

Chapter 10

Land Surface Phenology in a West African Savanna: Impact of Land Use, Land Cover and Fire

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Abstract Phenological change and variation have become increasingly relevant topics in global change science due to recognition of their importance for ecosystem functioning and biogeophysical processes. Remote sensing time series offer great potential for assessing phenological dynamics at landscape, regional and global scales. Even though a number of studies have investigated phenology, mostly with a focus on climatic variability, we do not yet have a detailed understanding of phenological cycles and respective biogeographical patterns. This is particularly true for biomes like the tropical savannas, which cover approximately one eighth of the global land surface. Savannas are often characterized by high human population density and growth, one example being the West African Sudanian Savanna. The phenological characteristics in these regions can be assumed to be particularly influenced by agricultural land use and fires, in addition to climatic variability. This study analyses the spatio-temporal patterns of land surface phenology in a Sudanian Savanna landscape of southern Burkina Faso based on time series of the Moderate Resolution Spectroradiometer (MODIS), and on multi-temporal Landsat data. The analyses focus on influences of fire, land use, and vegetation structure on phenological patterns, and disclose the effects of long-term fire frequency, as well as the short-

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term effects of burning on the vegetation dynamics observed in the following growing season. Possibilities of further improvements for remote sensing based analyses of land surface phenology are seen in using earth observation datasets of increased spatial and temporal resolution as well as in linking phenological metrics from remote sensing with actual biological events observed on the ground.

10.1 Introduction

Phenology has become an increasingly relevant topic in global change science (e.g. Rosenzweig et al. 2007). It addresses “the timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species” (Lieth 1974). During the last decades, changes in phenology have been observed in different regions of the world and could frequently be related to climatic variability and change or to alterations in land cover and land use practices (e.g. de Beurs and Henebry 2004; Heumann et al. 2007; Richardson et al. 2013). Phenological changes are of particular relevance as they may impact a number of ecosystem functions such as ecosystem productivity and carbon sequestration (e.g. Churkina et al. 2005; Richardson et al. 2010), reproductive patterns (e.g. Ramírez and Briceño 2011) and consumer-resource interactions (e.g. Kerby et al. 2012). Given the close link between phenology and resource availability for herbivores in many regions of the world, phenological variations can even impact land use decisions, such as long-distance movements of livestock (Butt et al. 2011). In addition to ecological aspects, phenology is closely linked to land-atmosphere fluxes of water and energy as it determines seasonal variations of biogeophysical land surface properties such as albedo (Ryu et al. 2008), leaf area index, or surface roughness length (Blanken et al. 1997).

Plant phenology is analyzed at the scale of individual plants or vegetation communities and is usually based on field assessments. Land surface phenology in contrast is studied at landscape, regional and global scales, where earth observation delivers information on the seasonal variations of the vegetated land surface (de Beurs and Henebry 2005; Henebry and de Beurs 2013). Space-borne, medium resolution (250 m–1 km) sensors provide daily to bi-weekly data of vegetation indices for large areas, and currently cover up to three decades of time series. This makes remote sensing an indispensable basis for many studies of phenology and phenological changes.

Tropical savannas cover approximately one eighth of the global land surface and more than half of the African continent (Scholes and Archer 1997). The land surface phenology of savannas has been studied at various scales, mainly focusing on the influence of climatic variability (e.g. Archibald and Scholes 2007; Butt et al. 2011; Heumann et al. 2007; Ma et al. 2013; Wagenseil and Samimi 2006). However, a detailed understanding of the phenological cycles of savanna ecosystems and their biogeographical patterns is still missing, particularly at landscape and regional scales (Ma et al. 2013). Furthermore, in regions like West Africa,

where population density and growth are high, the phenological characteristics of savannas can be particularly influenced, in addition to climatic variability, by agricultural land use and fires (e.g. Devineau 1999; Devineau et al. 2010).

The aim of this study is to analyze the spatio-temporal patterns of phenology in a typical region of the West Sudanian Savanna in southern Burkina Faso. A special focus is on investigating the interrelations of phenological patterns with fire, land use and vegetation structure. It is assumed that fire can have both long-term, and direct, short-term effects on land surface phenology. Long-term effects might be observable, when the average frequency of fires over long time periods influences average phenological characteristics. Such effects may be due to shifts in species or growth form composition as a result of the long-term fire repetition rates (e.g. Hoffmann 1998). On the other hand there might be direct, short-term effects of fire events on the phenological development of the subsequent growing season. These effects could be, for example, resulting from the removal of dead biomass that gives way for new sprouting, or from potential fire damage that hinders or delays vegetation development. This study is based on optical remote sensing time series of the Moderate Resolution Spectroradiometer (MODIS) with a spatial resolution of 250 m, on the MODIS burned area product MCD45A1 with spatial resolution of 500 m, and on multi-date Landsat spectral data with a spatial resolution of 30 m. Spatio-temporal information on phenology, land use, land cover and fire occurrence is derived from these datasets, and analyzed for a 14-year period from 2000 to 2013.

10.2 Study Region

The study region is located in southern Burkina Faso, just north of the national border with Ghana and covers an area of approximately 15,400 km² (Fig. 10.1, 2°23.5'W-1°10.25'W/11°58.75'N-10°58.4'N). It belongs to the tributary area of the White Volta and includes the northern part of the Sissili catchment. The topography is relatively flat with elevations between 250 m and 400 m above sea level. Pronounced seasonal alterations between a monsoonal rainy season and a dry season characterize the region. The mean annual precipitation ranges between 800 and 980 mm and falls mainly between May/June and September/October. Temperatures are relatively constant throughout the year with monthly averages between 26 and 30 °C. The study region is part of the Sudanian Savanna zone (White 1983) with different types of savanna vegetation ranging from open grassland savannas to closed woodland savannas and small patches of forests, mainly along rivers. The vegetation is characterized by alternating periods of vegetation growth during the rainy season and reduced vegetation activity during the dry season. Large parts of the study area are intensively used, mainly for the cultivation of crops, and partly for grazing. A further intensification and expansion of land use can be expected for the future years, given the high annual population growth of 2.9 % in Burkina Faso (The World Bank 2013), in a society where currently more than 90 % of the population work in the field of agriculture (FAO 2013). Some parts of the study region are protected areas, most importantly the Nazinga Game Ranch,

