Bistability and Feedbacks in Tropical Woodlands and Savannas:

Carbon cycle implications of changing climate and management

Principal Investigators

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New Mexico State University

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Bistability and Feedbacks in Tropical Woodlands and Savannas

Knowledge Gaps: Understanding of Current and Future Biomass Dynamics in Tropical Woodland and Savanna is severely limited by:
(1) lack of empirical data on woody biomass in drought-seasonal tropics (woodlands and savannas)
(2) incomplete process understanding of feedbacks, thresholds and potential bifurcations

Theme 1:
Biomass mapping

- What's there now? (Goal 1)
- Why? (Goal 2)
- Empirical modeling of change with future…
  - …climate?
  - …land use?
  - (Goal 3)

Theme 1: Biomass Estimates
Analysis of Current Woody Biomass and Future Scenarios

1a. African Savanna Tree Cover
- New remote sensing-based TC product for African savannas
- (earlier NASA-funding) Goal 1

1b. African Savanna Woody Biomass & Carbon
- A novel approach Goal 1

1c. Characterization of Biomass Distributions
- Relating to climate, soil, ag. intensity, fire and herbivore management Goal 2

1d. Scenarios for Future Biomass
- Empirical analysis of climate change/management impacts
- Using IPCC scenarios Goal 3

Theme 2: Pattern & Process
Woody Biomass Bistability and Sensitivity via Remote Sensing and Process Modeling

2a. Remote Sensing of Bistability
- Are bifurcations present? Where? Why?
- Tree cover, albedo, T_s, fire, canopy height
- MODIS-scale (0.25-1 km) Goal 4

2b. Nested Multi-Scale Analysis
- How do feedbacks operate across scales?
  - High-moderate resolution (1-30 m)
- Woody-herbaceous-bare soil cover Goal 4

2c. Tree-Grass Vegetation Model (TGVM)
- Calibration/Validation using remote sensing of TC and biomass
- Improved modeling of feedbacks based on bifurcation analysis
- (TGVM was developed with earlier NASA funding) Goal 5

2d. Scenarios for Future Biomass Distributions
- Model-based analysis of climate and management
- Using IPCC scenarios for climate, agricultural land use and management of fire, grazing and wood harvest Goal 5

Outcome: Improved Understanding of Current & Future Biomass in Tropical Woodlands & Savannas
GOALS:
1) Improved remote sensing of woody cover and biomass carbon stocks
2) Statistical analysis of carbon distributions with climate, soil type, fire and herbivory
3) Empirical analysis of climate change, fire and herbivore impacts on future carbon dynamics
4) Improved empirical and process understanding of savanna bistability and thresholds
5) Improved model-based prediction of climate change and management impacts

Theme 2:
Bi-stability mechanics

- When, where, why do bistable states emerge? (Goal 4)
- Dynamic savanna vegetation model with future…
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Goal 1: New tree cover and biomass for African savannas

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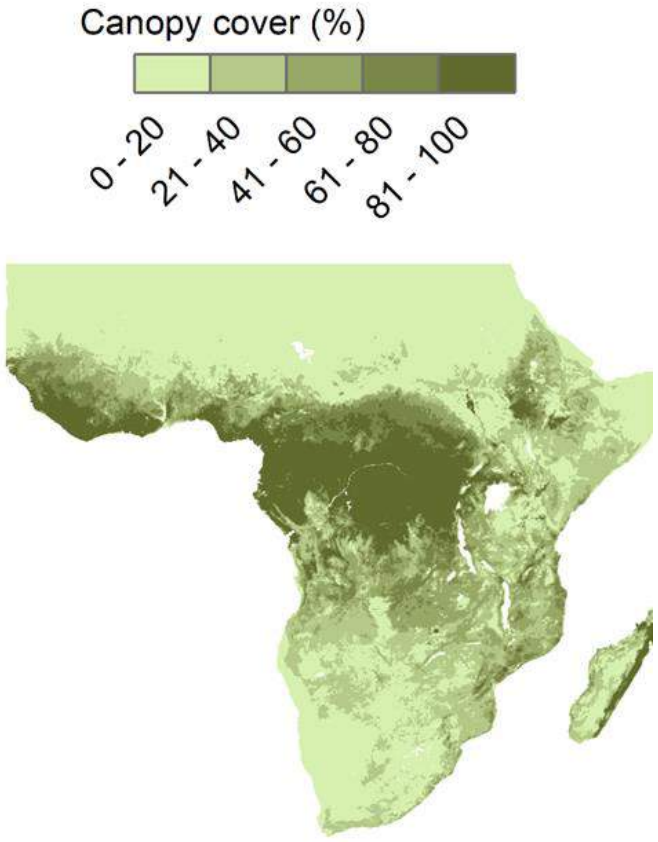

