three winter months (Jan-Mar)	5,8
Precipitation seasonality	Dry/wet	A ratio between the averaged accumulated precipitation during the driest month and the wettest month	5,8
Mean annual temperature	T (C°)	Annual temperature average over 17 years (Mar 2002 - Feb 2019)	5,8
Temperature Amplitude	T_amplitude (C°)	The difference in average temperature between cold and hot season. Calculated using Saha et al. (2019) approach.	5,8
Mean temperature of the coldest month	T_min (C°)	Monthly temperature averaged over the month with the lowest temperature	6

Ignition

The fourth switch is usually not considered as a fire predictor (Flannigan et al., 2009; Moritz et al., 2012) since ignition source is hard to attribute (Bradstock, 2010) and there is no accurate ignition source dataset at the global scale (Benali et al., 2017). Nonetheless, we propose a broad characterization of ignitions. There are two main sources of ignitions: lightning discharges and humans. While the problem with the first source is the lack of global dataset with cloud-to-ground flashes, human activity not only increases the number of ignitions but also suppresses fires which Pechony and Shindell (2009) argued can cancel each other out. Since in this study the goal was to define climatic niches for current natural fire regimes, we wanted to keep only ecoregions where fire activity would be present even without human as an ignition source. For that, we tested whether, in any ecoregion, lightning density could be a limiting factor.

Global gridded high-resolution lightning climatology can be retrieved from the spaceborne Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) instruments (Cecil et al., 2014). We used the high resolution monthly climatology (HRMC) product that contained monthly mean flash rate per km2 at 0.5° resolution averaged over the 1995-2010 time period. There were two problems with using this data: first, it provided information of the total flash rate while only cloud-to-ground flashes could provide ignitions for fire (Pechony and Shindell, 2009); second, this data was less accurate at high latitudes and high-resolution datasets like HRMC could be noisy due to insufficient sampling (Cecil et al., 2014). To resolve the first problem we applied an equation proposed by Prentice and Mackerras (1977) that explained the relationship between the ratio of intracloud to cloud-to-ground flashes z, and latitude λ:

$$z = 4.16 + 2.16\cos(3\lambda)$$

Prentice and Mackerras (1977) suggested to use this equation within 0°- 60° latitude since on higher latitude the information is sparse. Therefore, for higher latitude, we used z value for 60° but were conscious about uncertainties that it brought to our results together with uncertainties from the dataset at high latitude.

To find a threshold to define sufficient lightning density from previously published literature was not a trivial task since it depended on various factors and many studies provided only the probability of ignitions for a different level of lightning strike density and fuel moisture (Dowdy and Mills, 2012; Sedano and Randerson, 2014; Wotton and Martell, 2005). Considering the scale of our study, we applied the threshold of 0.04 strikes/km2 per month, based on a previous study (Balch et al., 2017) demonstrating that lower lightning density constrained fire activity across the United States.

Atmospheric conditions at the time of lightning occurrence also has to be accounted for: lightning during the rainy season has very little influence on fire occurrence. Therefore, the term “dry lightning” was introduced, which refers to lightning that occurs while rainfall is absent (Dowdy and Mills, 2012). To define atmospheric conditions for dry lightning, we used MAP threshold of 2.5mm per day which was suggested to be a breakpoint in Australia (Dowdy and Mills, 2012), U.S. Pacific Northwest (Rorig and Ferguson, 1999), Arizona and New Mexico (Hall, 2007). While up-to-date, no accurate global daily lightning dataset exists and no information about how many days per month with MAP less than 2.5mm is required for lightning to become a potential ignition source for fire, we tested if during the months with sufficient lightning activity at least 5 days had MAP lower than 2.5mm. Daily long term means of precipitation for each ecoregion were calculated from the NOAA Climate Prediction Center 0.5° Global Daily Unified Gauge-Based Analysis of Precipitation averaged over 1981-2010 (Chen et al., 2008).

Fire-regime metrics

Fire activity data were retrieved from two global remote sensing products: the MODIS Global Burned Area Product Collection 6 (MCD64A1) and the MODIS Active Fire Product Collection 6 (MCD14ML). MCD64A1 is a monthly gridded product that provides data of burned areas extend, and estimates the approximate day of burn at 500m resolution (Giglio et al., 2009). MCD14ML is also a monthly product but it contains the location of active fires that were detected during satellite overpass under relatively cloud-free conditions, date, brightness temperature and some additional information for each fire pixel at 1km resolution (Giglio et al., 2003). We used monthly composites of MCD64A1 and MCD14ML from March 2002 to February 2019. Although MODIS fire products were available from April 2000, the use of monthly products for August 2000 and June 2001 was deprecated because of extended outages (Giglio et al., 2016).

A suite of fire characteristics describing the extent of the burned area, fire size, and intensity was selected as commonly used in published local to global scales fire regime studies.

- Burned area (%). The extent of the burned area is the most studied and easiest to calculate fire metric (Archibald et al., 2013). The percent mean annual burned area within natural land was summarized from the MOD64A1 and averaged over the 17-years dataset using a fire year from March to February (Boschetti and Roy, 2008). Natural land was restricted by areas outside of croplands, urban, and unburnable surfaces.
- Fire size (km2). Fire size was calculated using the flood-fill algorithm but instead of identifying one specific temporal window, the uncertainty layer from MCD64A1 was used to adjust the temporal threshold for each cell individually. Due to reduced accuracy of small fire detection, fires less than 5 pixels (1.07 km2) were excluded from the analysis.
- Fire intensity (MW km-2). Fire intensity is a measure of the total rate of heat released from the fire (Wooster et al., 2005). This metric can help to distinguish between crown and ground fires (Archibald et al., 2013; Giglio et al., 2006) since directly this information cannot be retrieved from remotely sensed data. As was suggested by previous studies, we used the fire radiative power (FRP) as a proxy for fire intensity. FRP is the rate of radiant energy emission from the fire (Wooster et al, 2005; Xu et al., 2010) and it can be retrieved from satellite middle-IR wavelength measurements. In this study, we used FRP from the MODIS MOD14/MYD14 global active fire product, normalized by pixel area using the formulas presented by Giglio (2013), to account for the fact that the footprint of a MODIS pixel changes across-track as a function of the position of each pixel in the swath. Only fire detections with a confidence level higher than 50% and detected within natural lands (as defined above) were included in the analysis.

The 95th quantiles, rather than maximum, were used for fire size and FRP to avoid the influence of the outliers (Archibald et al., 2013).