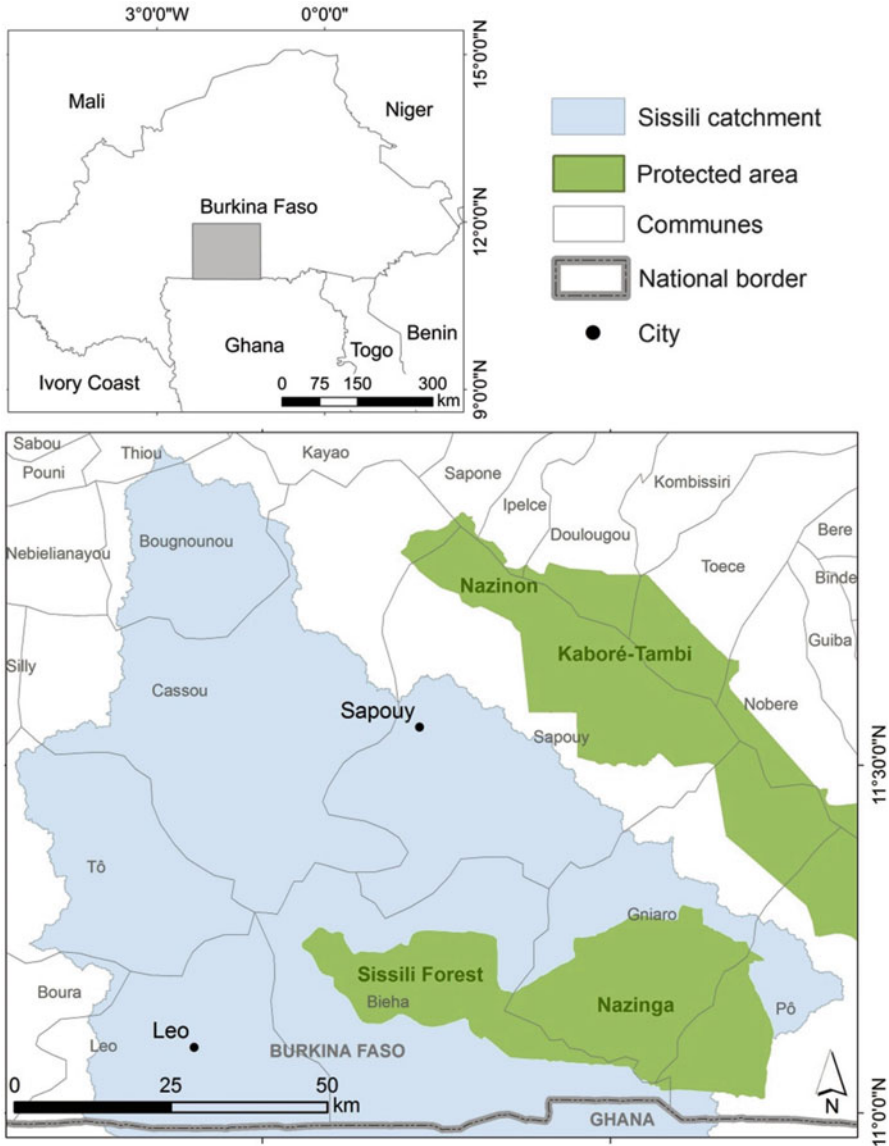


Fig. 10.1 Overview over the study region and its location in southern Burkina Faso

the Kaboré-Tambi (K.T.) National Park, the Sissili classified forest and the Nazinon reserved forest (Fig. 10.1). Regular fires are a typical feature of the study region and have a key influence on the vegetation structure of savannas (Rueth 2010; Wardell et al. 2004). While some fires in West Africa have natural causes, the majority of burnings are human-induced and often closely related to land use practices (Goldammer and Ronde 2004; Gornitz and NASA 1985). In the study region,

four fire seasons can be distinguished, the very early fire season in October, the early fire season in November and December, the late fire season in January and February, and the very late fire season in March and April (Rueth 2010). Controlled fire management is found within the protected areas. In major parts of the Nazinga Game Ranch for example, controlled early burning is undertaken. The aim is to prevent the more destructive late fires, to provoke a fresh grass flush for grazing animals, and to improve the visibility of wildlife for tourists. On the other hand, fire has been completely excluded by the park management from some parts of the southern Nazinga Game Ranch for more than 30 years, in order to study the long-term effect of fire suppression on the savanna ecosystem.

10.3 Material and Methods

10.3.1 Time Series of Land Surface Phenology

Phenological information was derived from time series of the MODIS Enhanced Vegetation Index (EVI, Eq. 10.1). This index considers the difference in blue and red reflectances for estimating influences of the atmosphere, and minimizes soil-brightness related variations (Huete et al. 1999, 2002). Compared to the frequently used Normalized Difference Vegetation Index (NDVI), EVI is more sensitive in areas of dense vegetation and is able to reduce canopy background effects and aerosols (Huete et al. 2002; Justice et al. 1998).

$$EVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + C_1\rho_{RED} - C_2\rho_{BLUE} + L} * G \quad (10.1)$$

where ρ_x = fully or partially atmospheric-corrected surface reflectances
 L = canopy background adjustment factor (L = 1)
 C₁, C₂ = coefficients of the aerosol resistance term (C₁ = 6; C₂ = 7.5)
 G = scaling factor (G = 2.5)

EVI time series were extracted from the MODIS product MOD13Q1 that delivers 16-day composites at a spatial resolution of 250 m. Despite the mentioned advantages of EVI, this global vegetation index product can still contain low quality values that are for example due to unfavorable observation geometries or due to remaining atmospheric effects. The latter is particularly relevant for situations of high and persistent cloud coverage, which are typical for the rainy season in the study area. With the aim to reduce such atmospheric and geometry related effects, all pixels were excluded from further processing that did not meet one or more of the three following conditions: (1) assignment of ‘good’ or ‘marginal’ in the MODIS quality information layer ‘pixel reliability’, (2) reflectance above 0.09 in the blue band, and (3) view zenith angle below 60°. In case these conditions excluded more than 18 composites of 1 year, the criteria were iteratively attenuated until at least 5 valid observations were available. This was done by keeping all data that met at least two, or finally at least one of the three conditions. In case even one

Table 10.1 Phenological metrics derived from EVI time series after Jönsson and Eklundh (2002)

Metric		Description
Start of season	(SOS)	Date for which EVI has increased to a level of 0.25 for the first time during the annual cycle
Rate of increase	(RIN)	Linear slope between the points where the time series reaches the 20 % and 80 % levels of its annual amplitude respectively
Maximum EVI	(MAX)	Largest EVI of the annual cycle
Large EVI integral	(LIN)	Integral of the fitted function from growing season start to growing season end (date at which EVI falls below a level of 0.25 for the first time during the annual cycle)

Table 10.2 Landsat data used for the classification of land cover and land use changes

Date	Sensor
18 November 1986	TM (Landsat-5)
3 November 2001	ETM+ (Landsat-7)
27 October 2013	OLI (Landsat-8)

All datasets were provided by USGS and cover WRS path 195, row 52

single criterion resulted in too few observations, the original data were kept. Time series were assembled for the period 2001–2013, and data gaps resulting from the removal of low quality composites were linearly interpolated.