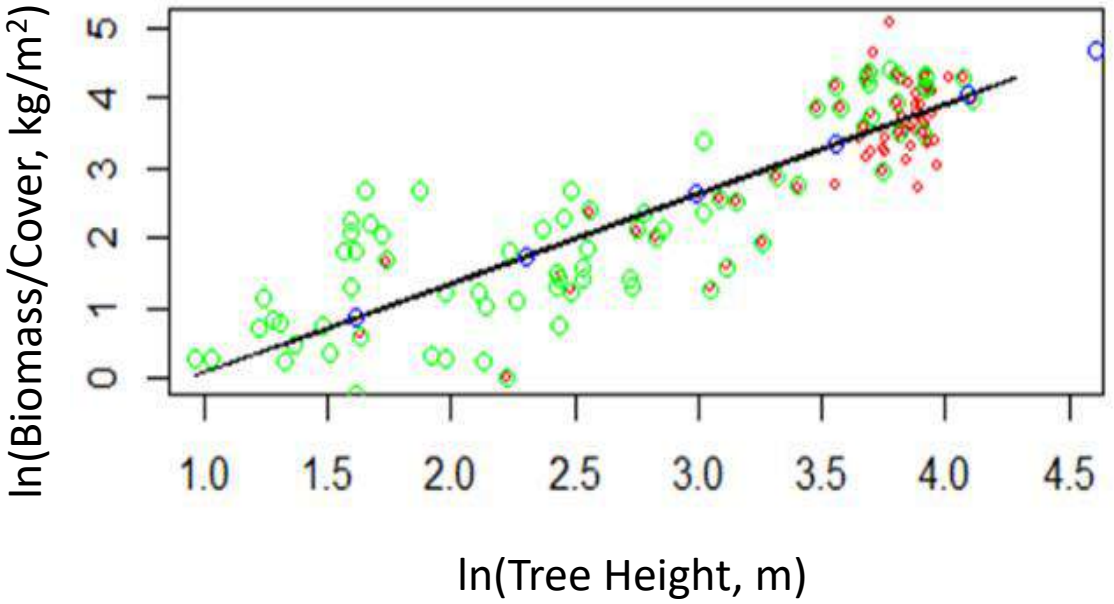

Woody canopy cover estimates (1 km) for Sub-Saharan Africa (left) derived based on ensemble GLM modeling. Biomass estimation based on allometric relationships between crown area, height and biomass (Hanan et al. in prep).

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Goal 1: New tree cover and biomass for African savannas

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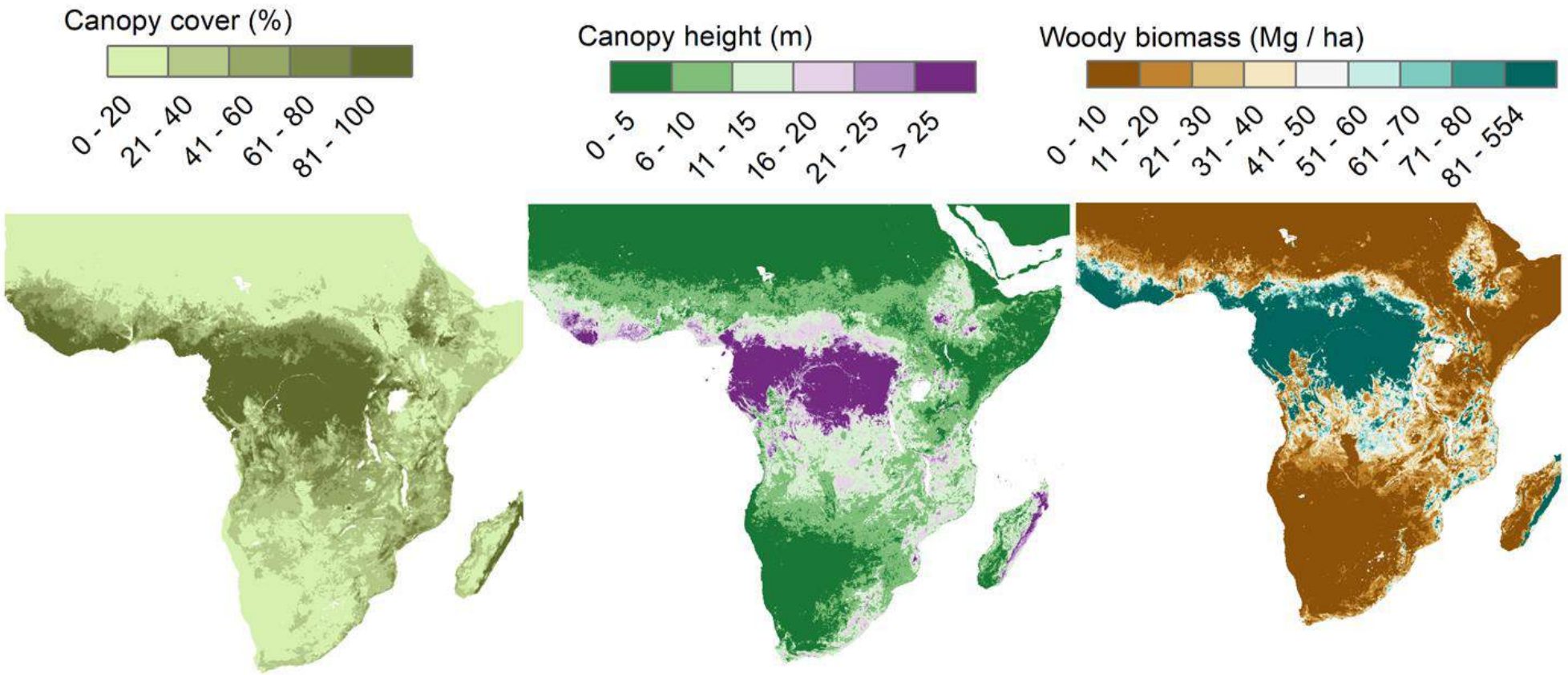

Woody canopy cover estimates (1 km) for Sub-Saharan Africa (left) derived based on ensemble GLM modeling. Center shows canopy height estimates (Simard et al. 2011), while right shows above-ground wood biomass estimates based on a canopy cover - height allometry (Hanan et al. in prep).

