The distribution of grasslands, savannas and forests in Africa: a new look at the relationships between vegetation, fire and climate at continental scale

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Introduction

- Savannas occupy about a fifth of the global land surface and store approximately 15% of the terrestrial carbon. They also encompass about 85% of the global land area burnt annually. Along an increasing rainfall gradient, they are the intermediate biome between grassland and forest.
- Current and future increasing temperatures and CO_2 concentrations, modified precipitation regimes, as well as increasing land-use intensity, are expected to induce important shifts in savanna structure and in the distribution of grasslands, savannas and forests.
- Owing to the large extent and productivity of savanna biomes, these changes could have larger impacts on the global biogeochemical cycle and precipitation than for any other biome, thus influencing the vegetation-climate system.
- The dynamics of these biomes has been long studied. However, despite their relevance, grasses and tree types have been studied mostly in small scale ecological studies, while continental analyses focused on total tree cover only.

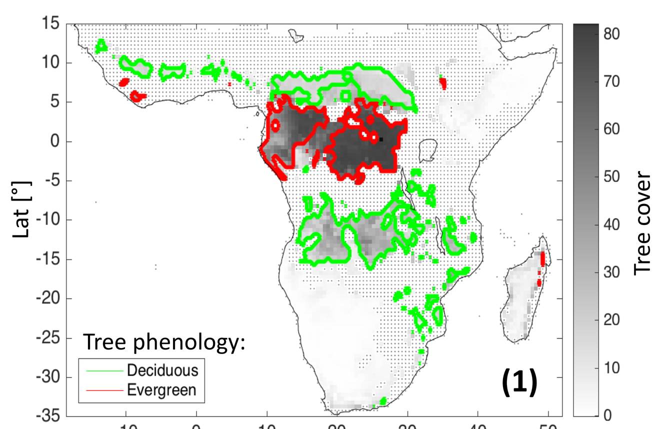
Objectives

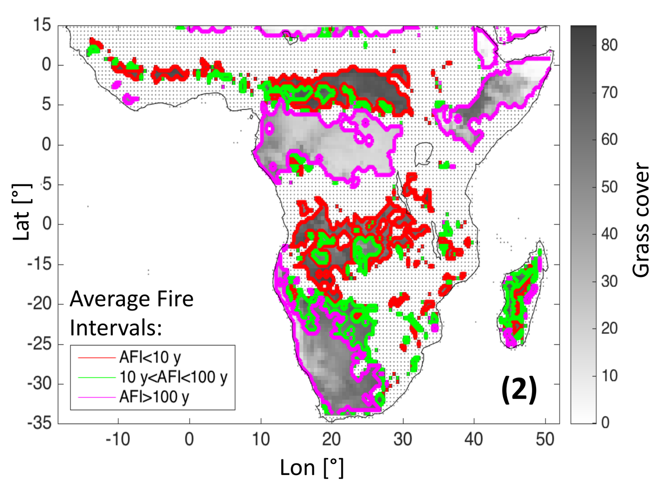
We analyse a recent MODIS product including explicitly the non-tree vegetation cover, allowing us to illustrate for the first time at continental scale the importance of grass cover and of tree-fire responses in determining the emergence of the different biomes in sub-Saharan Africa.

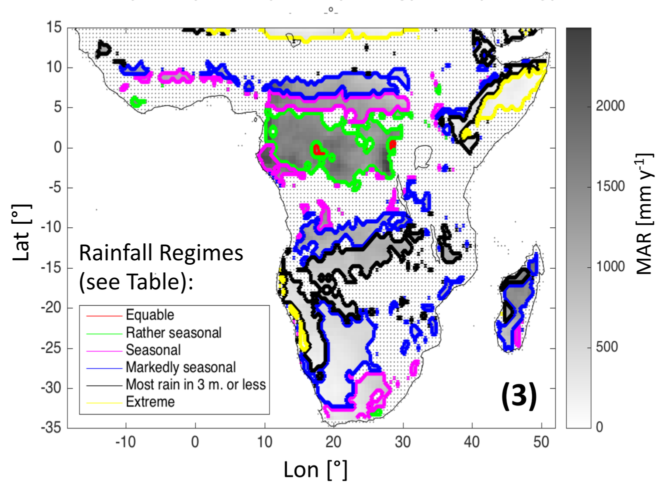
Methods

Observational data

We analyse the relationships of **African** (between **35° S and 15 ° N**) observed **% Tree cover** and **% Grass Cover** with **Mean Annual Rainfall (MAR), Rainfall Seasonality Index (SI) and Average Fire Intervals (AFI)** (from MODIS and TRMM satellite observations) averaged in time **from 2000 to 2010** and in space to the **resolution of 0.5°.** We include also **tree phenology information**, based on the ESA Global Land Cover map, also used to exclude areas with large anthropogenic land use.