Statistical analyses

Based on the method described in the previous chapter, principal component analysis (PCA) and hierarchical clustering were performed to stratify each realm into climate domains for which fire-regime characteristics were calculated. For each realm, the main environmental gradient was defined by collapsing the five key climate variables into two orthogonal components from PCA. Subsequently, clustering analysis was applied to this two-dimensional climate space to form groups of similar grid cells assemblages. Hierarchical clustering was particularly useful for this type of analysis since it showed the relative relationship between regions, therefore, provided information about underlying biogeographic processes (Kreft and Jetz, 2010). Finally, fire-regime components were analyzed in terms of climate and geographic space and compared within and between realms using the Welch student t-test. We referred to results as statistically significant where $p < 0.01$.

Results

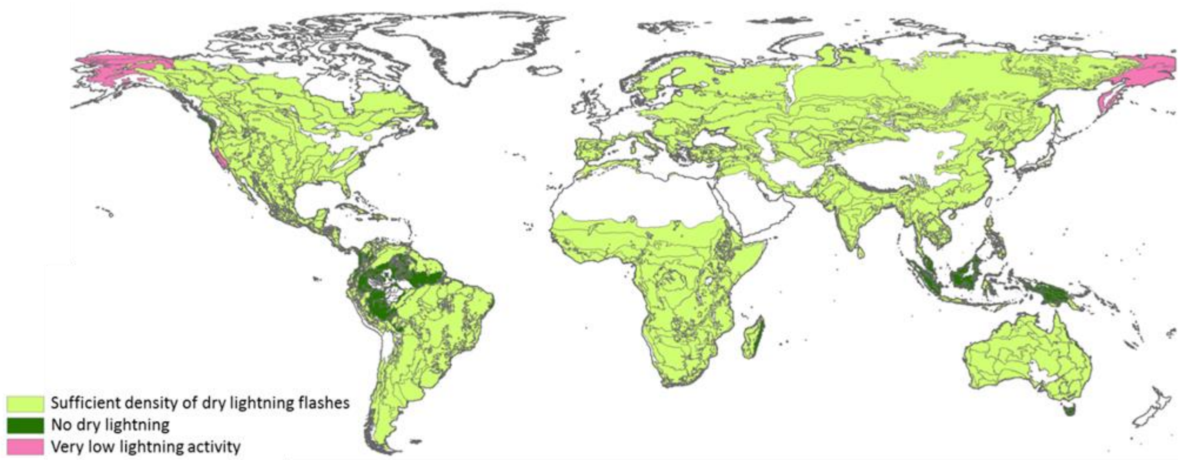

Figure 4.3. The density of dry lightning flashes during the dry season (amount of rainfall less than 2.5mm per day). Ecoregions with sufficient lightning density – light green, ecoregions with average climate condition too wet to have natural fire activity – dark green, and ecoregions with very low lightning density flashes regardless of rainfall season – pink. Ecoregions that burn less than 0.05% on average within natural land were not included (white).

Ignitions

The density of dry lightning flashes was sufficient to initiate fire activity in most of the globe (Figure 4.3). Not surprisingly, rainforests in South America and Southeast Asia were the only regions where the lack of days with rainfall lower than 2.5mm constrained ignitions, even though the overall density of lightning flashes was sufficient. It has been abundantly documented that fire activity in both of those regions is affected by human activity: most of those ecoregions in Southeast Asia have a high proportion of cropland, and fire in tropical forests in Brazil is used as a tool for deforestation and seasonal land clearing

(Krawchuk et al., 2009; Le Page et al., 2010; Morton et al., 2008). While accelerating anthropogenic pressure influences fire activity in those biomass-rich regions, naturally they rarely experience fires (Hoffmann et al., 2009). A notable exception is when especially extreme weather conditions forced by El Nino phases can create flammable conditions in tropical rainforests (Tacconi et al., 2007; van der Werf et al., 2004). Therefore, while fire activity in those wet regions was intensively modified by humans, fire was not completely disconnected from climate, and those ecoregions were included in the main analysis. In high latitudes, several ecoregions were detected with low lightning density year-round. Those were the regions with low population density where lightning was documented to be the main source of ignitions (DeWilde and Chapin, 2006; Sedano and Randerson, 2014; Stocks et al., 2002); therefore, uncertainties in dataset and formulas that were used for calculating the density of dry lightning might be the reason that insufficient lightning density was estimated there. A low level of lightning density was also detected in California, which agreed with previous work by Parisien and Moritz (2009); however, they suggested that natural fire activity was still possible even before this area became highly affected by human. As a result, based on our simple analysis we assumed that fire was naturally possible in all ecoregions that were used in this analysis, and fire regimes were identified for all ecoregions with none to moderate human pressure (355 ecoregions).

Fire regions

The results of the two primary climate gradients in each realm are presented in Figure 4.5. As in Chapter 3, these two gradients inform the definition of fire regions through hierarchical clustering. To allow for unambiguous labeling, in this section each region is identified by a two-digit numerical code where the first digit indicates the realm (with the order presented in Figure 4.2) while the second digit is based on the mean value of the first principal component, ranked from high to low.

In the Indo-Malay and Neotropical realms, the climate space was defined by two aspects of precipitation seasonality (P_amplitude and P_amplitude_perc), and the first two PCs explained a large proportion of variation in the five input climate variables (78.87% and 80.5% respectively). Moving to a higher latitude, the primary climate gradient was longitudinally driven by winter precipitation with precipitation increasing to the west in the

Palearctic realm and to the east in the Nearctic realm. The secondary gradient was a latitudinal gradient of temperature increasing south. The first two PCs explained 77.99% of the variation in the Palearctic realm and 83.06% in the Nearctic realm. Fire regimes in Afrotropical and Australasian realms were described in Chapter 3 and are therefore not repeated here.

While two main climate gradients vary between realms, the main constraints imposed by fuel moisture and productivity were universal. As noted in Figure 4.5 and Table 4.2, regions with intermediate to high levels of MAP and strong precipitation seasonality, defined by P_amplitude and SI which corresponded to savanna biomes (regions 11, 32, 41, 63), had the highest BA, especially tropical savannas in the Afrotropical and the Australasian realms. These regions are characterized by strong climatological seasonality (i.e. rainy vs. dry seasons) which is ideal for successive vegetation growth and drying which can support very frequent fires (Hoffmann et al., 2012). Regions that corresponded to the temperate savanna biome in the Nearctic and the Palearctic (regions 54, 84) also had the highest BA in the realm, but fire reoccurrence there was much lower due to less pronounced climate seasonality compared to tropics (Saha et al., 2019) that could support continuous flammable vegetation and therefore high BA. Additionally, anthropogenic effects, particularly high proportions of cropland, can explain low BA values, especially in region 54 since it is a large agricultural region in the U.S. (Le Page et al., 2010). Fire regimes in tropical and temperate savannas also differ from other biomes in terms of fire size and intensity: in tropical savannas, very frequent fires create patchiness and reduce fuel loads which limits fire size and intensity (Archibald et al., 2013) while in more fuel-limited temperate savannas, where fire is less frequent, when sufficient amount of fuel is accumulated the fire intensity can reach significantly higher level than in tropics.