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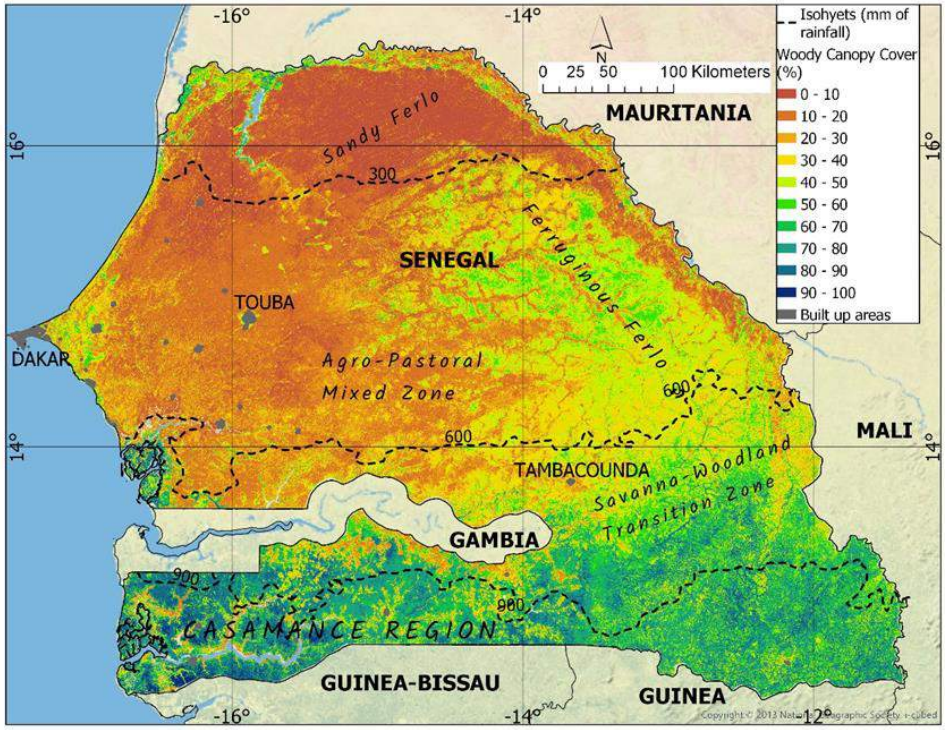
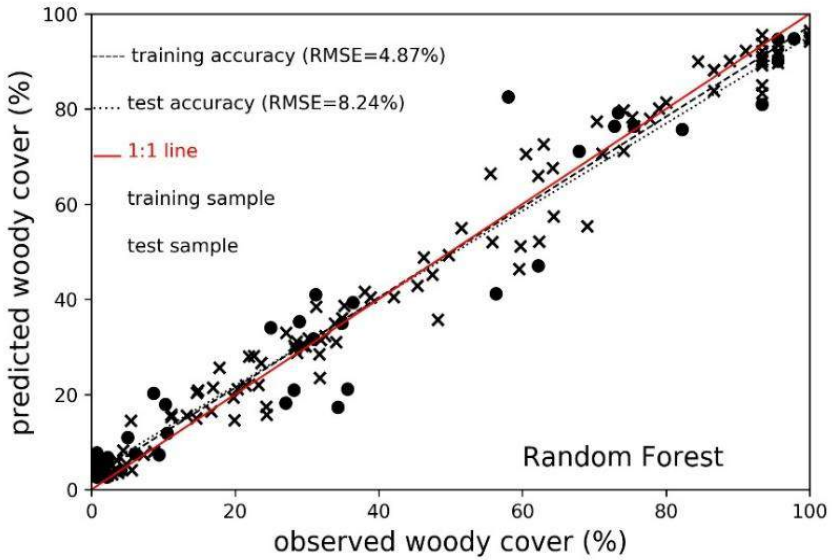
Goal 1: Moderate resolution savanna mapping for Africa





- Sentinel-I and –II derived radar and optical reflectance metrics
- Field data from ~100 plots across region
- Random forest predictions of % woody canopy cover (@ 40 m resolution)
- Implemented in Google Earth Engine (Anchang et al., in review).
- Scalable to arid and semi-arid countries of West, East and Southern Africa

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Goal 2: Characterizing biomass distributions

Theme 1:

Biomass mapping

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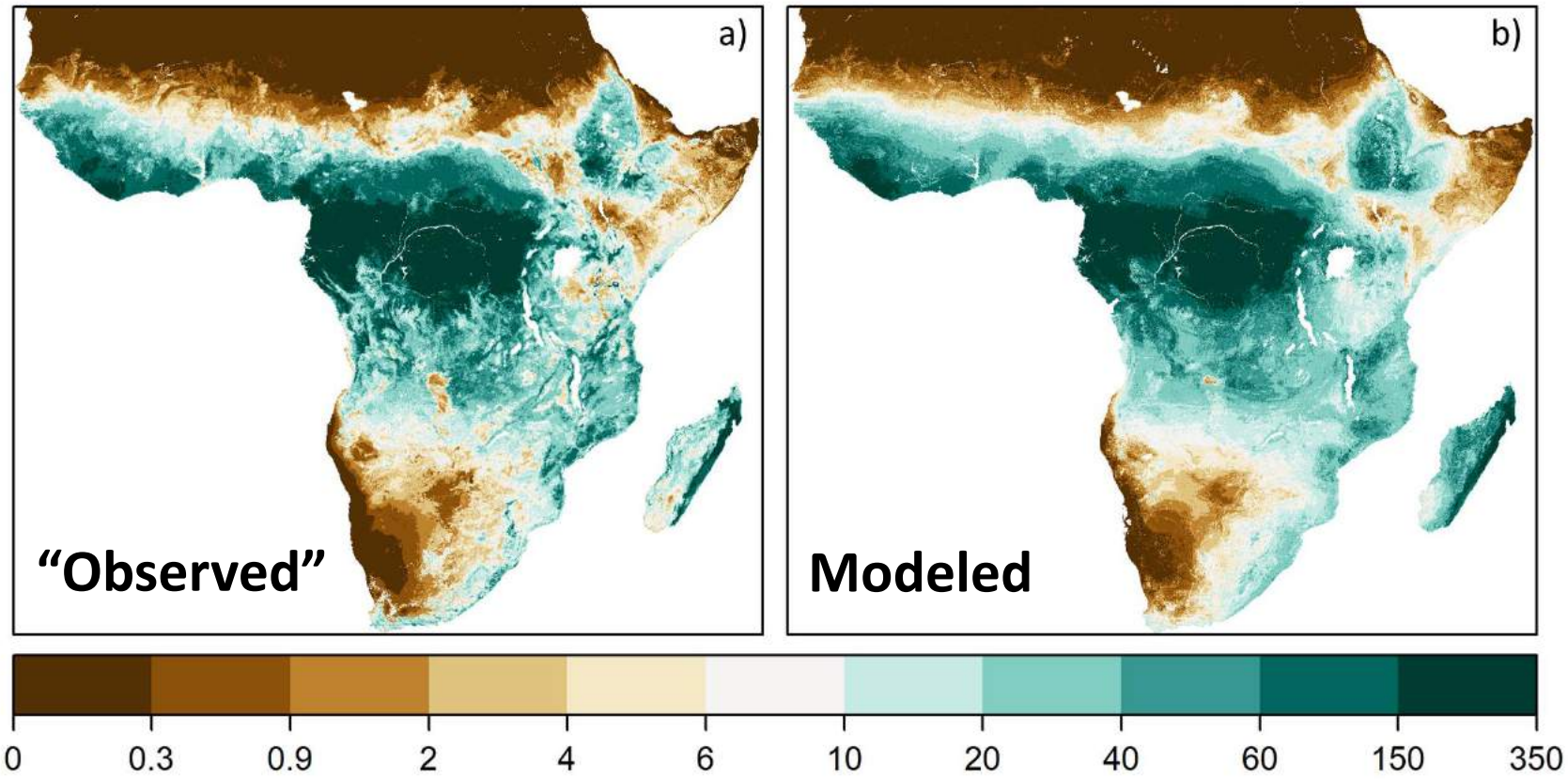