African % Tree cover **Fig.1**, % Grass Cover **Fig.2** and MAR **Fig. 3**; dotted areas, excluded from the observation data analysis, are 0.5°-pixels with more than 33% (50%) of the area influenced by humans (covered by shrublands) identified using ESA CCI-LC 2010, with 300 m resolution. ESA CCI-LC is also used to identify savanna trees (identified with the **deciduous** class) and forest trees (identified with the **evergreen** class) **(Fig. 1)**

Table: Correspondence between seasonality index and rainfall regimes

Rainfall Regimes	SI
Very equable	≤ 0.19
Equable with a definite wetter season	0.20-0.39
Rather seasonal with a short drier season	0.4-0.59
Seasonal	0.60-0.79
Markedly seasonal with a long drier season	0.80-0.99
Most rain in 3 months or less	1.00-1.19
Extreme, almost all rain in 1 to 2 months	$\geq$1.20

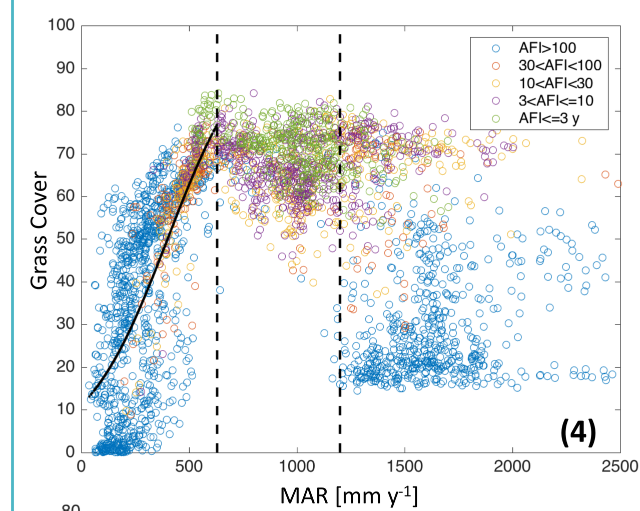
[1] Fire, tree and grass data, originally in MODIS sinusoidal projection, were re-projected and averaged on a 0.5° regular lon-lat grid.

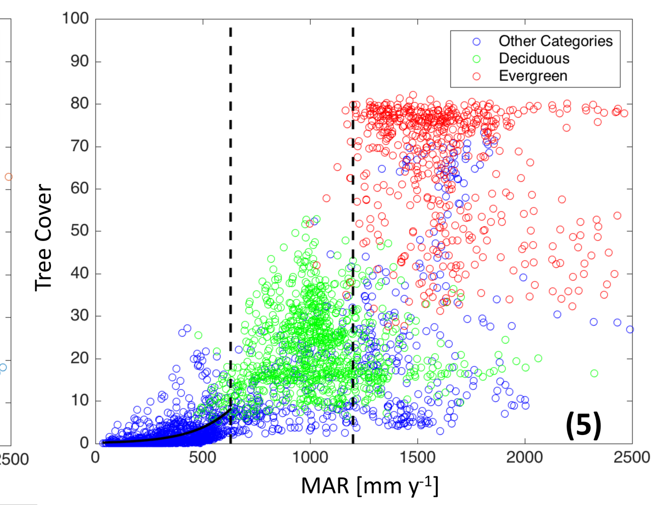
- **MAR (mm y^{-1}) and SI**: obtained from Tropical Rainfall Measuring Mission (TRMM 3B42), with 0.25° resolution. SI [1] describes the rainfall regimes as the contrast of monthly rainfall amount during the year.
- **% Tree and Grass cover [1]**: obtained from annual Terra MODIS Vegetation Continuous Fields product (MOD44B, V051), with 250 m resolution
- **AFI (y) [1]**: derived from the 0.5° area - annual burnt area obtained from the monthly MODIS MCD45A1 burnt area product, with 500 m resolution.