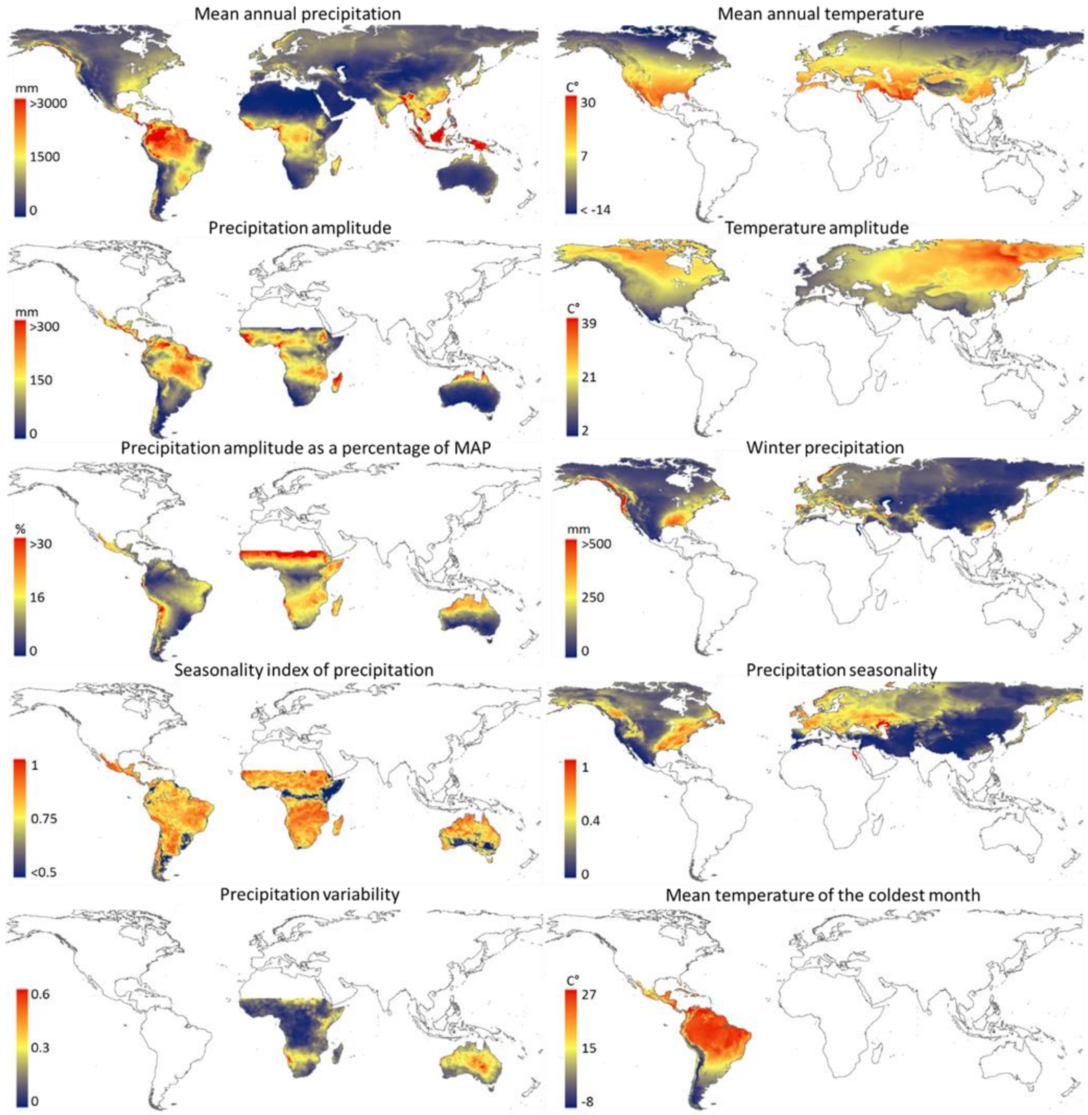

Figure 4.4. Ten 0.5º gridded climate variables. Climate variables are only presented for realms in which they were used as inputs for PCA. The description of each variable can be found in Table 4.1.

Moving towards the high end of the moisture gradient, fuel becomes too moist for combustion which can drastically decrease BA together with fire size and intensity. This low level of fire activity is common for the tropical forest biome where precipitation is distributed throughout the year (region 31, 43, 62). However, in the Indo-Malay and the Neotropical realms, the tropical forest biome was split into two fire regions based on differences in P_amplitude and SI. Regions 42 and 61, albeit similar to regions 43 and 62 in terms of high level of precipitation, had more defined dry seasons that created favorable conditions for fuel drying and fire spread. Those were presumably regions with transitional forests (Hoffmann et al., 2012), where BA and fire intensity were significantly higher compared to neighboring regions with low precipitation seasonality. At higher latitude, regions with the highest levels of MAP and winter precipitation were occupied by the temperate forest biome (regions 51, 81). While higher latitudes receive much less rainfall than tropical forests, demand for water from plants in these areas is much lower which, together with the absence of long dry seasons (especially in the Nearctic realm), created adverse conditions for fire propagation in forested ecosystems that require low levels of soil and atmospheric moisture for fire spread (Littell et al., 2016). Aside from biophysical conditions, high population density and extensive agriculture undoubtedly had a negative effect on fire activity in the eastern coast of North America and especially in Europe (Bedia et al., 2015; Lasslop and Kloster, 2017; Moreira et al., 2011; Syphard et al., 2017).

In warmer, arid regions where resources are sparse and highly variably across time and space, water availability during the growing season was the main limitation for fire (Krawchuk and Moritz, 2011). Fire regimes in dry regions (14, 33, 53, 83) were characterized by large, high intensity fires that occur after years with above-average precipitation that enhances vegetation growth and reduces fuel patchiness (Bird et al., 2012; Hantson et al., 2017; Mondal and Sukumar, 2016), while arid regions 34 and 65 experienced small infrequent fires with low intensity due to low MAP together with a less pronounced dry season that negatively affects biomass accumulation rates and the availability of fuels to burn (Saha et al., 2019). Conversely, in the boreal forest biome (regions 55, 85), fuel is typically abundant and fire was limited by the lack of weather conditions that promote curing of fuels (Littell et al., 2009; Saha et al., 2019). Low temperatures coupled with high temperature seasonality limited fire occurrence, but high lightning density during the summer months following by hot and dry conditions can accelerate fire spread that leads to mega-fires that are not limited anthropogenically due to the low human population in these areas (Abatzoglou and Kolden, 2011; Flannigan et al., 2009; Stocks et al., 2002; Veraverbeke et al., 2017).