The EVI time series were smoothed using the adaptive Savitzky-Golay filtering approach with a moving window width of 6 (96 days). Phenological metrics for the 13 years were derived from the fitted EVI time series as defined in Table 10.1. For Savitzky-Golay fitting and for the derivation of phenological metrics, the software tool TIMESAT was used (Eklundh and Jönsson 2012; Jönsson and Eklundh 2004; Jönsson and Eklundh 2002).

10.3.2 Land Cover and Land Use Changes

Baseline information on current land cover and land use as well as on the historic development of agricultural areas in the study region was derived from Landsat data. Nearly cloud free TM (Thematic Mapper), ETM+ (Enhanced Thematic Mapper Plus), and OLI (Operational Land Imager) data were available for the years 1986, 2001 and 2013 at a spatial resolution of 30 m (Table 10.2). These datasets, provided by the United States Geological Survey (USGS), did not need any further geometric correction as they showed satisfactory agreement with GPS records taken in the field. Calibration and atmospheric correction was done using Atcor-2 (Richter 1996) for flat terrain which is suitable for the flat topography in the study region.

Based on in-situ field plots taken in October and November 2013 and on very high resolution (0.6 m), pansharpned QuickBird data of October 2013, training

areas of seven major land cover/use classes were defined for the year 2013. The considered classes are *forest* (tree cover > 65 %), *closed woodland* (woody cover 40–65 %), *open woodland and shrubland* (woody cover 15–40 %), *grassland* (woody cover 5–15 %, grass cover > 15 %), *bare to sparsely vegetated areas* (vegetative cover < 15 %), *agriculture* and *water*. In addition, training areas for agricultural and non-agricultural land in 1986 and 2001 could be identified directly from the respective Landsat data. As very high resolution imagery and in-situ information were missing for these years, a further subdivision of the non-agricultural vegetation types was not possible. Based on the training information, the Landsat data were classified with a combined random forest and maximum likelihood approach.

10.3.3 Time Series of Burned Areas

Spatial distribution, timing, and frequency of fires in the study area were derived from time series of the MODIS burned area product MCD45A1 (Justice et al. 2006). This dataset is based on MODIS Terra and Aqua observations and provides information on burned areas as well as the approximate date of burning at a spatial resolution of 500 m. The MCD45A1 approach identifies fire-affected areas as sudden changes in daily MODIS reflectance time series by considering bi-directional reflectance variations. Further details on the MODIS burned area mapping algorithm can be found in Justice et al. (2006) and Roy et al. (2002). The approximate date of burning was extracted from MCD45A1 for the years 2000–2012. From this information, fire frequency and fire seasonality were determined considering very early and early fires occurring between October and December as well as late and very late fires occurring between January and April.

10.4 Results

10.4.1 Land Cover Types and Land Use History

The land cover and land use map of 2013, based on OLI data, visualizes the spatial patterns of land cover types in the study region (Fig. 10.2). The protected areas (Fig. 10.1) are characterized by heterogeneous patterns of the semi-natural vegetation types closed woodland, open woodland and shrubland as well as grassland. Forests occur in smaller patches and frequently follow courses of rivers (gallery forests). Agriculturally used areas dominate outside the protected zones, intermingled by fragments of woodlands and forests, and in the northern part of the Nazinon reserved forest.

The history of clearing for agriculture since the mid-1980s is shown in Fig. 10.3a–c. While previous to our study period, the overall extent of agricultural

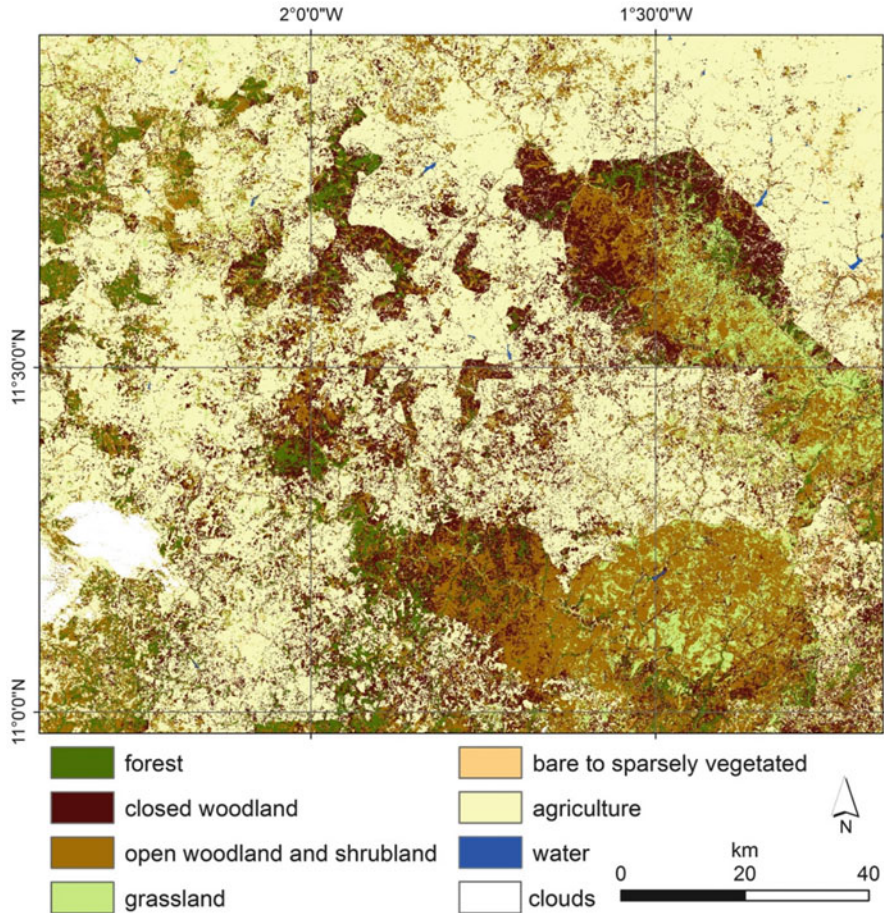


Fig. 10.2 Land cover and land use in the year 2013, based on OLI data

area has been relatively stable (1986: 3,869 km²; 2001: 3,804 km²), it has increased to approximately double the size of 2001 within the last 12 years (2013: 7,724 km²). This increase in agricultural area since 2001 is marked in red color in Fig. 10.3d. Despite these enormous changes, some parts of the study region show only minor alterations with respect to agricultural land use over the last 28 years. As an example, the land to the northeast of K.T. National Park has been cultivated since the mid-1980s already (yellow color in Fig. 10.3d). The situation is also stable within most protected areas and in a buffer zone parallel to the northeastern border of K.T. National Park, where hardly any agricultural land use has been observed for the period of study. The considerable increase in cultivated area has thus concentrated on the land between and to the west of the protected areas (orange color in Fig. 10.3d). During the past 13 years, agriculture has more and more advanced

