Vegetation and fire dynamics of savanna ecosystems assessed using satellite data

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CHAPTER 6

Summary

This chapter summarizes the key findings of this dissertation and provides recommendations for future research. I will start with a short summary of the research field, followed by separate sections providing a summary of the individual chapters of the dissertation. The final section synthesizes these findings followed by future research directions.

6.1 INTRODUCTION

The savanna biome exists of grasslands interspersed by trees. Tree cover density within the landscape is strongly affected by mean annual precipitation, and precipitation is often characterized by large seasonal and interannual variation. Frequent disturbance, in the form of grazing and browsing or fire, also plays an important role in the competition between various plant species, including competition between grasses and trees. The strong seasonality in precipitation creates an ideal environment for frequent fire occurrence. Lightning can be an ignition source in the (sub)tropics, but humans have also used fire as a landscape management tool since prehistoric times. To date, savannas are widely used for agriculture and livestock grazing. These types of human land use are expected to increase during the coming century, driven by socio-economic developments, in parallel with changing livelihoods. Climate change and rising CO_2 concentrations may further affect plant functioning and livelihoods within the biome during the coming century. The objective of this dissertation was to better understand large-scale savanna ecosystem dynamics and changes. Special attention was paid to the role of fire, which plays an important role in ecosystem dynamics, affects regional air quality and global climate. The data used within this dissertation were mostly derived from satellite observations. Although field studies are needed for fundamental process understanding, satellite images provide the means to upscale these results.

Over the past decades many new satellite-derived data sets have become available to study the environment. Time series now start to become long enough to study trends and separate different drivers using statistical modeling, the subject of the first two studies of this dissertation. During the following two studies, the dynamics of fire within the savanna biome were further investigated. The emphasis shifted somewhat from studying trends to better understanding fire emissions in these savannas.

6.2 GLOBAL CHANGES IN DRYLAND VEGETATION DYNAMICS

The first study, presented in chapter 2, analyzed long-term trends (1988 – 2008) in vegetation dynamics using two complementary vegetation indices. Vegetation Optical Depth (VOD) is based on passive microwave remote sensing and sensitive to the vegetation water content, while the Normalized Difference Vegetation Index (NDVI) is based on observations in the visible and near-infrared part of the spectrum and is responsive to vegetation greenness. In savannas and more arid regions with mixed woody – herbaceous vegetation, I found that long-term trends in VOD were most sensitive to changes in the woody vegetation component, while trends in NDVI were most sensitive to changes in the herbaceous vegetation component. The study focused on long-term trends in both data sets and assessed their drivers. A statistical model based on optimal correlation between the vegetation indices and antecedent precipitation was developed to separate climate from other drivers.

Precipitation was driving much of the interannual variation in both data sets. NDVI was most responsive to short-term variations in precipitation, while VOD was more sensitive to multi-year trends, as would be expected from the respective herbaceous or woody vegetation components. After correction for the precipitation-induced variations, some trends in the respective data sets disappeared, while others remained and new trends appeared. Opposing trends between VOD and NDVI were found in many arid regions. In those regions a positive trend in VOD and decreasing NDVI indicated an increase in the woody vegetation component at the expense of the herbaceous vegetation component. A key finding of the work presented in Chapter 2 is that because of the large scale at which these trends occurred in drylands across the globe, a global driver, such as increasing CO_2 levels, could be responsible. This suggests that these trends may continue into the future and lead to a substantially different landscape in the next decades to centuries. In more productive ecosystems a wider range of trends was observed, and except for precipitation, drivers including fire, land cover conversion, and livestock density all played a role in this. Advances in agricultural practices caused increasing trends in both vegetation indices in many agricultural regions.

6.3 RECENT TRENDS IN AFRICAN BURNED AREA

The next study (Chapter 3) focused on recent trends (2001 – 2012) and drivers of burned area in Africa. The shorter time period in this chapter compared to the previous one, is related to the shorter satellite record of fire. Africa is sometimes called ‘the burning continent’, due to the extensive use of fire by humans. Over the study period, a clear increase in burned area was observed over most of southern Africa and a clear decrease over most of northern Africa. The reason behind these opposing trends (which were unique in the fire satellite record) was not understood, but previous work had shown that changes in rainfall as well as land use may have contributed. I therefore developed a statistical model to estimate the individual contribution of precipitation and land cover changes on the observed trends.