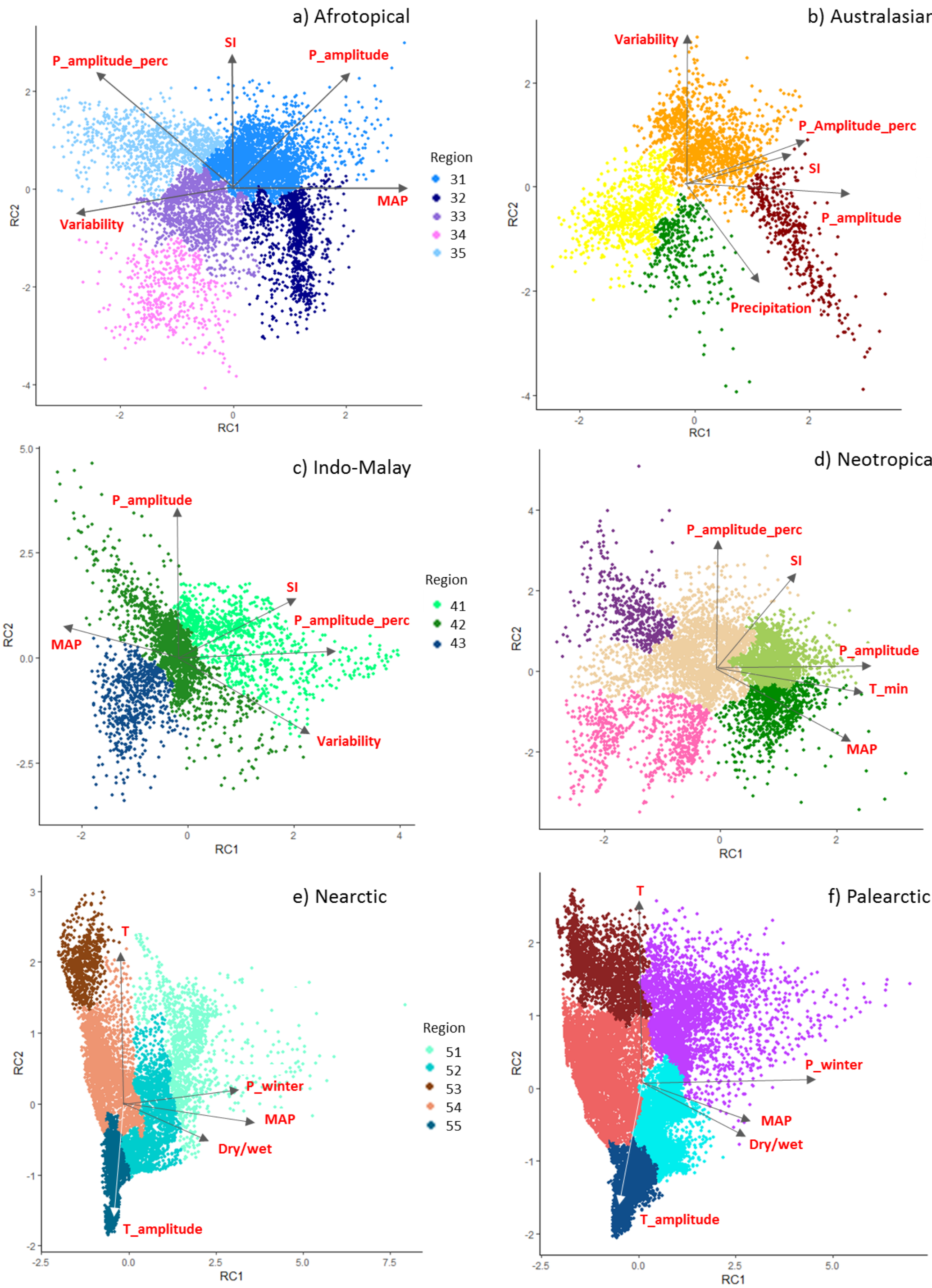

Figure 4.5. Climate domains of the fire regimes in 6 realms. Biplots showing the ordination of 0.5° cells along the first two principal axes, the five climate variables are presented by arrows overlaid on rotated components of PCA using Varimax to improve the interpretation of the results. Abbreviations of the climate variables can be found in Table 4.1.

Comparing fire regions between realms, with the exception of temperate forest regions in the Nearctic and Palearctic realms (regions 51 and 81), all other fire regions were significantly different in terms of at least one fire metric. Additionally, some differences between regions with similar climate conditions should be noted. Our findings agreed with previous studies that found that in boreal forests, fire size and intensity in the Nearctic realm were significantly higher than the Palearctic realm where fires were more frequent (de Groot et al., 2013; Wooster et al., 2005). Similarly, in agreement with Hantson et al. (2017), tropical savanna fires were bigger and more intense in the Australasian realm comparing to the Afrotropical realm. Those differences in fire regimes were explained by vegetation composition, species fire ecology and different levels of anthropogenic pressure (de Groot et al., 2013; Lehmann et al., 2014; Stevens et al., 2017).