Observed (left) and modeled (right) biomass distributions based on a random forest model using current climate, environmental and anthropogenic independent data (right) (Ross et al., in prep)

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Goal 2: Characterizing biomass distributions

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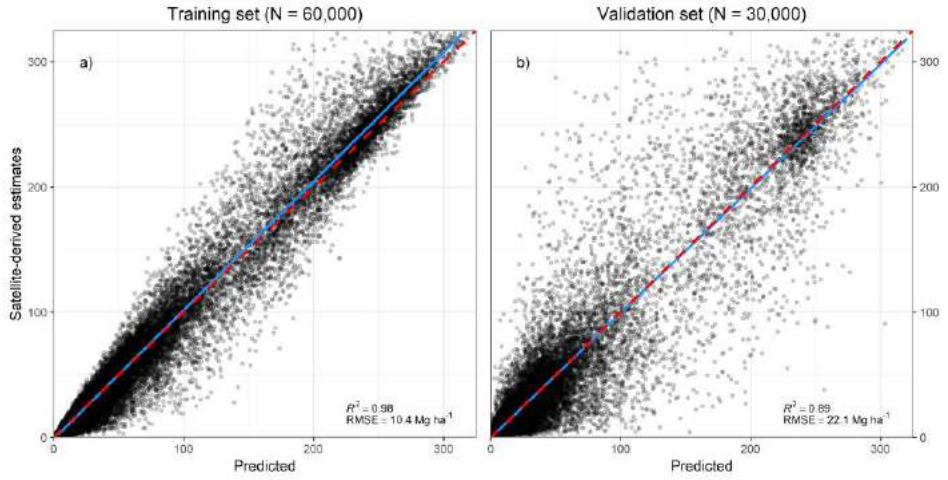
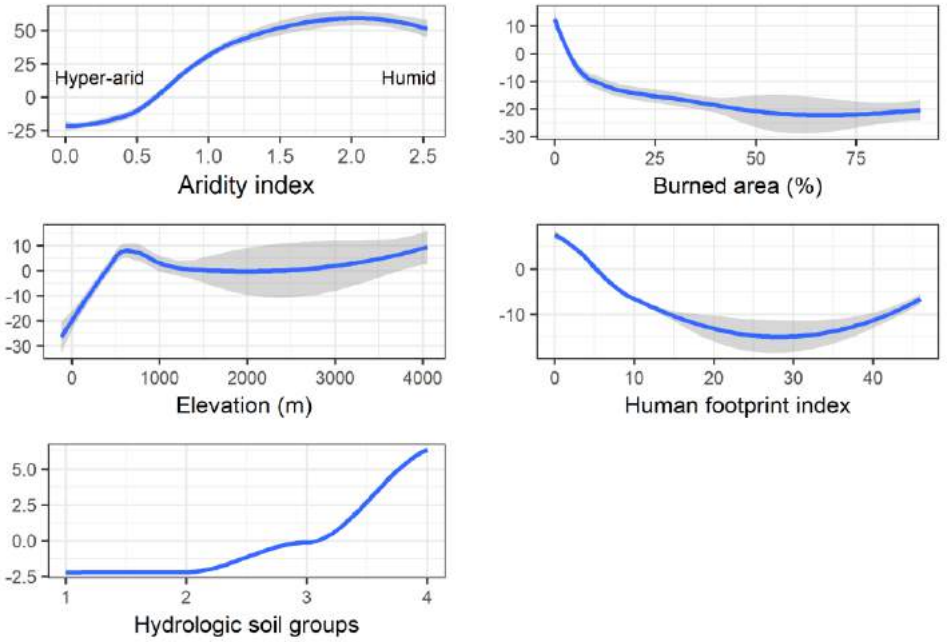


Above-ground biomass Mg/ha

Satellite-derived vs predicted biomass using a RF model (training and validation datasets).



RF marginal response functions with environmental and anthropogenic factors (Ross et a. in prep)

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Goal 3: Scenarios for future biomass

