Vegetation-fire-climate interactions in sub-Saharan Africa: evaluating and comparing dynamic global vegetation models

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Introduction

- Tropical savannas cover about one third of the African land surface. At the wetter end of their distribution range, savannas transition into tropical forests.
- Their dynamics and transitions are determined by complex interactions between vegetation and environmental factors (e.g. climate and disturbance).
- Fire has an important ecological role influencing the vegetation distribution, and possibly in maintaining savannas and forests as alternative stable states.
- Dynamic Global Vegetation Models (DGVMs) are useful tools for simulating the distribution of global vegetation, but display high uncertainty in predicting tropical vegetation.
- This difficulty is often a consequence of the representation of the main ecological processes and feedbacks between biotic and abiotic factors [1].

Objectives

We compare the observed and modelled relationships of vegetation cover with climate and fire and use the current ecological understanding of the mechanisms driving the forest-savanna transition in Africa to:

1. evaluate the outcomes of the LPJ-GUESS and JSBACH DGVM
2. assess which key ecological processes need to be included or improved within these models.

Material and Methods

Observational data

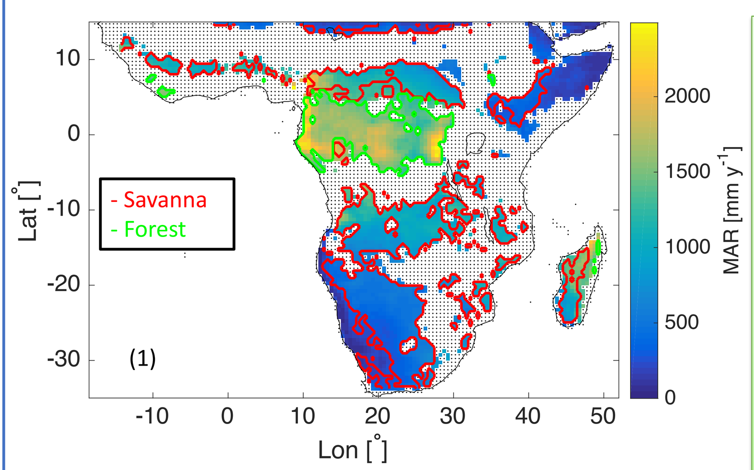


Fig. 1: African land MAR (0.5° res.); dotted areas, excluded from the observation data analysis (areas human influenced/covered by shrubland from ESA CCI-LC 2010). Coloured lines: savanna areas identified with deciduous trees and grasslands classes; forest areas identified with evergreen and flooded trees classes from ESA CCI-LC 2010.

- **Mean annual rainfall (MAR) (mm y^{-1}) and seasonality index (SI)**: from Tropical Rainfall Measuring Mission (TRMM 3B42). SI [2] describes the rainfall regimes as the contrast of monthly rainfall amount during the year.
- **% Tree and Grass cover**: from annual Terra MODIS Vegetation Continuous Fields product (MOD44B, V051)
- **Average fire intervals (AFI) (y)**: from monthly MODIS MCD45A1 burnt area product. AFI=1/BA, where BA is the annual burnt area. We use $\log_{10}$(AFI).

Observations were averaged **from 2000 to 2010** and interpolated to the **resolution of LPJ-GUESS (0.5°) and of JSBACH (1.875°)**

DGVMs: main characteristics, experimental setup and outputs

	LPJ-GUESS [3]	JSBACH [4,5]
Type	Individual-processes-based	Processes-based
Earth System model (ESM)	EC-Earth, here used offline	Max Planck Institute (MPI) ESM, here used offline
Spatial Resolution	0.5°	1.875°
Fire algorithm	Simple fire module	Complex fire module (SPITFIRE)
Climate input data	CRU data (1901-2013)	MPI-ESM 1.1 (1850-2005)

DGVM outputs where averaged over **the last 10 years of simulation.**

We identify:

- Savanna biome with deciduous tree and C_4 grass PFTs in **LPJ-GUESS,** with deciduous tree, shrub and C_4 grass/C_4 pasture PFTs in **JSBACH**
- Forest biome with evergreen tree PFTs in both models.

Analysis:

We analyse the relationships between observed and modelled biotic and single abiotic variables using **Generalized Linear Models (GLMs)** in **three MAR intervals** (dashed vertical lines in all figures), **identified from** changes in slope and spread of the relative tree-grass dominance, as in [6]:

I Low MAR (R1): 0 – 590 mm y^{-1} (upper limit: minimum of best fit with MAR)

II Intermediate MAR (R2): 590 mm y^{-1} – 1200 mm y^{-1} (upper limit: where the 90th quantile of T-G becomes positive