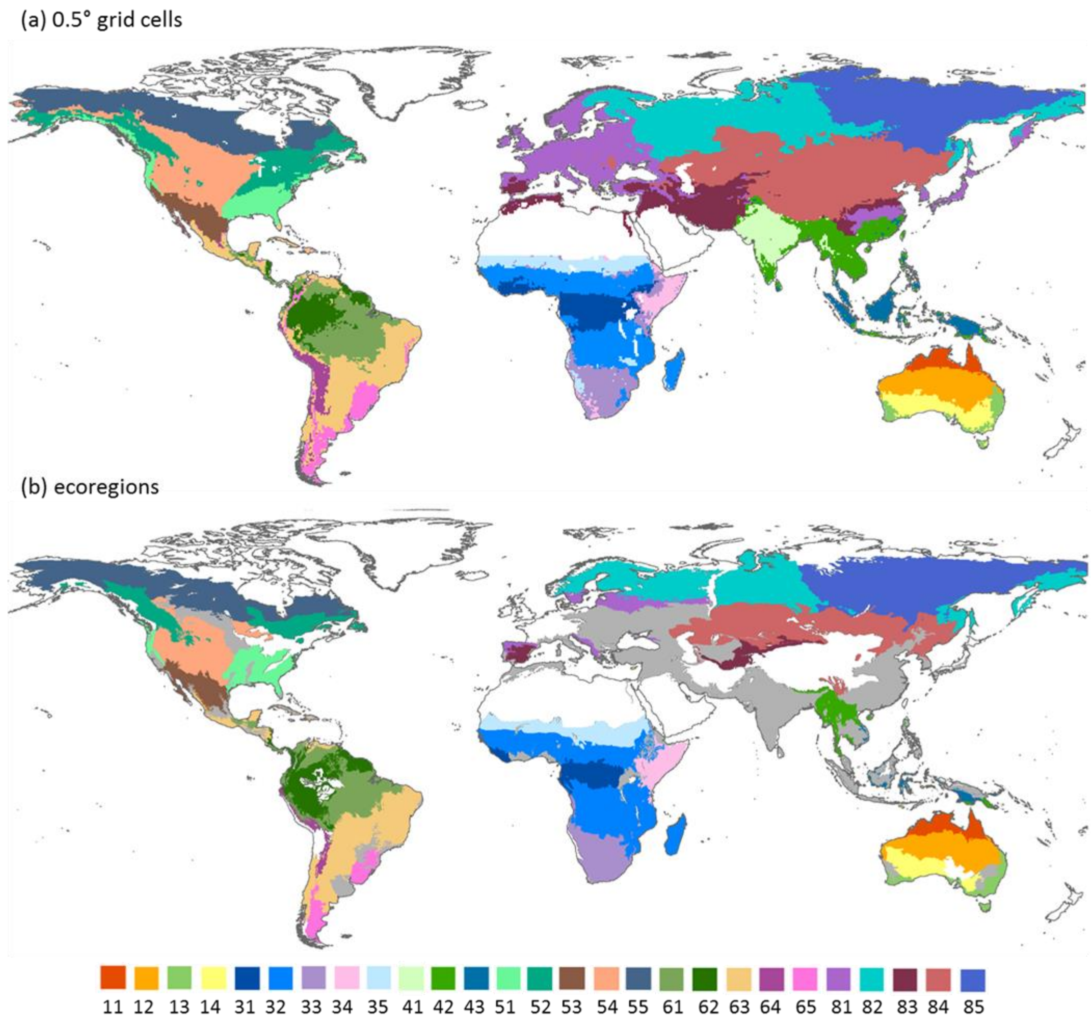

Figure 4.6. Spatial distribution of major global fire regions. (a) The output of hierarchical clustering; (b) Final map of fire regions using ecoregions as a spatial unit. The first digit of region ID is based on their realms (see Figure 4.2). Ecoregions that burn less than 0.1% on

average were not included (white). Grey color represents ecoregions with population density higher than 140people/km^2 and/or with a proportion of cropland higher than 70%.

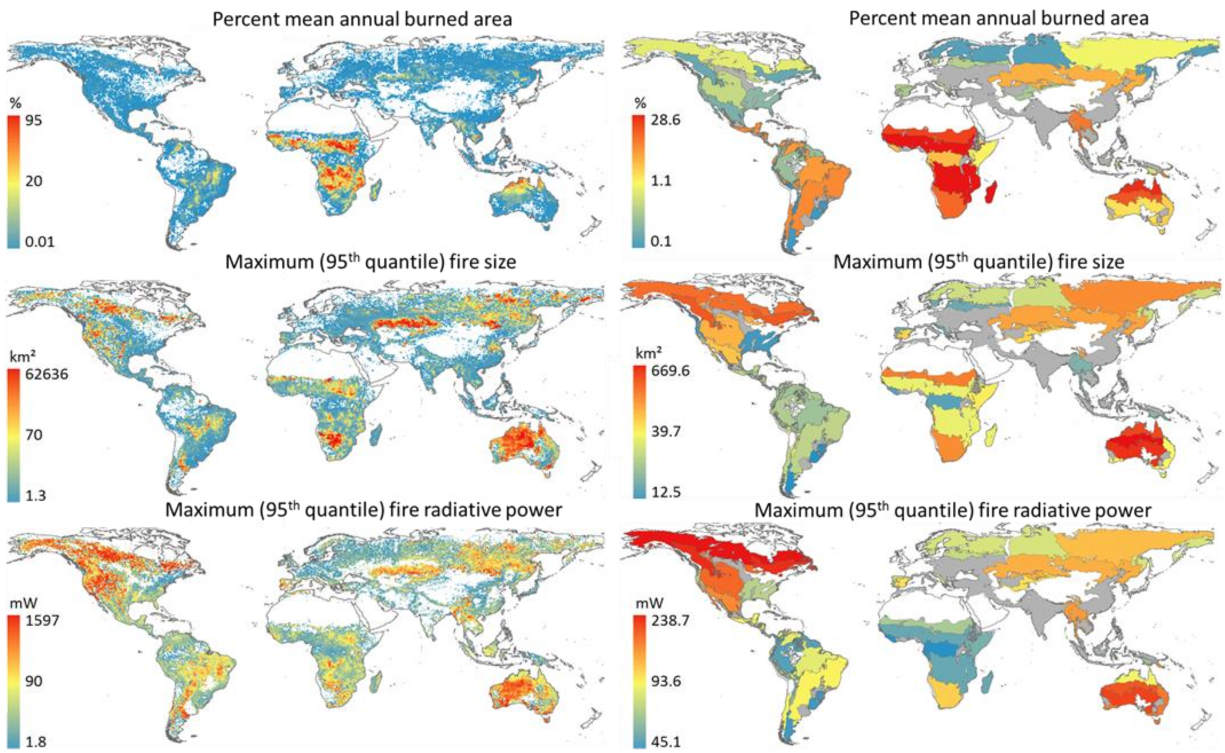

Figure 4.7. Spatial distribution of three fire regime characteristics. On the left: fire characteristics calculated within 0.5° grid cells; on the right: fire characteristics calculated within each fire region.

Discussion

Some limitations must be considered when analyzing our results. The accuracy of climate domains and fire-regime metrics depends on the quality of the remotely sensed data. Precipitation datasets are less accurate in regions with inadequate rain gauge network (Dinku et al., 2014; Tote et al., 2015), while MODIS products do not capture small, low intensity fires that are predominant in croplands and tropical forests (Chang and Song, 2009; Randerson et al., 2012, Boschetti et al., 2019). The time span of this study was limited by data availability and included only 17 years for which the two MODIS global fire products were available – it is possible this time series is too short to analyze fire regimes especially in ecosystems with long fire return periods. Additionally, we only included three fire regime components due to limitations of the available global, multiannual fire datasets. The development of more advanced fire thematic products will allow the inclusion of additional fire characteristics such as fire type and severity, and more broadly will expand our knowledge and understanding of fire activity and its relationship with the climate.

Table 4.2. Three fire metrics estimated for each fire region. BA – percent mean annual burned area, FSize – 95th percentile of fire size, FRP – 95th percentile of fire radiative power. Fire metrics that are statistically different compare to other regions within the realm are denoted by one asterisk, and between the realm by two asterisks, p-value<0.01. Fire metrics were not calculated for region 41 since all ecoregions there had population density higher than 140people/km^2.