Theme 1:
Biomass mapping

- What's there now? (Goal 1)
- Why? (Goal 2)
- Empirical modeling of change with future…
  - …climate?
  - …land use?
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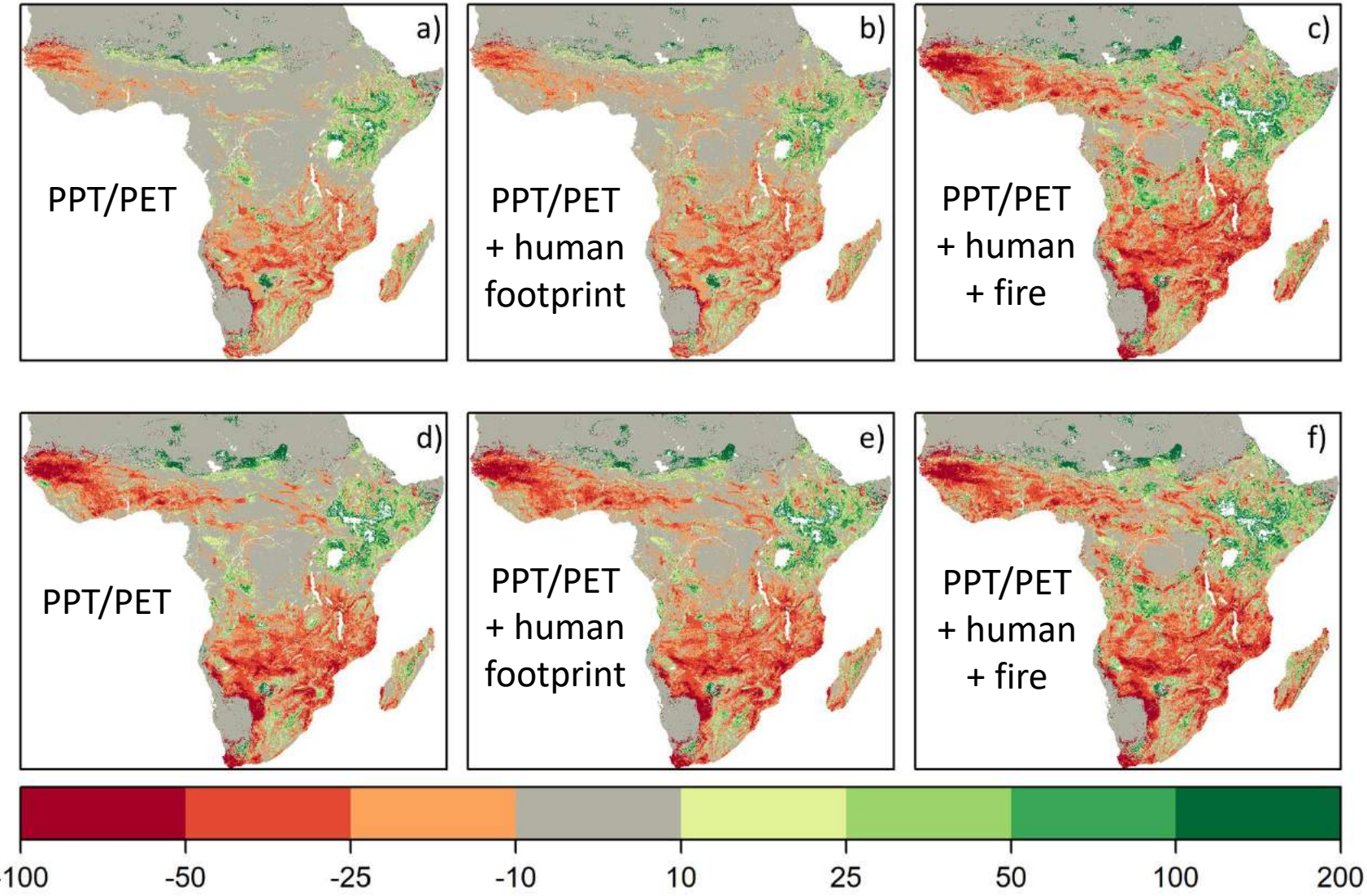

(Ross et al., in prep)

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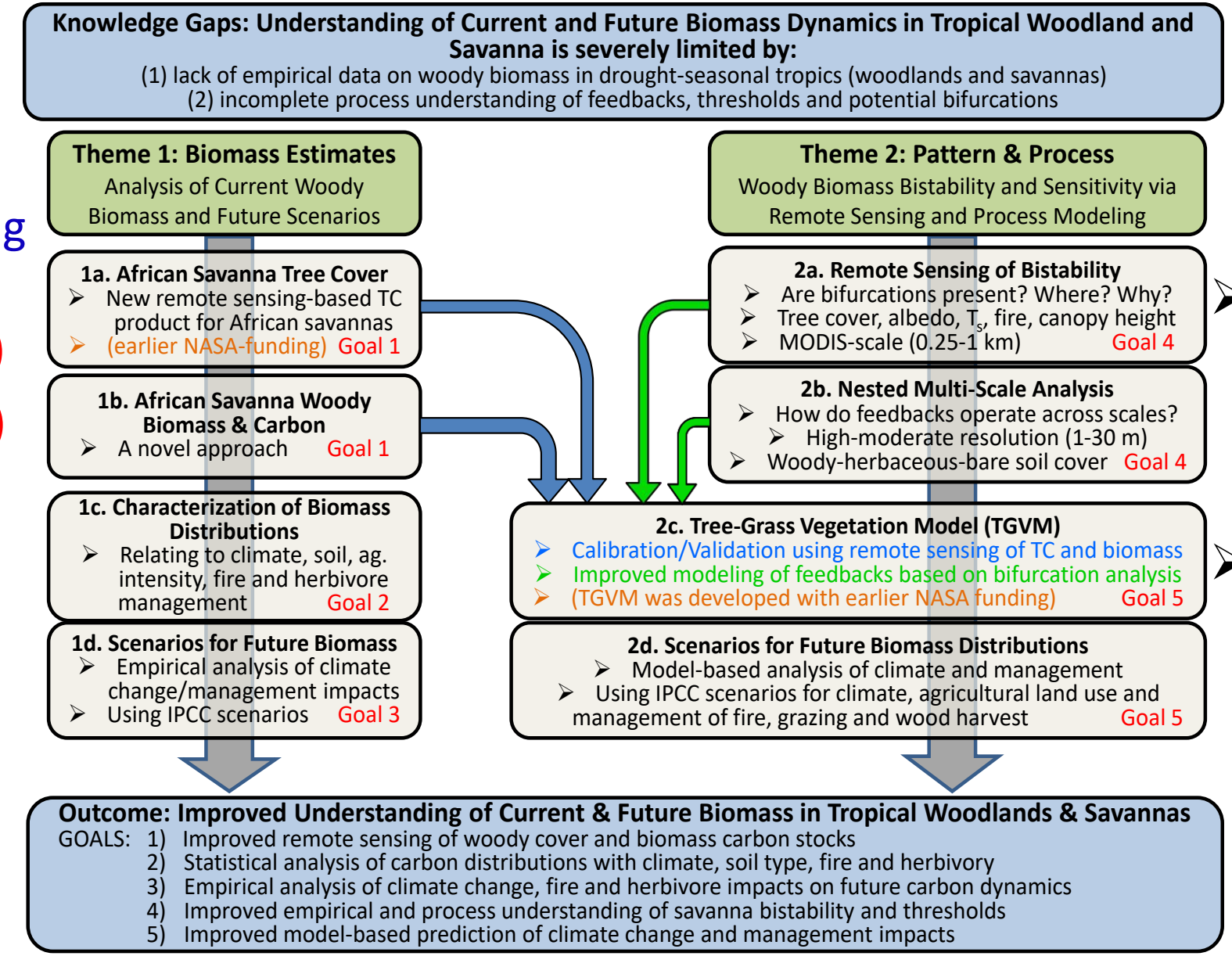
Theme 1:
Biomass mapping