Analysis

We analyse the relationships between biotic and abiotic variables in **distinct MAR intervals** (where the relative tree-grass dominance shows marked changes in structure and behavior) using **Generalized Linear Models (GLMs)**

Results and Discussion





Grass Cover (**Fig. 4**) and Tree cover (**Fig. 5**) vs. MAR. Colors indicate: AFI in **Fig. 4**, tree phenology in **Fig. 5** Continuous lines represent best GLM fits in low MAR range

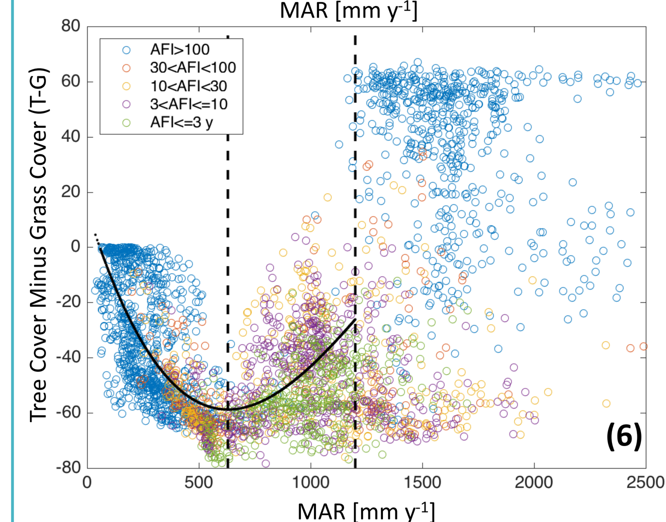


Fig. 6: relative tree-grass dominance (T-G) as a function of MAR Colors indicate AFI; Continuous line represents best GLM fits with MAR

The changes in slope and spread of the relative tree-grass dominance identify three MAR ranges (dashed lines in all figures):

- I Low MAR: 0 – 630 mm y^{-1} (upper limit: minimum of best fit)
- II Intermediate MAR: 630 – 1200 mm y^{-1} (upper limit: max(T-G)=0)
- III High MAR: 1200 – 2500 mm y^{-1}

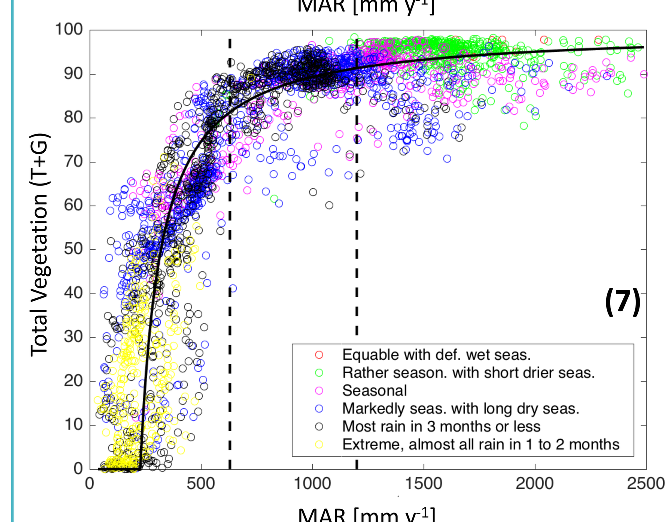
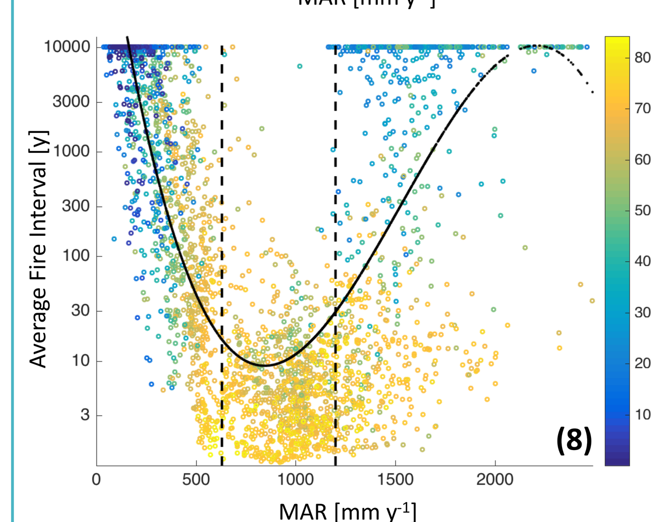
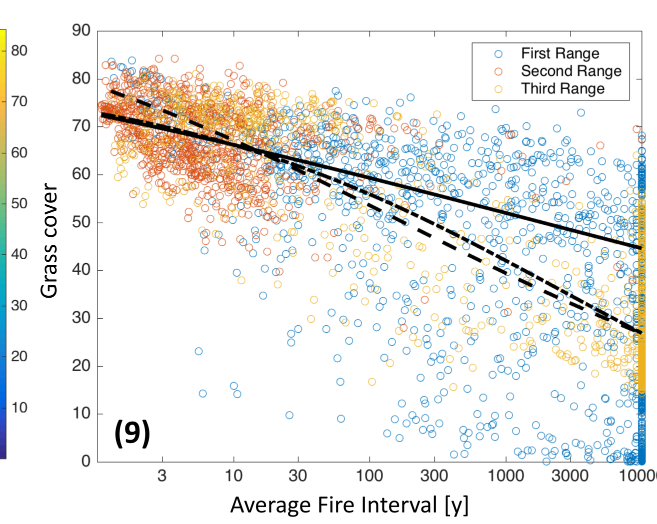