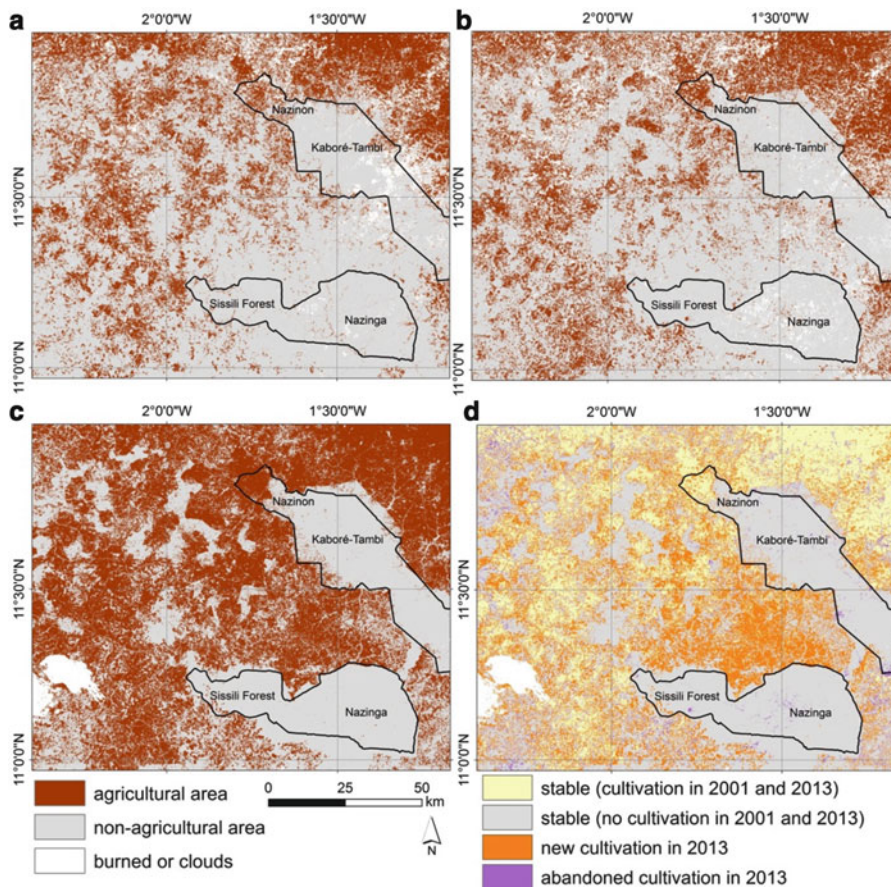


Fig. 10.3 Agricultural land use in (a) 1986, (b) 2001, and (c) 2013; for color coding see *bottom left*. (d) Changes in cultivated areas between 2001 and 2013 (d); for color coding see *bottom right*

towards the protected zones, resulting today in sharp fence line contrasts at the park borders.

Any areas affected by land use changes during the period of study (2001–2013) might disturb the intended phenological analyses and therefore need to be excluded from further investigations. The semi-natural savanna vegetation types existing in 2013 were not agriculturally used in 2001 (hardly any purple color in Fig. 10.3d), so that for these land cover types only minor changes during the period of study can be assumed. Considering the major transformations that have occurred since 2001 on the present cultivated land, only those agricultural areas that have existed in 2001 and in 2013 are considered in the following analyses.

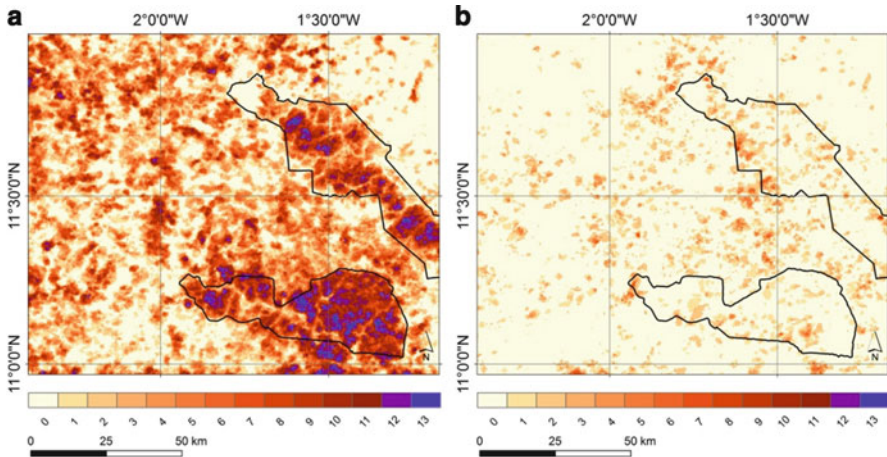


Fig. 10.4 Number of fires in a 13 year period (2000–2012) according to MOD45A1: (a) very early and early fires (October–December); (b) late and very late fires (January–April)

10.4.2 Spatio-Temporal Patterns of Fires

Figure 10.4 shows the number of very early and early (a) as well as late and very late (b) bushfires for the years 2000–2012, extracted from the MODIS burned area time series. Very late and late burnings are comparatively seldom; only 20 % of the study area was affected at least once, and 2 % of the region at least three times by a late fire in the 13 year period (Fig. 10.4b). In contrast, very early and early fires are found to a far larger extent and at higher frequencies. They affected almost 75 % of the study region and more than half of the area has experienced early fires more than three times between 2000 and 2012. Frequent burnings are concentrated in the protected areas where fires are usually found in intervals of 1–2 years. In the following analyses, only very early and early fires were considered as they are most typical for the study region.