- What's there now? (Goal 1)
- Why? (Goal 2)
- How will it change with future…
  - climate?
  - land use?
  - (Goal 3)

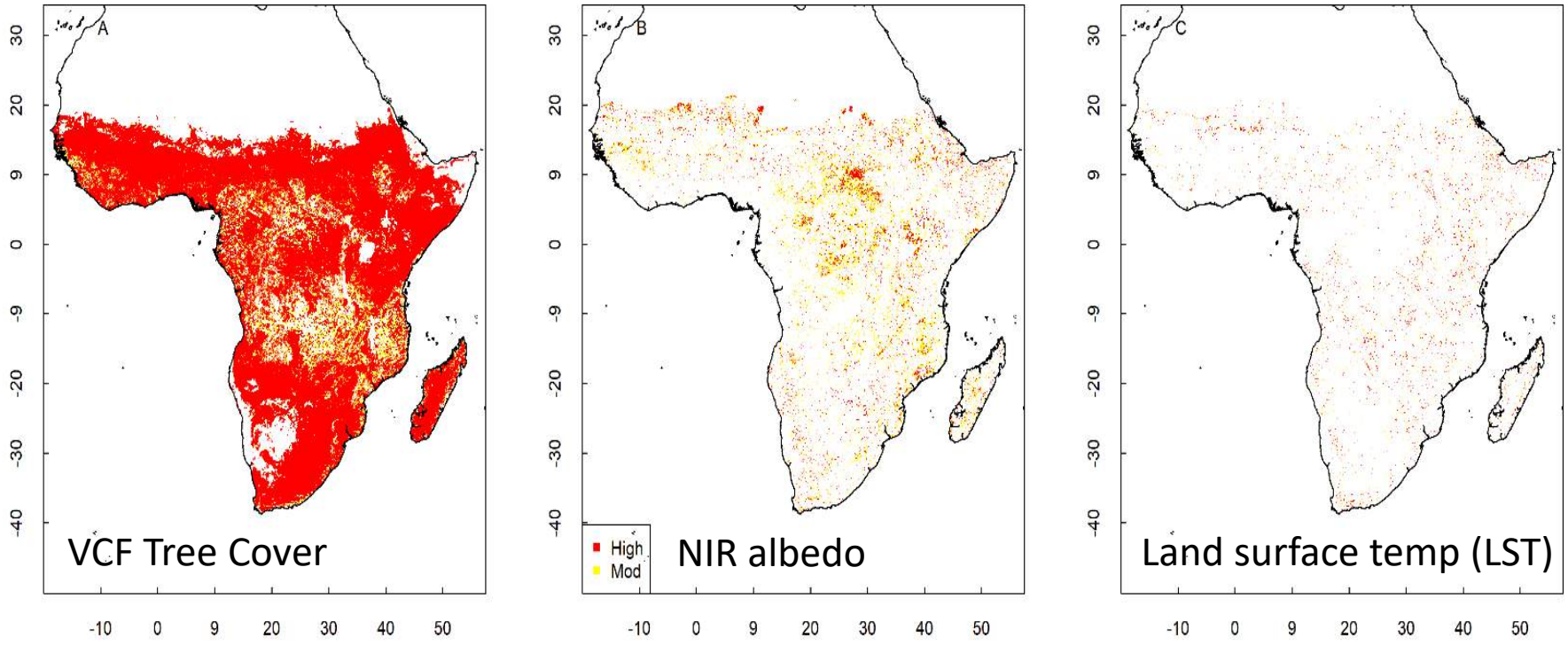


Theme 2:
Bi-stability mechanics

- When, where & why do forest-savanna bi-stable states emerge? (Goal 4)
- Dynamic savanna vegetation model
  - …climate?
  - …land use?
  - (Goal 5)

Bistability and Feedbacks in Tropical Woodlands and Savannas

Goal 4: Alternative stable states: when, where and why?



Local bifurcations (15 × 15 km windows) in (A) tree cover, (B) NIR albedo, (C) Land surface temperature. Red and yellow colors show landscapes with statistical evidence for local bifurcations. Bimodality emerges consistently with VCF, but in relatively fewer locations in albedo and LST data streams. (Kumar et al., 2018).