Name	BA,%	FSize, sq.km	FRP, MW
11	22.18**	227.98**	92.37*
12	4.89*	669.62**	170.21*
13	1.25	39.71**	160.81**
14	1.21	563.48**	204.29**
31	1.45	15.67*	45.07**
32	28.55**	36.28	69.42**
33	4.65*	55.81**	106.73*
34	1.08	41.22*	69.97*
35	7.15*	68.05	77.65*
42	3.96*	18.68	128.38**
43	0.46*	21.25	75.44*
51	0.36	15.04*	78.22*
52	0.30	99.60	224.6*
53	0.34	47.01*	142.24**
54	0.42	49.37**	165.64*
55	0.47	98.74	238.69*
61	2.47*	23.83	90.41*
62	0.37*	24.26	62.81*
63	3.71*	26.40	93.58*
64	0.16	28.69	70.82*
65	0.25	12.45**	45.67**
81	0.40	17.39*	78.65*
82	0.29	26.83*	80.27*
83	0.38	45.51*	97.46*
84	2.26*	52.16*	119.94*
85	0.59	55.81*	117.56**

Moreover, we acknowledge that human drivers were only superficially considered in the analysis, mostly due to the lack of global, multitemporal datasets. While we excluded ecoregions intensively modified by human, not many areas in the globe are left untouched by anthropogenic activity. Humans can change ignition pattern, quality and quantity of fuel, and landscape connectivity (Daniau et al., 2012; Whitman et al., 2015). Therefore, fire regimes in the majority of ecoregions are shaped not only by biophysical processes but also, to a variable degree, by human actions and future work is required to find appropriate methods to adequately incorporate anthropogenic factors (Krawchuk et al., 2009; McWethy et al., 2013; Pechony and Shindell, 2009; Syphard et al., 2007). With increasing human population, we can expect that this influence will be even more relevant when considering scenarios of future fire activity.

We do however expect the framework developed in the present work to be relatively robust with regard to these limitations. The methodology for the delineation of fire regions was not based on fire characteristics, but on climate variables. The choice of climate variables considered in the analysis was informed by previously published work and we believe it represented the most important top-down controls of fire that affect fuel accumulation, availability to burn and fire spread.

Conclusions

In this study, we proposed a new approach for delineating global fire regimes that is based on defining broad climate domains – termed 'fire regions' – based on the analysis of key drivers of fire activity. Our approach did not only identify the spatial pattern of fire regime across biomes and continents but also top-down controls of fire activity. This stratification is reproducible and, since it is based on statistical clustering, no arbitrary judgment was involved in determining boundaries between regions. We expect our analysis to contribute to the broader body of knowledge on the linkages between fire, climate and vegetation.

While fire regions have some similarity with biomes, there are some significant differences. We note that the same biome exhibits very different fire characteristics in different realms, but that in some cases even within the same realm a biome is split in multiple fire regions. This is not unexpected, and it is consistent with previous literature.

Biomes cover broad bioecological regions and while they are uniform in terms of the major vegetation type, variations in climate, soil properties, and species composition are present (e.g. Moncrieff et al., 2016) leading to heterogeneity in fire activity. For each realm, we chose a set of climate variables that drive biomass accumulation, fuel moisture reduction, and fire spread, therefore, regions where multiple key climate variables limit fire activity could be identified. Previous studies typically linked fire regimes to a single climate driver in each region considered. Additionally, this approach presented spatial gradients in the relative importance of factors that control fire activity. For example, in our framework it was not necessary to assume that each region had to be either strictly fuel-limited/or energy-limited.

We also showed how fire regions that exhibit the same fire characteristics (e.g. low fire frequency), could have different biophysical processes driving the fire activity.

While this study could be considered an initial first step for the delineation of global fire regimes using climate gradient, and undoubtedly improvements are needed, we believe that our proposed fire regions reflect current global fire activity and can be useful for fire model validation, provide context within which analysis of change can be extrapolated, and as a scale unit for statistical analysis and summarizing global fire activity. Additionally, numerous studies predicted alterations in fire activity under climate change (Batllori et al., 2013; Bradstock, 2010; Krawchuk et al., 2009; McKenzie and Littell, 2017) and our results can bring a new insight of which processes have dominant influence on fire in different part of the globe and how variation in climate promotes fire with different fire characteristics. Our findings can be used together with future climate scenarios to identify vulnerable areas where environmental changes will be more apparent since a shift in fire regime components has the potential to trigger a cascade of ecological changes (Johnstone et al., 2010; Krawchuk et al., 2009).

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Chapter 5: Conclusions

This research has demonstrated the importance of climate as a top-down control on fire activity, even in the current scenario where most of the planet has been, in some way, modified by anthropogenic activity. The results thus meet the main overarching goal of the research, i.e. improving our understanding of a broad-scale fire-climate relationship and proposing a new approach to describe and map the diversity of fire regimes at continental to a global scale. The results of this research improve in particular our understanding of multi-scale spatio-temporal interactions between fire and the environment, which is relevant to fire management, climatological studies, and fire ecology. This was accomplished through three key study components: first, the relationship between burned area and climate factors was established to understand fire activity dynamics at the ecoregion level in Africa; then, based on lessons learned about the climate-fire relationships in Africa, a framework was proposed for describing continent-wide fire regimes in Africa and Australia based on a series of fire metrics used as input to a principal components model; finally, this framework was adapted and applied globally to create a global map of fire regimes which allow quantitative and geographic description of the variability of fire regime components and address a fundamental questions of what drives fire activity across biomes.

An important first step towards the goal of identifying global fire regimes is understanding the relationships between climate and fire. While numerous studies analyzed the climate-fire relationship in the past two decades, most of these studies focused on small study areas or were concentrated on regions with decades of high-quality fire data records (e.g. North America or Europe) which do not exist globally (Batllori et al.; 2013, Littell et al.; 2009, Parisien et al., 2009; Parks et al. 2016; Whitman et al., 2015). Africa is a particularly important continent for understanding fire, because it is responsible for over half of the global annual burned area and atmospheric emissions from fire (van der Werf et al., 2017). Despite the importance of fire activity in Africa, not only for local biodiversity and ecosystem services but also for global emissions (Archibald et al., 2010b; van der Werf et al., 2017), only a limited set of studies addressed the drivers of fire activity in Africa, and most of them focused on Southern Africa only, building simple relationships between the amount of burned area and the accumulated precipitation prior to the fire season (Andela and van der Werf, 2014; Archibald et al., 2010a). Many studies, however, have emphasized that the relationship between moisture and fire is non-linear and depends on the key processes that limit fire activity in a particular ecosystem: fuel accumulation, fuel desiccation, extreme weather conditions, or ignitions or a combination of several factors (Boer et al., 2016; Bradstock; 2010; Littell et al. 2016; Whitman et al., 2015). Taking this into consideration, the implicit assumption that one factor limits fire activity across biomes might not stand, and the use of physically meaningful accumulation time intervals illustrates the geographic variation in processes and timescales that limit fire occurrence. This has been demonstrated by several studies in the U.S. which showed stronger linkages between fire and variables that are more mechanistically related to plant-available water and flammability compared to standard climate variables like annual or seasonal temperature or precipitation (Abatzoglou and Kolden, 2013; Littell et al., 2011; Westerling et al., 2011).