When regarding the typical temporal fire patterns of different vegetated land use and land cover types in the study region, a relationship between fire frequency and vegetation structure can be observed (Fig. 10.5). With decreasing woody and increasing herbaceous components of land cover, fire frequency is increasing. While forests are on average affected by fire in only 3 out of 13 fire seasons, the fire frequency increases in more open woodland and shrubland types and reaches highest values for grasslands that burn in 11 out of 13 fire seasons, on average. Burning of agricultural areas in contrast was detected very rarely with a median value of 1 fire within 13 years.

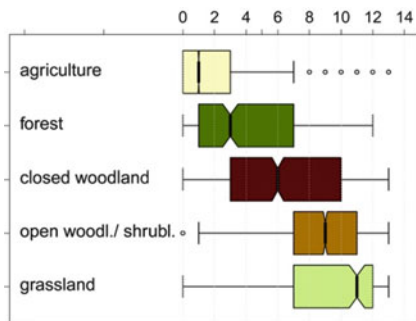


Fig. 10.5 Number of fires in the period 2000–2012, differentiated by land cover/use types. Only pure MODIS pixels that contain at least 80 % of one single land cover type are considered. Boxplot elements: *box* = values of 2nd and 3rd quartile; *horizontal line* = median; *whiskers* = lowest/highest values; *circles* = outliers beyond 1.5 times the inter-quartile range; *notches* = indication of the 95 % confidence interval of the median after Chambers et al. (1983)

10.5 Spatio-Temporal Patterns of Phenology

10.5.1 Multi-annual Average Patterns of Phenology

The spatio-temporal patterns of phenological characteristics in the study region are illustrated in Figs. 10.6 and 10.7. Displayed are the 13 year average (left column) and variability (right column) of the start of season, the rate of increase in EVI, the maximum EVI and the EVI integral of the growing season (cf. Table 10.1). The statistics of the same phenological metrics, grouped by vegetated land cover/use classes, are displayed in Fig. 10.8. Here, the semi-natural land cover types are ordered from left (forests) to right (grasslands) according to their vegetation structure with decreasing woody and increasing herbaceous components.

Figures 10.6 and 10.7 show that the agricultural areas in the north and northeast of the study region which had been widely cleared for agriculture in 1986 already (cf. Fig. 10.3a), show distinct phenological characteristics when compared to the more recently cleared agricultural land in the center and west of the study region (cf. orange color in Fig. 10.3d). In the areas of longer agricultural land use in the north and northeast, greening starts later (Fig. 10.6, top left), the rate of seasonal increase in green vegetation is smaller (Fig. 10.6, bottom left), and both the maximum and integral of EVI indicate a lower productivity (Fig. 10.7, left column). In terms of inter-annual variability of phenological characteristics however, the behavior of all cultivated land in the study region is similar (Figs. 10.6 and 10.7, right columns).

With regard to the semi-natural land cover types, which are found mainly inside the protected areas, the spatial patterns (Figs. 10.6 and 10.7) and the statistical distributions (Fig. 10.8) reveal a general relationship between phenological characteristics and vegetation structure. The start of season tends to be later with

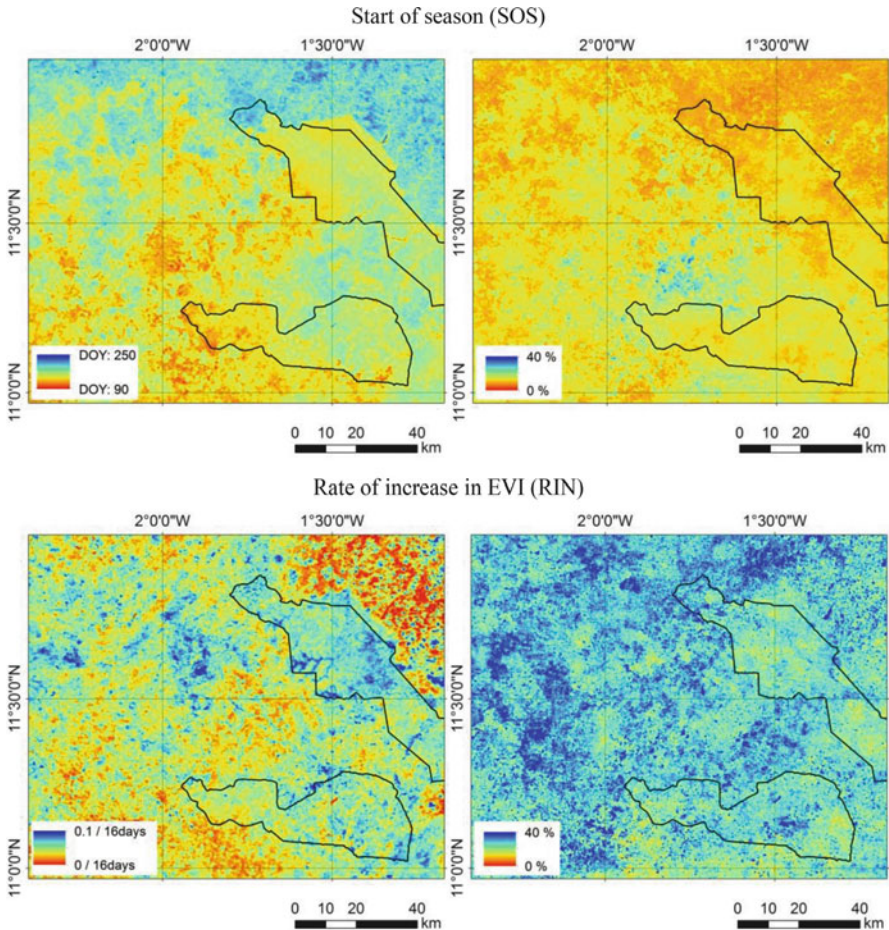


Fig. 10.6 Multi-annual (2001–2013) mean (*left column*) and coefficient of variation (*right column*) of start of season (*top row*) and rate of increase in EVI (*bottom row*). For the purpose of orientation, borders of protected areas are included in the maps (cf. Fig. 10.1)

decreasing woody and increasing herbaceous components with differences around 40 days between forests and grasslands. Likewise, the maximum and the integral of EVI are clearly related to vegetation structure, showing decreasing values with decreasing woody components. However, when considering the rate of increase in greenness, a dependency on vegetation structure is not as obvious. The statistical distributions (Fig. 10.8) show a decelerating green-up with decreasing woody cover from forests over closed woodlands to open woodlands/shrublands. For grasslands however the rate of increase in EVI is elevated again. Regarding the spatial patterns, the rate of increase is relatively high in the K.T. National Park as well as in the remaining forest and woodland fragments in the center of the study region