I found that the increase over southern Africa and part of the decrease over northern Africa was related to variations in precipitation driven by variability in sea surface temperatures. These changes were directly related to the El Niño-Southern Oscillation (ENSO) mode, and likely short-lived. In addition, in northern Africa a clear underlying decline was caused by conversion of savannas into croplands. Given the relatively large impact of land cover conversion over the study period and the expectation that this conversion will continue in future, it can be anticipated that fire activity in all of Africa will decline during the coming decades. When studying the spatial distribution of savannas, savannas converted into cropland, and annual burned area, we found that burned area did not only decline within the area actually converted to agricultural land but also in the remaining savannas in the vicinity. Especially at the onset of savanna conversion a large decline in annual burned area was observed. For example, when 10% of a given grid cell was converted from savanna to cropland annual burned area typically declined from roughly half of the grid cell when it was fully covered by savanna to about a quarter. The reduced fire return periods in the remaining savannas may result in competitive advantages of woody vegetation over herbaceous species. In the long-term, the declining fire activity in savannas, combined with increases in fire activity in forests around the world due to climate change, may cause a shift in global pyrogeography from being savanna dominated to being forest dominated.

6.4 SATELLITE-DERIVED FUEL CONSUMPTION ESTIMATES

This study (Chapter 4) explored the possibilities of estimating fuel consumption per unit of area burned by combining fire radiative power (FRP) detections with burned area estimates. With the increasing quality of satellite-derived burned area estimates, fuel consumption is becoming the weakest link in estimating fire emissions. We developed a new method to derive long-term mean fuel consumption estimates by combining FRP detections and burned area estimates of the polar orbiting MODerate-resolution Imaging Spectroradiometer (MODIS) instruments. In this method, first the spatial variability in fire radiative energy (FRE) was estimated by assuming that the limited number of daily MODIS observations are representative for daily fire activity. A large sample of MODIS FRP detections was included for each grid cell by calculating the long-term mean at 0.25°. This way, several sensor specific limitations averaged out. In a follow-up step, fuel consumption estimates were derived by calibrating the results against available field measurements. Because tree cover may obscure part of the FRP signal, results were only presented for low tree cover regions (including savannas) in South America, Sub-Saharan Africa and Australia.

Results were compared to an existing method based on FRP detections of the geostationary Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument for Africa.

Geostationary satellites provide high temporal resolution data and thus observe the full fire diurnal cycle. However, they are located relatively far from the Earth resulting in a coarse pixel size and low sensitivity to small fires. For comparison, the estimated FRE of both methods was converted into dry matter burned using a conversion factor based on laboratory experiments. Finally, the results were compared to modeled fuel consumption estimates by the preliminary version 4 of the Global Fire Emission Database (GFED). In addition, the spatial distribution of the drivers of fuel consumption were explored.

The spatial patterns in fuel consumption derived from the geostationary and polar orbiting instruments compared favorably, giving confidence in the spatial distribution of the fuel consumption estimates using this approach. However, absolute values remained more uncertain. Following previous studies, I found that FRE estimates based on SEVIRI FRP data were about half of the FRE estimates derived from MODIS FRP data, mostly related to the low sensitivity of the SEVIRI instrument to small fires. Moreover, when calibrating against field observations the fuel consumption estimates were about 1.5 times higher than when using a conversion factor based on laboratory experiments. This may partly be explained by the reduced sensitivity of the MODIS instruments towards the swath edges, resulting in an underestimation of FRE. The comparison of long-term average fuel consumption estimates derived from satellite data to field studies was complicated, mostly because of the differences in spatiotemporal scales and the heterogeneity of fuel consumption in both space and time. Additionally, many field studies have been carried out in the pre-satellite era precluding direct comparison.

When analyzing the spatial distribution of fuel consumption, NPP and fire return time could explain some but not all the variation in the fuel consumption estimates. Vegetation type played an important role driving the fuel build-up mechanism. For example, well connected grasslands tend to burn more frequently than shrublands or disconnected Hummock grasslands (covering much of interior Australia), resulting in lower fuel consumption. However, clear differences in fuel build-up rates between Australian and African grasslands were also observed, with generally faster fuel build-up in Australian grasslands than in African grasslands of similar productivity, possibly driven by different grazing intensities or decomposition rates. Different fuel build-up mechanisms between different types of grasslands and shrublands are currently not incorporated in GFED, potentially explaining some of the differences found between fuel consumption estimates derived from satellite data as I have shown here and by modeling. Effects of human land management on fuel consumption also clearly stood out, for example in areas of active deforestation or with degradation fires (i.e., fires that burn part of the woody vegetation in addition to the grasses) that showed enhanced fuel consumption. Moreover, in regions where savannas were converted into croplands, the fuel consumption was typically low.