III High MAR (R3): 1200 mm y^{-1} – 2500 mm y^{-1}

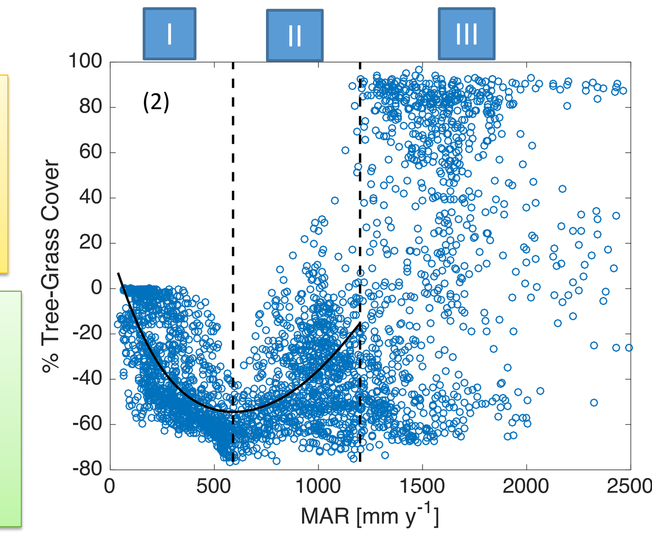
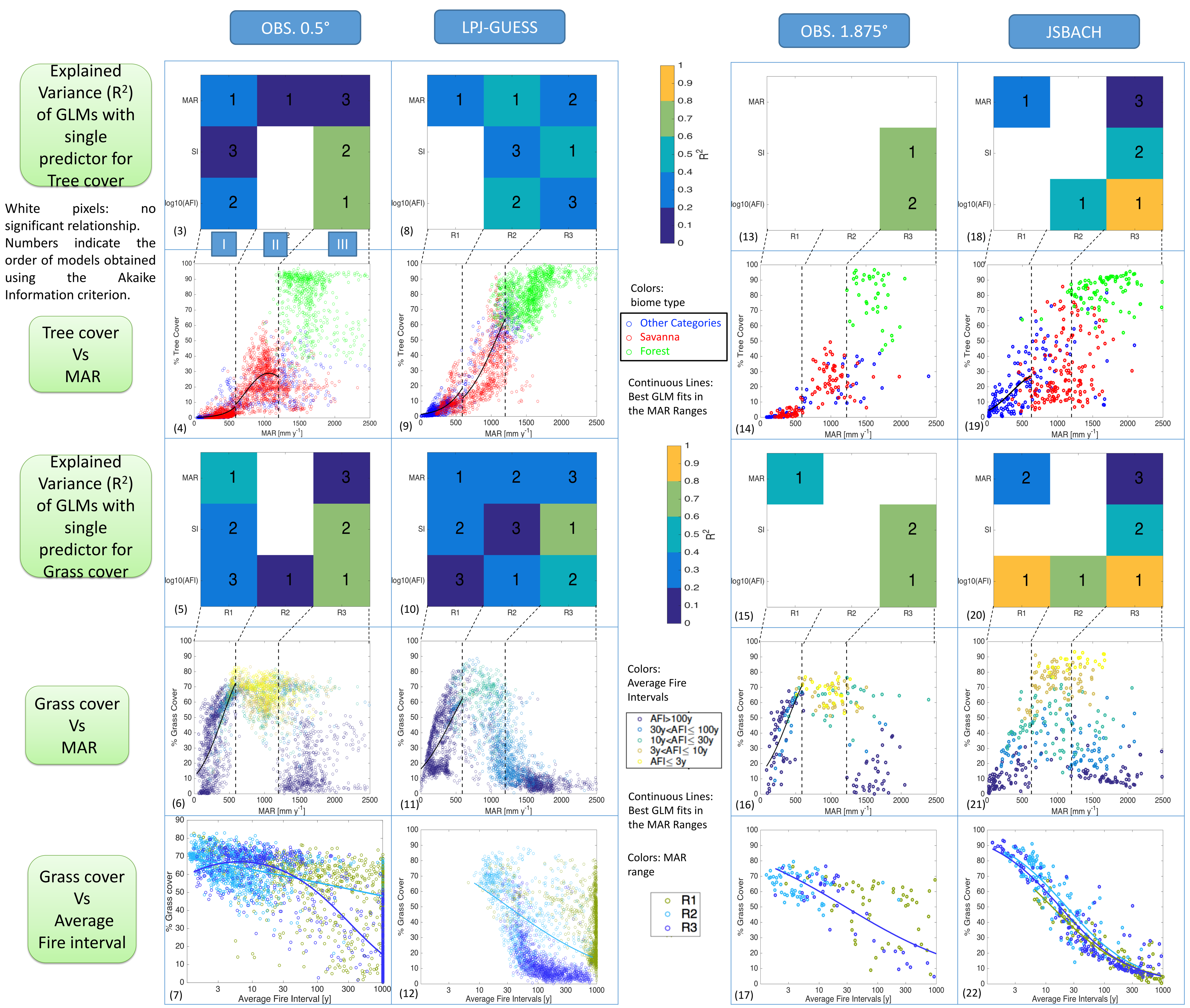