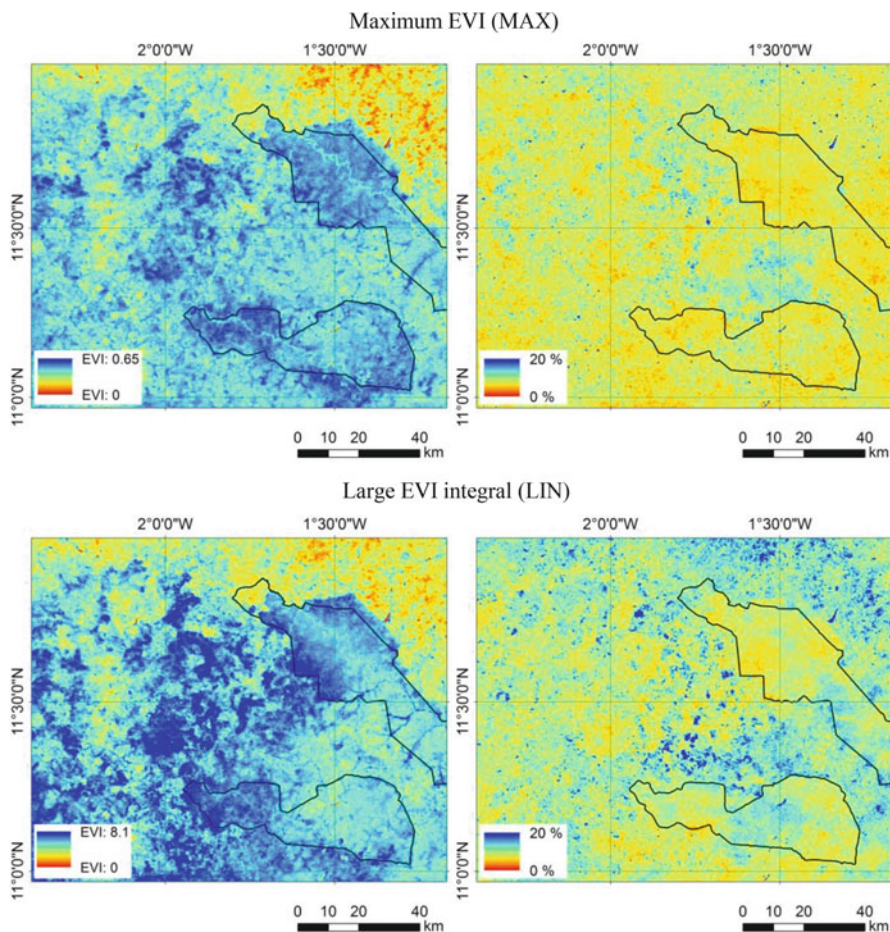


Fig. 10.7 Multi-annual (2001–2013) mean (*left column*) and coefficient of variation (*right column*) of maximum EVI value (*top row*) and large EVI integral (*bottom row*). For the purpose of orientation, borders of protected areas are included in the maps (cf. Fig. 10.1)

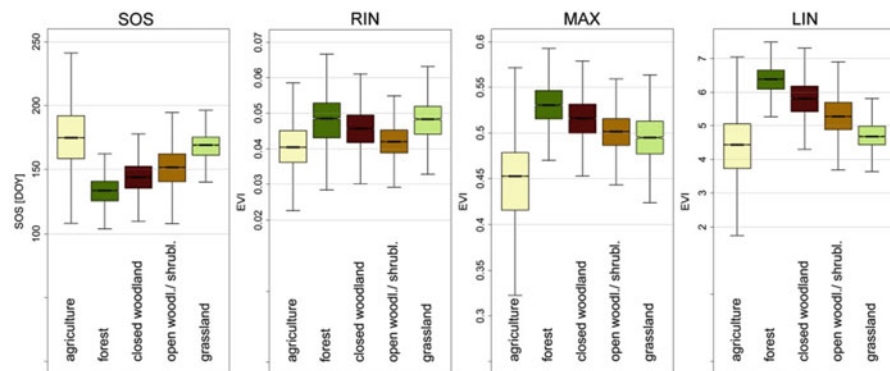


Fig. 10.8 Statistics of multi-annual (2001–2013) mean phenological metrics, grouped by vegetated land cover/use types. Only pure MODIS pixels that contain at least 80 % of one single land cover type are considered. Boxplot elements: *box* = values of 2nd and 3rd quartile; *horizontal line* = median; *whiskers* = lowest/highest values, except for outliers; *notches* = indication of the 95 % confidence interval of the median after Chambers et al. (1983)

(Fig. 10.6, bottom left). Noticeable is also the particularly strong seasonal EVI increase in the river valleys, e.g. in those of K.T. National Park, but for the closed woodlands in the Sissili forest and the riparian vegetation in the Nazinga Game Ranch, the rate of increase is comparatively low.

10.5.2 Effects of Fire Frequency on Phenological Characteristics

For assessing potential long-term effects of fire on land surface phenology, the 13-year averages of phenological metrics were further differentiated by land cover type and fire frequency (Fig. 10.9). Here, the land cover types were grouped into areas of low, medium and high fire frequency with fires occurring less than three times, between three and five times, and more than five times in 2000–2012. Agricultural areas were excluded from this analysis, as crop plants and their phenology are not directly affected by fire because sowing takes place after burning.

The differentiation into fire frequency classes reveals that frequent fires tend to delay the multiannual average start of season. This effect is stronger in grasslands and open woodlands/shrublands than in the tree dominated closed woodlands, and it