6.5 FIRE DIURNAL CYCLE AND EMISSIONS ESTIMATES

The final study (Chapter 5) explored the fire diurnal cycle and the drivers of its spatial variation. Using data assimilation, two potential new methods were developed to include the fire diurnal cycle in the near real-time emissions estimates of the Global Fire Assimilation System (GFAS). Currently GFAS is based on the FRP detections of the polar orbiting MODIS instruments because they provide relatively high-resolution images, allowing for the detection of fires with relatively low FRP. However, the MODIS instruments only provide about four daily observations in the (sub)tropics. Geostationary instruments, such as SEVIRI, provide high (15-minute) temporal resolution images but are unable to detect the lowest FRP fraction due to the lower spatial resolution caused by their location relatively far from the Earth. Despite this limitation, the high temporal resolution of the SEVIRI instrument can be used to study the fire diurnal cycle, the effect of the fire diurnal cycle on observations at MODIS overpasses, and to explore potential methods to implement the fire diurnal cycle in GFAS, the subject of this work.

Fire showed a clear diurnal cycle across all ecosystems. Peak fire activity is generally reached during the afternoon, when ambient conditions are optimal, while nighttime fire activity is typically strongly reduced. I found that the shape of the fire diurnal cycle was dependent on various drivers, such as land cover type but also a clear climatic gradient was observed in the fire diurnal cycle when moving from the arid grasslands to humid savannas. In more humid regions, the fire diurnal cycle was generally more pronounced, with shorter duration over the day and nighttime fire activity often below the SEVIRI detection threshold. In regions where grass-fuelled fires dominated biomass burning (e.g., savannas), fire size was found to be a good predictor for the fire diurnal cycle. Information on fuel load and conditions is thus partly contained within the remote sensing data.

Using SEVIRI data sampled at MODIS detection opportunities to derive FRE while ignoring the fire diurnal cycle led to several structural errors. First, the shape of the diurnal cycle and the typical timing of the MODIS overpasses (01:30, 10:30, 13:30 and 22:30h, equatorial crossing time) affected the total estimates of FRE. Total FRE was generally overestimated because the 13:30h Aqua overpass captures the (near) peak fire activity and is therefore not representative for the full period until the next overpass of the Terra satellite at 22:30h. This effect decreased at higher latitudes due to orbital convergence (i.e., an increased number of daily observations due overlapping swaths of two overpasses). In addition, when day or nighttime observations were missing (e.g., no overpass or cloud cover), this introduced large erroneous day-to-day variation in the FRE estimates. Missing daytime observations would likely result in underestimated FRE because the generally lower nighttime FRP detections then dominate the FRE estimate, and vice versa for missing nighttime observations. To overcome these shortcomings I presented a modeling approach based on information on the climatology of the fire diurnal cycle, which was recommended for implementation within GFAS and the Copernicus Atmosphere Monitoring Services (CAMS).

6.6 GENERAL CONCLUSIONS AND FURTHER RESEARCH

For those who view the savanna as a pristine biome, maybe the most striking aspect of it is the large impact of humans on the ecosystem. I have shown this for the satellite era, but this is going well back into human history. An important mechanism through which humans manage savannas are fires. To date, the ongoing changes in fire regimes and consequences for ecosystem functioning and fire emissions remain to a large extent unknown. While investigating the interaction between vegetation, climate and human land management, it became apparent that over the period that satellite data was available, changes in the more productive savannas were often driven by human activity, while climate often played a larger role in arid regions. Here I will further focus on the different approaches used in this dissertation and how they have helped to give new insights in some aspects of these systems. In addition, I will look forward to the role that the new generation recently or soon to be launched satellites can play in increasing our understanding.