Theme 2:

Bi-stability mechanics

- When, where, why do forest-savanna bistable states emerge? (Goal 4)
- Dynamic savanna vegetation model with future…
  - …climate?
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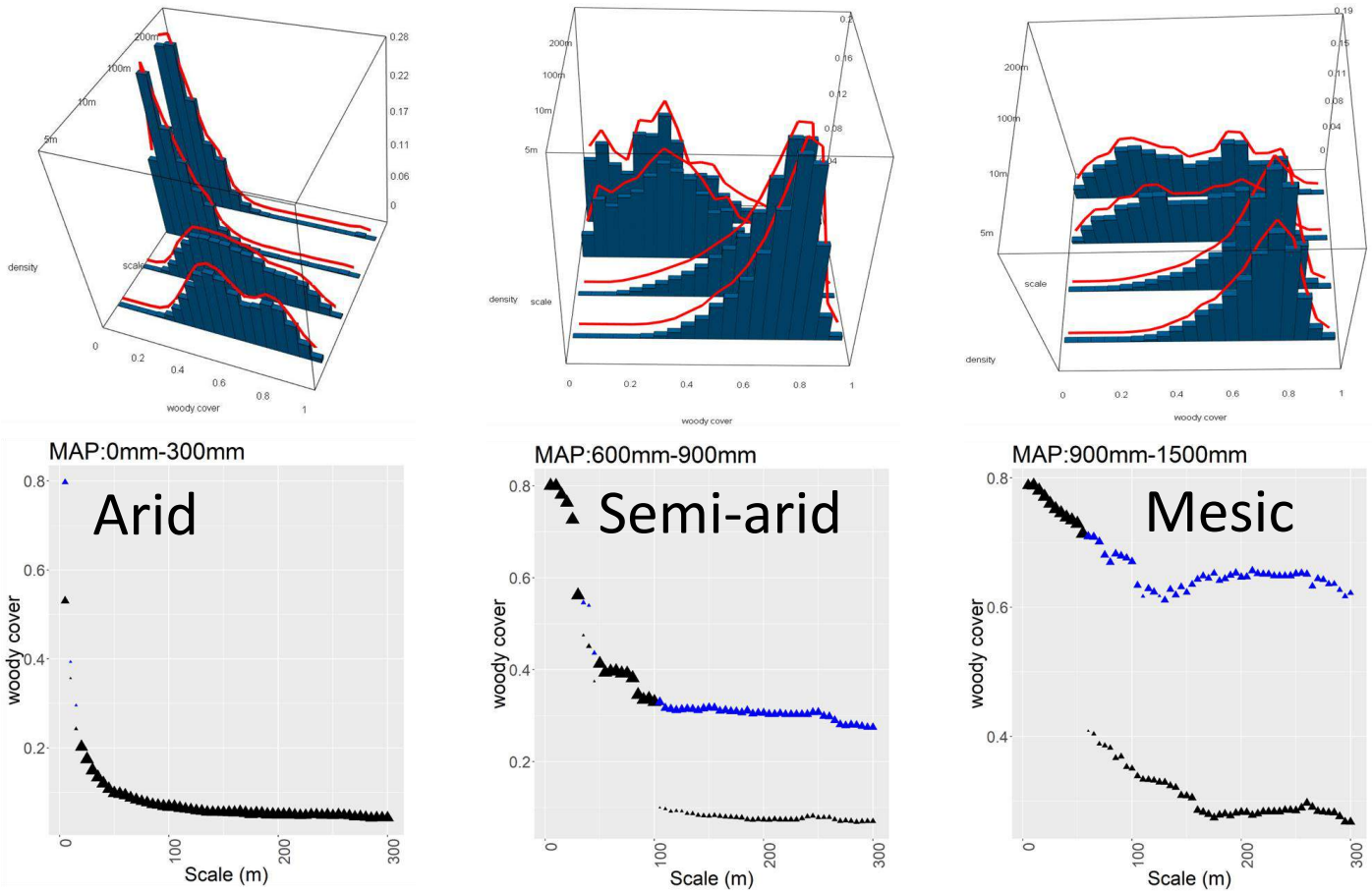
Bistability and Feedbacks in Tropical Woodlands and Savannas

Goal 4: Alternative stable states: when, where and why?



Low TC mode
Attractor Intensity

▲ 0.5
▲ 1.0
▲ 1.5
▲ 2.0

High TC mode
Attractor Intensity

▲ 0.5
▲ 1.0
▲ 1.5
▲ 2.0

Multiscale analysis of tree cover and multimodality for arid, semi-arid and mesic savannas in Africa (Yu et al., in prep).

Theme 2:

Bi-stability mechanics

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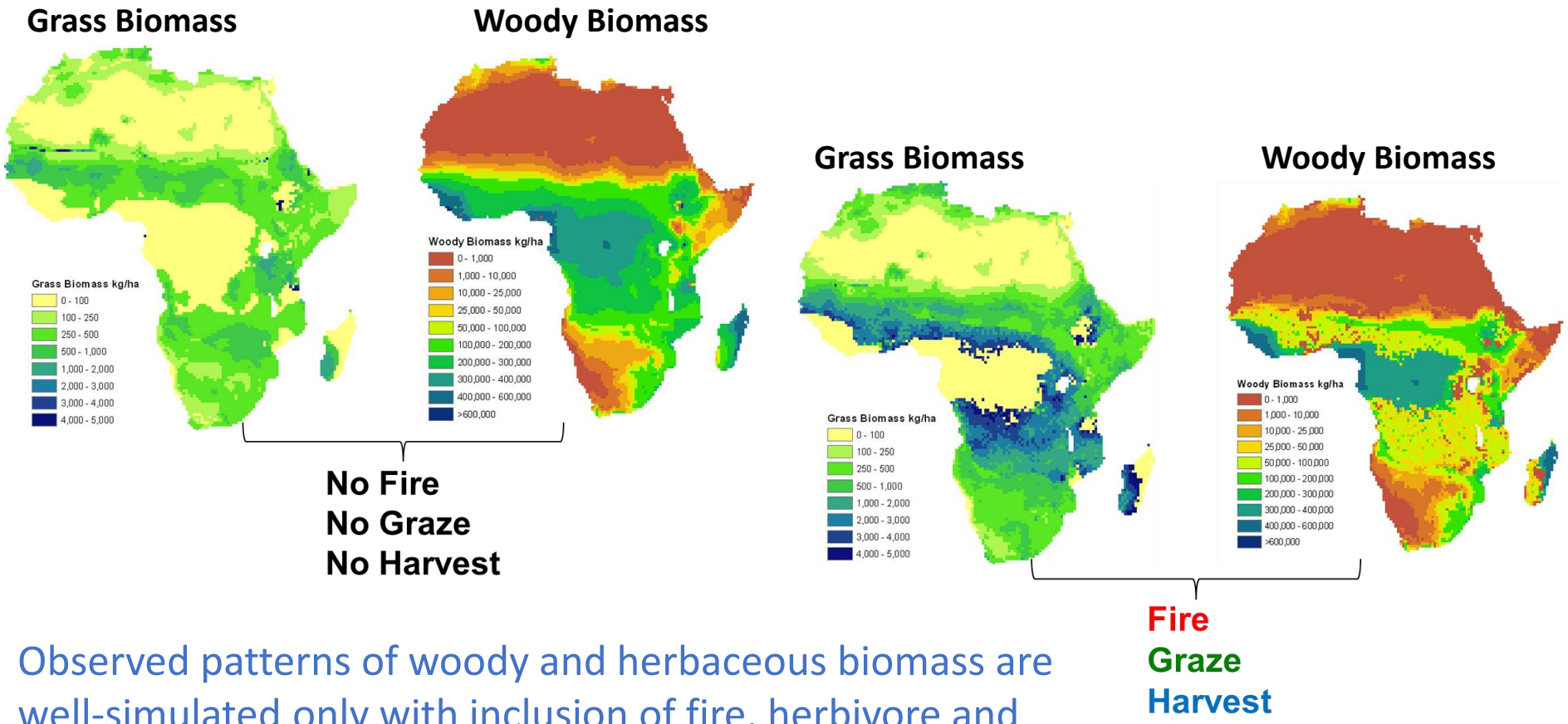
Goal 5: Dynamic vegetation modeling of carbon in bifurcating systems