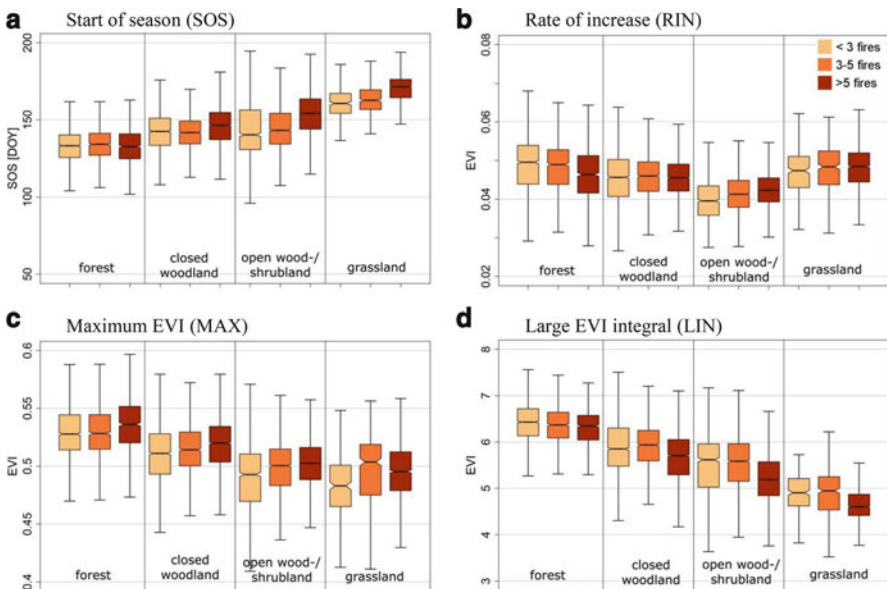


Fig. 10.9 Multi-annual (2001–2013) mean of phenological metrics differentiated by land cover type and fire frequency. (a) SOS, (b) RIN, (c) MAX, (d) LIN. Only pure MODIS pixels that contain at least 80 % of one single land cover type are considered. Boxplot elements are described in Fig. 10.8

is not observable in forests (Fig. 10.9a). The increase in greenness (Fig. 10.9b) decelerates in forests at high fire frequencies, while no significant effect could be observed in closed woodlands and grasslands. For open woodlands/shrublands in contrast, higher fire frequencies are associated with an accelerating increase in greenness. The seasonal maxima of EVI (Fig. 10.9c) generally rise with increasing fire frequencies, except for grasslands where intermediate fire frequencies lead to highest seasonal EVI maxima. There is no observable, significant effect of fire frequency on the EVI integral in forests while in the other semi-natural land cover classes, the integrated EVI is significantly smaller at high fire frequencies when compared to medium and low fire frequencies (Fig. 10.9d).

10.5.3 Effects of Fire Events on Phenological Characteristics

The direct, short-term effects of fire events on the phenology of the subsequent growing season are presented in Fig. 10.10. In this plot, land cover types and fire frequency classes are further differentiated into seasons with and without previous fire. As we are considering annual phenologies in this analysis, it needs to be assumed that fire effects on phenology are overlaid by rainfall effects in years of extraordinarily high and low precipitation. Therefore, only years with close to average rainfall amounts were considered here. Annual rainfall sums were assessed based on precipitation datasets of the Global Precipitation Climatology Centre (GPCC, Schneider et al. 2011a, b). Only those years that had experienced an annual rainfall within a range of one standard deviation around the multi-annual (2001–2013) mean were selected. The forest class could not be accounted for in this analysis due to its small areal coverage that resulted in too few data points within the once more subdivided and reduced groups.

In grasslands and open woodlands/shrublands the start of season (Fig. 10.10, first column) is observed slightly earlier (up to 8 days) when fire has occurred previously while for the more tree dominated closed woodlands this effect is not significant. For all considered classes, the average increase in greenness (Fig. 10.10, second column) is accelerated in growing seasons with previous fires. This effect is strongest in grasslands and closed woodlands with medium to low fire frequency. Similar patterns are found for the average maximum EVI (Fig. 10.10, third column) which is slightly higher in the growing seasons after burnings except for open woodlands/shrublands with high fire frequencies. The integral of growing season EVI (Fig. 10.10, fourth column) is weakly affected by previous fire occurrences with a tendency towards increased values after burnings in grasslands and open woodlands/shrublands. In closed woodlands, a significant effect could only be found at high fire frequencies where fires tend to lower the next year EVI integral.