All studies in this dissertation used satellite-derived data sets as the primary source of information. Several strategies to derive new information from the satellite imagery or to better understand its dynamics were particularly successful. Over the past decades, different satellite based sensors have been brought into orbit, resulting in a wide variety of data sets to study the environment today. The lengthening time series offer chances to use statistical modeling to study the drivers of variation and trends. Such statistical models were used in the first two studies to separate different drivers of vegetation and burned area dynamics, respectively. Another recurrent aspect of the studies presented here was that they were all based on the combination of several satellite based sensors and data sets. Often the differences between the sensors and data sets could be used to derive new information, or resolve sensor specific limitations. This strategy was used to understand long-term trends in vegetation structure, but it was also found useful when studying fire, for example when combining burned area and FRP data sets to derive estimates of fuel consumption.

During this work I found an interesting relationship between the spatial and temporal dimensions of the data. Combining spatial and temporal patterns often yielded more robust results and under certain conditions the two dimensions were interchangeable. For example, socio-economic developments driving increased cropland extent, caused a clear decline in burned area in northern Africa over the last decade (Chapter 3). These conclusions were supported by the spatial distribution of burned area, savannas and cropland as well as by recent trends in burned area that were analyzed using the temporal data and a statistical model. During follow up studies, this “swapping space for time” approach could be used to understand the implications of land management beyond the limits of satellite records. Today’s fire regimes in some of the African savannas are still managed using traditional ecosystem knowledge, which may provide valuable insights in possible past fire use in Africa. A similar approach could be applied to South America or Australia, where fire regimes have changed drastically after western colonization. In the same way, it was also found that fuel consumption estimates could be derived from the combination of burned area and FRP data. However, due to the high spatiotemporal variability of fire activity and the limited number of daily MODIS overpasses, the FRP detections contained a large random error and only large enough samples of active fire (FRP) observations resulted in robust fuel consumption estimates (Chapter 4). The sample size can be increased by aggregating data at either coarser spatial or temporal resolution, and the two dimensions were thus found to be interchangeable. In our study we choose a relatively high 0.25° spatial resolution and aggregated data over the full period of data availability to get robust sample sizes, even for areas with infrequent burning. When interested in the temporal dynamics of fuel consumption, such choices could be reconsidered.

During the next decade data will become available from a new generation of instruments aboard satellites that have been launched recently or will be launched in the near future. Improved data sets of environmental conditions and fire will for example become available from the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument and the Sentinel-series of satellites. These missions assure continuity of the MODIS based data sets while for example higher spatial resolutions provide new insights in small fire activity and fire behavior. In addition to these moderate resolution instruments, Landsat 8 (launched in 2013) provides 30 meter resolution global data on fire activity and ecosystem variables. New developments, like the laser based Global Ecosystem Dynamics Investigation Lidar (GEDI) instrument (expected in 2018) will provide global high resolution estimates of canopy structure. These high resolution instruments have relatively low revisiting times compared to the moderate resolution instruments, but offer ideal data for validation and may bridge some of the gaps between field studies and satellite observations. In addition, the high resolution data of Landsat may be used to study tree cover loss, land use change or when data is combined with information on canopy structure, species or vegetation trait distribution and biomass may be studied. Airborne field campaigns using hyperspectral data have also shown to be able to effectively map species distribution in addition to, for example, detailed information about photosynthesis. Improved computational power and the availability of high resolution data sets will likely provide many new insights in ecosystem function during the coming decade.

One of the key findings of this dissertation was that much of the fire dynamics in terms of fuel consumption, fuel conditions, fire diurnal cycle and fire size are contained within the satellite data available today. For studying fires, the use of various complementary data sets (e.g., polar- or geostationary orbit, or FRP detections and burned area) seemed to be a particularly promising research direction. However, when deriving new information on fires from satellite remote sensing, validation was often difficult. To date, the available field studies on these aspects are limited and not particularly well suited to meet the needs of the remote sensing community. New satellite based or airborne high resolution data sets may be used for validation of moderate resolution data sets to some extent, but a combined effort of field studies designed for calibration and validation and satellite-derived data sets is needed. Making the link between field studies and remote sensing is crucial because ecosystem changes driven by socioeconomic or climate change can often only be fully appreciated at larger scales. In addition, new high resolution sensors open up opportunities to study aspects of the ecosystems that to date have only been studied at the field level. When setting up a field campaign for validation of the previously mentioned satellite-derived fire characteristics, ideally the measurements would follow gradients of precipitation, vegetation types or fire return periods. One of the science challenges of the coming decade is to effectively use the wide range of data sets at different spatiotemporal resolutions available, something that can only be achieved by collaboration and open data policies.