The methods used in Chapter 2 tested whether more complex mechanistic variables (effective rainfall and soil moisture) are more appropriate for modeling fire behavior than standard simple climate variables (e.g. precipitation) and if different accumulation periods (concurrent and antecedent) can strengthen the observed fire-climate relationship. Linear models that considered interannual variability in climate factors directly related to biomass productivity and aridity explained about 70% of the decline in burned area in natural land cover. While the analysis of the anthropogenic drivers of fire relied on several simplifying assumptions, it was a reasonable compromise, given the lack of time-series human data and was more advanced compared to previously published correlation analyses (e.g. Andela et al., 2017). Additionally, the analysis presented in Chapter 2 demonstrated that climate – particularly climate factors directly related to biomass productivity and aridity – are effective predictors of changes in fire activity in Africa. These results of the study provide evidence that although most fires are human-caused in Africa, increased terrestrial moisture from 2002 to 2016 is linked to the decline in fire activity in Africa, which might provide insights for future global change scenarios.

Based on the results from Chapter 2, a new framework for describing and mapping the diversity of fire regimes at a continental scale was proposed in Chapter 3. The framework is based on the analysis of variables that biophysically link key climate drivers to fuel availability and fire spread. In contrast to traditional empirical approach where several fire metrics are used as an input for an unsupervised classifier without taking in consideration interactions and feedbacks between processes that lead to a particular combination of fire characteristics, the proposed method led to the delineation of ecologically meaningful fire regions. The method was based on the conceptual model of the key drivers of fire regimes proposed by Bradstock (2010). Fire regions were defined through principal component analysis of climate variables. For each continent, we identified five key climate drivers of fire based on previous literature, which were subsequently collapsed into two primary climate gradients which determined the large-scale distribution of fuel, moisture availability, and fire weather. This approach was tested in the two continents, Africa and Australia, that are responsible for the majority of global annual area burned. A comparison of fire activity in these two fire-prone continents with similar biomes but a drastically different level of anthropogenic pressure is important not only from the perspective of climate and vegetation but also in relation to environmental changes from anthropogenic causes. To contribute to the relevance of the analysis, it should be noted that a few studies have characterized the spatial extent of fire in Australia within “fire regime niches” based on seasonal rainfall distribution (Russell-Smith et al., 2007) and land cover type (Murphy et al., 2013), but to the best of our knowledge no similar analysis is available Africa.

The findings of this research confirmed the results of Chapter 2: the strong decline of burned area in mesic savanna can be attributed to ecoregions where fire activity was not water-limited. Arguably, it is the excess of moisture to limit the fire activity. Furthermore, mesic savanna is the ecosystem with the highest amount of area burned, and our analysis identified the seasonality of the precipitation - rather than the total annual amount - as the main fire activity driver. This further points to the significance of the analysis for projecting the impact on fire activity of climate change scenarios, where precipitation spatial and temporal patterns could potentially change.

In the analysis we accounted for human activity similarly to Chapter 2, and we excluded from the analysis all areas with a high level of anthropogenic pressure. Overall, the results supported previous research that identified the negative effect of humans on fire activity in most of the globe, with the exception of tropical forests where fire is a very rare event in the absence of human but become more susceptible for fire activity once fire is introduced (Cochrane, 2003). Our results also indicate that human activity might have – in both continents – a greater effect on fire size than on fire intensity, which is somehow unexpected considering that both fire size and intensity are driven by the amount of available fuel. Arguably this could be explained by considering that fire size is largely restricted by land fragmentation, which is tightly connected to anthropogenic activity, whereas fire intensity is controlled by weather conditions that promote flame length and depth, such as high temperature, low humidity and strong winds (Bradstock, 2010). It follows that, while humans can limit the amount of fuel which will negatively affect fire size and to some extent fire intensity, they cannot control weather conditions without altering the fire season (Archibald, 2016; Elliott et al., 2009). The results of Chapter 3 are also in agreement with Hantson et al. (2017), in demonstrating that fire activity in Africa and Australia exhibits different characteristics even within the same ranges of precipitation: while fire occurrence is higher in Africa, fires in Australia are hotter and spread over much larger areas.

The approach implemented in Chapter 3 was applied globally in Chapter 4 to create a spatially explicit characterization of the fire patterns which can expand our understanding of diverse region-specific biophysical constraints of fire activity. While overall the global pattern of fire activity is similar to the only recent global study of fire regimes by Archibald et al. (2013), which was not surprising considering it was based on the same fire data and used three main fire regime metrics (the amount of burned area, fire size, and intensity), our study points to the fact that the five global fire regimes or “pyromes” identified in their work might not be able to capture full complexity of global fire activity. The methods introduced in Chapter 3 of this dissertation, were extended globally with consideration given to overcoming the limitations affecting previous studies. Most significantly, this meant using so-called “climate gradients” to capture fire niches at the ecoregion level, nested within larger fire realms. This enabled the method to distinguish between regions with significantly different fire activity, while also providing information about the specific constrains on fire activity for each region. We notice that, unlike the Archibald et al. (2013) pyromes, the global fire regions defined in the present study were able to distinguish between different fire regimes in the boreal forest - not only between North America and Russia but also within the Eurasian boreal forest.

Additionally, our study shows that characterizing global fire activity as a single cohesive entity is likely an oversimplification of such a highly complex process. Without differentiating between continents and vegetation cover, “fire regimes” based on the classification of fire characteristics might confound very different fire conditions. For example, infrequent large and very hot fires can be found in arid regions in Australia, but also boreal forest but their consequences on ecosystems are drastically different. While global data for fire type and severity do not exist, Archibald et al. (2013) suggested that fire intensity can be used to distinguish between ground and crown fires which is only possible when one fire regime does not include forest and non-forest fires. Furthermore, previous studies did not consider the complex, highly variable effects of human activity on fire characteristics. For example, in Mediterranean regions high population density suppresses fire activity and over segment landscape which leads to less frequent fires smaller in size (Turco et al., 2016), in tropical forest human activity promotes fire activity which otherwise will be closer to none existence (Cochrane, 2003). Those human-driven fire regimes have the opposite nature and merging them in one fire regime can be confusing if not wrong.