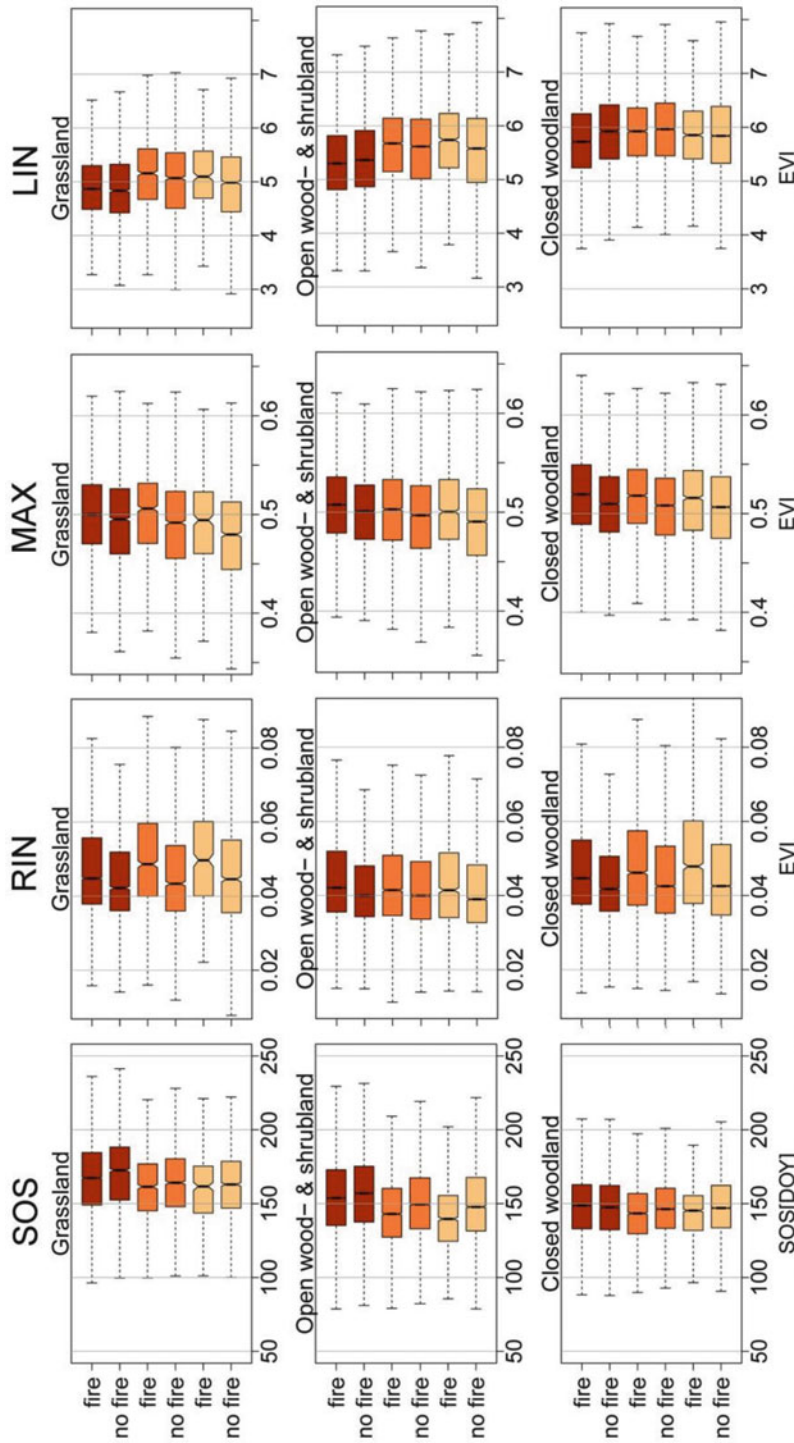


Fig. 10.10 Annual phenological metrics differentiated by land cover, by long-term fire frequency, and by occurrence of fire in the fire season previous to the respective growing season. Only pure MODIS pixels that contain at least 80 % of one single land cover type, and only close to average rainfall years (2004–2006, 2008–2009, 2011–2013) were considered. For color coding see Fig. 10.9. Boxplot elements are described in Fig. 10.8

10.6 Discussion and Conclusions

This study analyzed the influence of fire, land use, and vegetation structure on phenological patterns in a savanna region in southern Burkina Faso. For a 13-year period (2000–2012), the spatio-temporal patterns of land surface phenology were delineated from phenological metrics based on time series of MODIS EVI data. Multi-temporal Landsat data (1986–2013) was used for assessing current and historic land use patterns and vegetation structure. Time series of the MODIS burned area product were analyzed for identifying annual fire patterns and for assessing multi-annual spatio-temporal patterns of fire frequency.

The fire frequency in the study region was found to increase with the proportion of herbaceous components in savanna land cover types (Fig. 10.5). This finding is in agreement with other studies in West Africa and can be related to fine fuels from dry grasses that contribute to elevated fire frequencies, whereas leaf litter in tree dominated land cover types shows lower ignitability (e.g. Devineau et al. 2010; Hennenberg et al. 2006). Burned areas were hardly observed for agricultural fields even though these areas are known to be, at least to some extent, subject to fires as burning is used e.g. for clearing fields (Wardell et al. 2004).

A reason for this probable underestimation could be the fact that agricultural burnings usually occur on single fields that are too small for being detected as burnt areas at a spatial resolution of 500 m (Devineau et al. 2010). Moreover, a general dependency of land surface phenological metrics on vegetation structure was found in the presented study (Fig. 10.8). The shift towards an earlier start of season with increasing tree proportions can be explained by the fact that deciduous tree species in West Africa frequently start sprouting before the first rains (Bie et al. 1998) while grass development is restricted to the rainy season. The larger growing season integral of EVI in tree- and shrub-dominated land cover types can serve as an indicator for higher seasonal vegetation productivity in these areas, in dependence on what has been found in other studies for NDVI (cf. Budde et al. 2004; Lo Seen Chong et al. 1993). Similarly, the integrated EVI indicates that productivity is higher on agricultural areas that have been cleared since 2001 (center of the study area) than for areas that had been already cultivated in the mid-1980s (northeast of the study area).

Moreover, the presented analyses reveal certain effects of fire on phenological patterns. These can be subdivided into effects of long-term fire frequency, and into direct, short-term effects of fire events on the subsequent growing season. Here, several interesting aspects arise, e.g. in the context of the delayed start of season in grasslands and open woodlands/shrublands with increasing fire frequencies (Fig. 10.9a). At the first view, there seems to be a contradiction when comparing this long-term effect to the observed direct, short-term effect which implies that the start of season tends to be earlier in years of previous fire than in years without previous fire (Fig. 10.10). However, we assume that these findings can be explained by two separate effects. There might be a general shift in species composition with differing green-up phenologies due to long-term fire frequency on the one hand. For

example Sawadogo et al. (2005) found in the Sudanian Savanna that frequent fires result in a long-term increase of annual and a long-term decrease of perennial grasses. On the other hand, as a direct, short-term effect, an enhanced sprouting of grasses can be assumed when the dry grass biomass of the previous growing season has been removed by fire. Reasons could be that a large detritus component on unburnt sites usually reduces light for emerging shoots, and alleviates tillering (Knapp and Seastedt 2014). However, the litter component on unburnt sites could also reduce bare soil evaporation which could, in a semi-arid environment, lead to an enhanced grass development. For a reliable understanding and interpretation of these findings, further research is needed that includes in-situ assessments in addition to remote sensing analyses and puts an additional focus on soil moisture.

Another interesting aspect is the observation that the average maximum EVI broadly increases with increasing fire frequency (Fig. 10.9c), while the integral of growing season EVI decreases (Fig. 10.9d). This shows that the peak of vegetation activity during the growing season tends to be more pronounced in areas of high fire frequency but, at the same time, the overall productivity, as indicated by the EVI integral, tends to be smaller. It can thus be concluded that investigating vegetation productivity based on single snapshots that are for example only covering the peak of the growing season, will lead to different results than when analyzing continuous time series of vegetation development.

This study allowed the detection of interrelationships between land surface phenology, land use, vegetation structure and fire in a typical West African Sudanian Savanna, based on remotely sensed time series of vegetation indices and burned area information as well as on multi-date land use/cover data. The spatial and temporal resolutions of land surface phenology and burned area time series were sufficient for delineating a number of relationships; however some of the observed tendencies were not statistically significant. Remotely sensed time series of higher spatial and temporal resolution might improve the validity of the analyses here. The use of near to daily time series of vegetation indices, for example from MODIS or from the upcoming Sentinel-3, might be a suitable option for increasing the temporal resolution. A simultaneously increased spatial resolution is a challenge that might be solved by advanced fusion techniques of daily medium resolution time series and high resolution acquisitions that cover only few dates per month (e.g. from Landsat or Sentinel-2). Furthermore, the additional consideration of moisture and its potential forcing on land surface phenology is likely to contribute to a better explanation of the interrelationships between fire occurrence, land use/cover and land surface phenology. Another variable that could be included in future studies is fire intensity as its influence on savanna vegetation is assumed to even exceed the influence of frequency (Ryan 2009). Furthermore, the combined analysis of land surface phenology based on remote sensing time series with plant phenology based on in-situ assessments is of great potential for further improving current phenological studies. Here, a major challenge will be to link remotely sensed phenological metrics with biological events observed in the field (Knauer et al. 2014).

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