Fig. 2: Percentage of tree to grass dominance (Tree cover – Grass cover) as a function of MAR at 0.5°res. Continuous line: best GLM fit shown up to 1200 mm y^{-1}

Observed vegetation cover data were rescaled to represent crown cover as in models

Results and Discussion



Obs. Vs DGVMS	Possible ecological mechanisms	Suggestion
I: Low MAR — **Obs:** Grasses are dominant, tree cover is low (Fig. 4,6,14,16). At 0.5° res. they mainly depend on MAR (Fig. 3,5) (only grasses at 1.875° res., fig. 13,15); fires are rare (fig. 6,16). **LPJ-GUESS:** Quite good agreement with obs.. (fig. 8-12) **JSBACH:** Tree cover varies with MAR (Fig 18,19); grass cover increases with MAR but the dependence on AFI is stronger (Fig. 20,22); max tree cover is overestimated and grasses are overall underestimated (fig. 19,21).	**Obs:** Tree and grass growths are water-limited [6,7]; tree and grass compete for water [8]. Fires are limited by fuel continuity [9]. **JSBACH:** Trees don't suffer enough for water scarcity and outcompete grasses too much. Grasses are water limited as in obs. but the positive grass-fire relationship is stronger than in obs.	**JSBACH:** Revising tree establishment, tree-grass competition for water, relation of fire spread to fuel continuity
II: Intermediate MAR — **Obs:** savanna is the predominant biomes (fig. 4); fires are frequent (Fig. 6). Trees depend only on MAR and grasses only on fire, but weakly (fig. 3-7), and there are no significant relations at 1.875° res. (fig. 13,15) **LPJ-GUESS**: Fire is the main process for grasses, but its frequency is underestimated (fig. 10-12). Tree dependence on MAR is too strong (fig. 8) with steeper increase (fig. 9). Grasses still depend on MAR and have larger spread (fig. 10,11). **JSBACH:** Tree and grass covers strongly depend on fire (fig. 18,20) and have a larger spread (fig. 19,21); The grass-fire relation is steeper than in obs. (fig. 22)	**Obs:** Vegetation is no longer (or little) water limited. Fire, through the positive vegetation-fire feedback, is important in maintaining open canopies [8]. Savanna trees are fire resistant but cannot outcompete grasses because intolerant to shade. Forest tree establishment is water-limited. **LPJ-GUESS**: unlike obs., grass can dominate without frequent fires, suggesting that the mechanisms of tree-grass competition for water is stronger than the grass-fire feedback. **JSBACH**: The closed canopies (>50%) prevent fires and in presence of fire grasses have too much advantage compared to trees leading a steeper grass-fire relationship (fig. 22).	**LPJ-GUESS**: revising grass establishment linked to water, grass-fire relationship in order to obtain more open savannas. **JSBACH:** Revisiting the grass-fire relationship, fire-tolerance and shade-intolerance of savanna trees
III: High MAR — **Obs:** Bimodality of savannas and forests in vegetation cover and tree types (fig. 4,6,14,16). Tree and grass cover mainly dependon AFI and SI (fig. 3,5,13,15). **LPJ-GUESS**: Precipitation is more important than fire (fig. 8,10), whose frequency is underestimated (fig. 11,12). There is the coexistence of savannas and forests (fig. 9), but few areas of open savanna (underestimation of grass cover) (fig. 9, 11) **JSBACH:** The fire process has a greater importance than SI in explaining the variation of both tree and grass cover (fig. 18,20); Grass cover is overestimated in presence of frequent fires (fig. 21) and in many points savanna trees are overestimated (fig. 19)	**Obs:** Water is enough for the development of the forest. The different seasonality and the positive vegetation-fire feedback permit forest-open savanna occurrence and transition [10]. **LPJ-GUESS**: The absence of frequent fires leads the model to produce mainly closed canopies and not the observed open savanna; **JSBACH**: The different seasonality and the grass-fire feedback permit the forest-open savanna occurrence, but there are similar problems as described above for the intermediate MAR range	**LPJ-GUESS/JSBACH:** Revising fire process and savanna tree traits as suggested above for the intermediate MAR range

Conclusions

- This comparative process-based analysis permits to easily highlight the main processes that determine the African tropical vegetation distribution in observation and models, suggesting possible improvements in models.
- LPJ-GUESS has good performance mostly at low precipitation, while in humid and mesic areas the fire process should be probably improved for obtaining more open savanna.
- JSBACH can reproduce the grass-fire feedback that maintains open savannas at intermediate and high precipitation, although is stronger than in observation, while at low precipitation it probably needs improvements especially in tree-grass competition for water
- This type of analysis allows to compare DGVMs in tropical areas, helping to understand their ability in representing key ecological processes and to improve earth system model simulations.

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