Fig. 7: Total vegetation as a function of MAR Colors indicate rainfall regimes, based on SI [1]; Black line represents a Michaelis-Menten curve

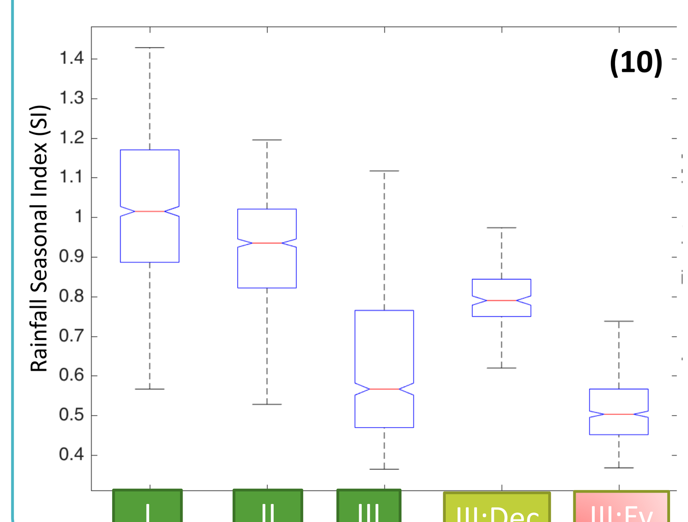
Total vegetation depends on MAR: good agreement with a curve representing the stable solution of an implicit-space logistic equation for vegetation cover [2]

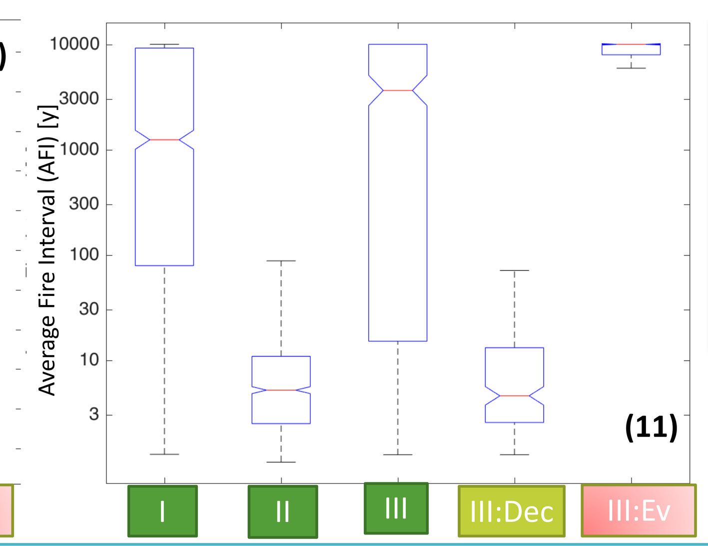




AFI vs. MAR (**Fig. 8**) and Grass cover vs. AFI (**Fig. 9**) Colors indicate grass cover in **Fig. 8**, MAR ranges in **Fig. 9**; **Fig. 8**: Continuous line=best fit **Fig. 9**: Dot-dashed, continuous and dashed lines are the best fits over the whole dataset and over the MAR ranges II and III, respectively.