Although this approach for delineating fire regions based on climate gradient has advantages compared to previous methods, it also has some limitations. Similar to the traditional empirical approaches, the results are dependent upon the choice of variables for statistical analysis. The selection in this work was based on the Bradstock (2010) conceptual model and previously published literature for each realm. While seasonal and interannual climate variation was included, as advocated by several studies (Russell-Smith et al., 2007; Saha et al., 2019), incorporating information about more complex variables like those presented in Chapter 2 could improve the precision of proposed fire regions. Additionally, stratification based on a more ecologically meaningful unit for analysis like ecoregions may overcome some data limitations due to a short time span, but ecoregions are not always homogeneous in terms of vegetation cover (Abatzoglou and Kolden, 2013) and were defined almost two decades ago, meaning they might not reflect changes in the ecoregions due to recent anthropogenic activity, invasive species, or disturbances. Moreover, as was discussed in previous chapters, satellite data suffers from limitations which can negatively impact the results of fire studies. In particular, short data time series preclude accurate characterization of fire regimes in places with infrequent fires (Bowman et al., 2009; Daniau et al., 2012;

Krawchuk and Moritz, 2014, Benali et al., 2015) and the omission of small fires at coarse spatial resolution (Boschetti 2019) may limit the significance of observed trends in fire activity (Knorr et al., 2014). The latter point is especially important for any human-fire analysis since human tends to reduce fire size which, together with the lack of accurate anthropogenic data on a broad scale and absent of any gridded yearly human-related data, leads to exclusion of highly anthropogenically modified regions from many global fire analyses which makes our understanding of this complex phenomenon incomplete. This is of particular concern because the increasing human population and urbanization will undoubtedly have a strong effect on fire, directly and indirectly, by changing climate and vegetation (Archibald, 2016; Bowman et al., 2011; Pausas and Keeley, 2009).

Drawing from the present study, it is recommended that future research be undertaken to improve (a) the delineation of fire regions by testing if moisture-related variables along a productivity gradient can better reflect biophysical controls of fire; (b) characterization of fire regions by improving the quality and the quantity of fire regime metrics; (c) human representation to define and characterize human-driven fire regimes globally. For instance, the work of Boer et al. (2016) provided an example that fuel- and energy-limited fire regimes can be determined by climatic water balance in Australia. It is a question of how the proposed method will work in higher latitudes where fire regimes are determined not only by precipitation patterns but also temperature gradient. Fire-weather indices and water balance metrics were used broadly in the U.S. and a few global studies which found them closely related to fire activity (Abatzoglou et al., 2018; Abatzoglou and Kolden, 2013; Bedia et al., 2015; Littell et al., 2016).

While including three fire regime metrics is an improvement over most previous fire studies that only used information about the amount of burned area for global analysis, the broad definition of fire regime consists of several other fire characteristics like fire seasonality, frequency, type, and severity. Of these, only the seasonality of fire can be fully observed using satellite data (Bedia et al., 2015; Le Page et al., 2010). Fire frequency can be observed for ecoregions with a very short fire return period due to the relatively short data span of satellite observations (Murphy et al., 2011; Parks et al., 2014). Information about fire severity which, defined as the degree of ecosystem change due to fire (Ryan and Noste, 1985), is needed to understand the effects of fire and recovery dynamics across ecosystems but fire severity data on a global scale does not exist. Furthermore, the use of a new generation of global fire products like Landsat-8 and Sentinel-2 with higher spatial resolution will improve the accuracy of the fire data especially in regards to human-fire relationships. Higher spatial resolution will allow users to identify fine details in fire spread, increasing the ability to assess the effectiveness of fuel breaks, fire suppression techniques, and landscape heterogeneity on slowing or stopping the propagation of fire across the surface – these features are otherwise lost at coarser spatial resolutions (Roteta et al., 2019; Roy et al., 2019).

Better evaluation of how anthropogenic activity potentially transforming a different aspect of fire regimes is one of the main goals of current fire research (Bowman 2011). Several methods were proposed to account for anthropogenic influences on fire activity through methods such as analyzing changes in fire seasonality (Benali et al., 2017; Calef et al., 2017; Le Page et al., 2010), comparing size of naturally ignited fires to anthropogenically ignited fires (DeWilde and Chapin, 2006), or using an extensive list of human variables (Archibald et al., 2009; Calef et al., 2017; Syphard et al., 2007). But the lack of reliable and comprehensive data on a broad scale ultimately limits our understanding of the complexity of human-fire interaction (Benali et al., 2017). Researches have not come to an agreement about whether humans have a strong enough impact on fire activity to create a dedicated anthropogenic fire regime, and if it should be mapped and characterized independently from natural fire regimes – this is influenced by whether or not climate is considered the main constraint to fire activity globally (Bowman et al., 2011; Knorr et al., 2014; Marlon et al., 2008; Syphard et al., 2017).

Finally, although the concept of “fire regimes” was proposed several decades ago, understanding of the variables which constitute global fire regimes is still lacking in spite of recent advances in broad scale fire detection and fire modeling. This raises a question whether mapping modern fire regimes on a global scale without a long list of uncertainties is feasible, or this concept should be analyzed on a smaller-scale due to the complexity of fire phenomenon. Without an agreement on the definition of what constitutes a ‘fire regime’, of how the fire regime metrics should be computed, and without an agreement on the appropriate scale for the analysis, it is highly questionable whether a rigorous description of global or continental fire regimes is possible. Fire activity within a space-time window is limited not only by climate but also by extreme weather events that occur during short time interval (Aldersley et al., 2011; Parisien and Moritz, 2009); plant traits with different fire adaptations (Lehmann et al., 2014; Stevens et al., 2017); soil properties (Lehmann et al., 2014; Staver et al., 2011; Stevens et al., 2017), topography (Hantson et al., 2017, Dillon et al., 2011), herbivory (natural grazing and livestock (Archibald and Hempson, 2016; Pausas and Keeley, 2014), proximity to roads and settlements (Archibald et al., 2009; Calef et al., 2017), and socio-economical changes and traditions (Benali et al., 2017; Pausas and Keeley, 2009; Turco et al., 2016). Currently, not all of these factors can be determined globally using the available datasets, though the necessity of any specific dataset can change depending on the continent, biome, or ecoregion being considered. Moreover, barriers to further improvements in any approach for delineation fire regimes on a broad scale include the absence of validation data (Murphy 2011) which makes it more challenging to evaluate any of the existing methods.

This study contributes to a growing body of fire research, improving the current knowledge of global fire activity by focusing on complex fire-climate-human interactions. Conducting studies on a broad scale and analyzing a wide range of environmental and anthropogenic factors that operates at a range of temporal scales is necessary to account for the relative importance of weather, climate, and socio-economic changes on fire (Murphy et al., 2011). Although the fire regime concept for a broad characterization of fire activity remains a research challenge – and it is further restricted by data limitations - there is a global concern for changing fire activity and its effects on biodiversity and economy (Bowman et al., 2011; Dellasala et al., 2004). Acknowledging and quantifying the complex manner of how changes in temperature and rainfall influence fuel productivity, fuel moisture and ultimately fire characteristics, will improve our understanding of global trends in fire activity, and help defining scenarios of future fire regimes influenced by a changing climate.

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Appendix A

Changes in Fire Activity in Africa from 2002 to 2016 and Their Potential Drivers

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