Fig. 8: AFI varies approximately in a specular way to grass **(Fig. 4)**
Fig. 9: Over the whole dataset grass cover decreases ~linearly with AFI (in logarithmic scale)

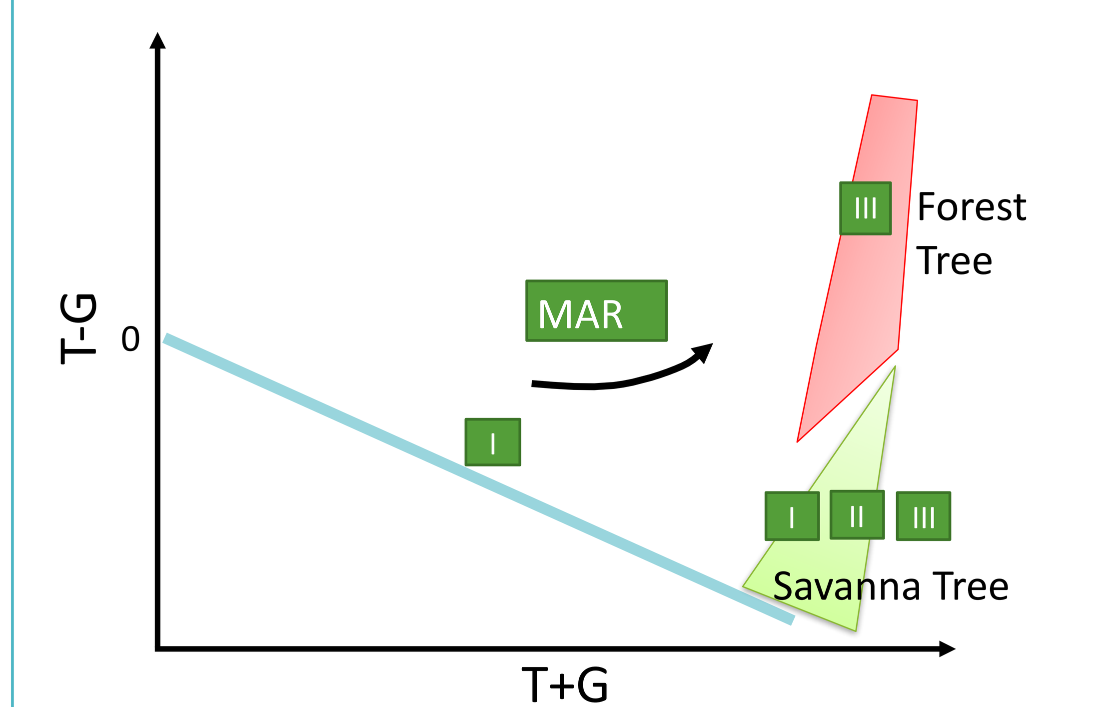




Box plots of rainfall seasonality index (**Fig.10**) and average fire intervals (**Fig. 11**) in the three MAR ranges, and for deciduous and evergreen pixels in the third MAR range.

Precipitation →

	I: Low MAR	II: Intermediate MAR	III: High MAR
Vegetation-climate-fire patterns ad GLM results:	- Grasses are dominant, tree cover is low, fires are rare and seasonality is marked-extreme (**Fig.s 4-6,10,11, Table**). - Tree and grass depend on MAR.	- Savannas and grasslands are the predominant biomes (**Fig.s 4-6**); fires are frequent, seasonality is marked (**Fig.s 10,11, Table**). - Grass increases with fire frequency. - Trees decreases with fire frequency and increases with MAR.	- Bimodality of forest and savannas in vegetation cover and tree types (**Fig.s 4-6**), associated to bimodality in seasonality and fire frequency (**Fig.s 10-11, Table**). - Grasses (trees) increase (decrease) with fire frequency (related to seasonality).
Main Ecological Mechanisms:	Tree and grass growth is water-limited; tree and grass compete for water and grass has strong competitive effects on tree seedlings [3,4].	Positive vegetation-fire feedback: grass-fuelled fires suppress grasses and savanna saplings, and low tree cover promotes fire spread since grass can regrow rapidly after fire [5]. Savanna trees are fire resistant but cannot outcompete grasses because are shade intolerant. Forest tree establishment is water-limited.	Water is enough for the development of the forest. The positive vegetation-fire feedback permit savanna-forest occurence [5].



Schematic relationship between Tree-Grass dominance (T-G) and total vegetation (T+G) in the three different MAR ranges

Conclusions

From this analysis we distinctively observe that tropical vegetation dynamics changes along a rainfall gradient more markedly than previously observed, in particular identifying three zones:

(i) A low rainfall range, where grasses are dominant and water-limited, and fires are rare;

(ii) An intermediate rainfall range, where savanna with grass dominance is the predominant biome, maintained by frequent fires and rainfall seasonality;

(iii) A high rainfall range, where both savannas and forests can occur, as determined by the grass-fire feedback, driven by seasonality and the occurrence of different types of trees.

The analysis of these important ecological processes can also be applied to the evaluation of Dynamic Global Vegetation Models, that currently have particular difficulties in simulating tropical vegetation [6].

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