Observed patterns of woody and herbaceous biomass are well-simulated only with inclusion of fire, herbivore and human harvest direct effects and interactions (feedbacks).

Savanna DGVM analysis of tree cover and thresholds for alternative states in African savannas (Prihodko et al. in prep).

Theme 2:

Bi-stability mechanics

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Bistability and Feedbacks in Tropical Woodlands and Savannas

Data, products and publications

Publications Supported by this Grant

Anchang, J. Y., Prihodko, L., Ji, W., Kumar, S. S., Ross, C. W., Yu, Q., Lind, B. M., Sarr, M. A., Diouf, A. A. and **Hanan, N. P.**, 2019, Towards operational mapping of woody canopy cover in tropical savannas using Google Earth Engine, *Frontiers in Environmental Science* (in review).

Hanan, N. P., 2018, Agroforestry in the Sahel, *Nature Geoscience,* **11,** 296-297 (DOI: 10.1038/s41561-018-0112-x; *Nature* SharedIt Link: https://rdcu.be/LGq4).

Hanan, N. P. Lara Prihodko, Gabriela Bucini, Andrew T. Tredennick, et al., 2019, Woody cover and biomass mapping in Africa: combining optical and radar remote sensing with allometric relationships for improved prediction in the savannas (in preparation).

Kahiu, M. N. and **Hanan, N. P.**, 2018, Estimation of woody and herbaceous leaf area index in Sub-Saharan Africa using MODIS data, *JGR-Biogeosciences,* **123** (1) 3-17 (DOI: 10.1002/2017JG004105).

Kumar, S. S., Hanan, N. P., Prihodko, L., Anchang, J. Y., Ross, C. W., Ji, W., Lind, B. M., 2019, Alternative vegetation states in tropical savannas: the search for consistent signals in diverse remote sensing data, *Remote Sensing, 11, 815* (DOI: 10.3390/rs11070815).

Kumar S. S., Prihodko, L., Hanan, N. P., Lind, B. M., Anchang, J., Ji, W., Ross, C. W., Kahiu, M. N., 2019, Remotely sensed thermal decay rate: a novel index for woody vegetation monitoring and modelling (in preparation)

Ross, C. W., L. Prihodko, Hanan, N. P., et al., 2019, The future of woody biomass in sub-Saharan Africa: An analysis of climate change and anthropogenic drivers (in preparation)

Ross, C.W., L. Prihodko, J. Anchang, S. Kumar, W. Ji, and **N. P. Hanan**. 2018. Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling, *Scientific Data,* **5,** 180091 (DOI: 10.1038/sdata.2018.91; www.nature.com/articles/sdata201891.pdf)

Yu, Q., Prihodko, L., Hanan, N. P., et al., 2019a, Alternative states and feedback mechanisms in tropical savannas diagnosed via length-scales of canopy aggregation (in preparation)

Yu, Q., Prihodko, L., Hanan, N. P., et al., 2019b, Rage against the machine: ecological learning from machine learning (in preparation)

Bistability and Feedbacks in Tropical Woodlands and Savannas

Data, products and publications

Datasets Supported by this Grant

Axelsson, C. and Hanan N.P., 2018, Supplementary materials from: Rates of woody encroachment in African savannas reflect water constraints and fire disturbance, *J. Biogeography* 45, (6) 1209-1218 (DOI: 10.1111/jbi.13221).

Kahiu, M. N. and Hanan, N. P., 2017, Data from: Estimation of woody and herbaceous leaf area index in Sub-Saharan Africa using MODIS data, Dryad Digital Repository, http://doi.org/10.5061/dryad.v5s0j.

Ross, C.W., L. Prihodko, J. Anchang, S. Kumar, W. Ji, and N.P. Hanan. 2018. Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1566.

Hanan, N. P., L. Prihodko, G. Bucini, A. T. Tredennick and C. W. Ross. 2019. Tree cover in African savannas. ORNL DAAC, Oak Ridge, Tennessee, USA. (in prep).

Bistability and Feedbacks in Tropical Woodlands and Savannas

Take Homes

1. Forest-savanna bistability – alternative forest-savanna states emerge in tropical savannas, but not as pervasive as sometimes thought/expected

2. Wood resource mapping tool – Earth Engine Application for woody canopy cover, fuel wood resources and carbon M&E

3. Bistability == amplifying feedbacks == spatial scales depend on mechanisms

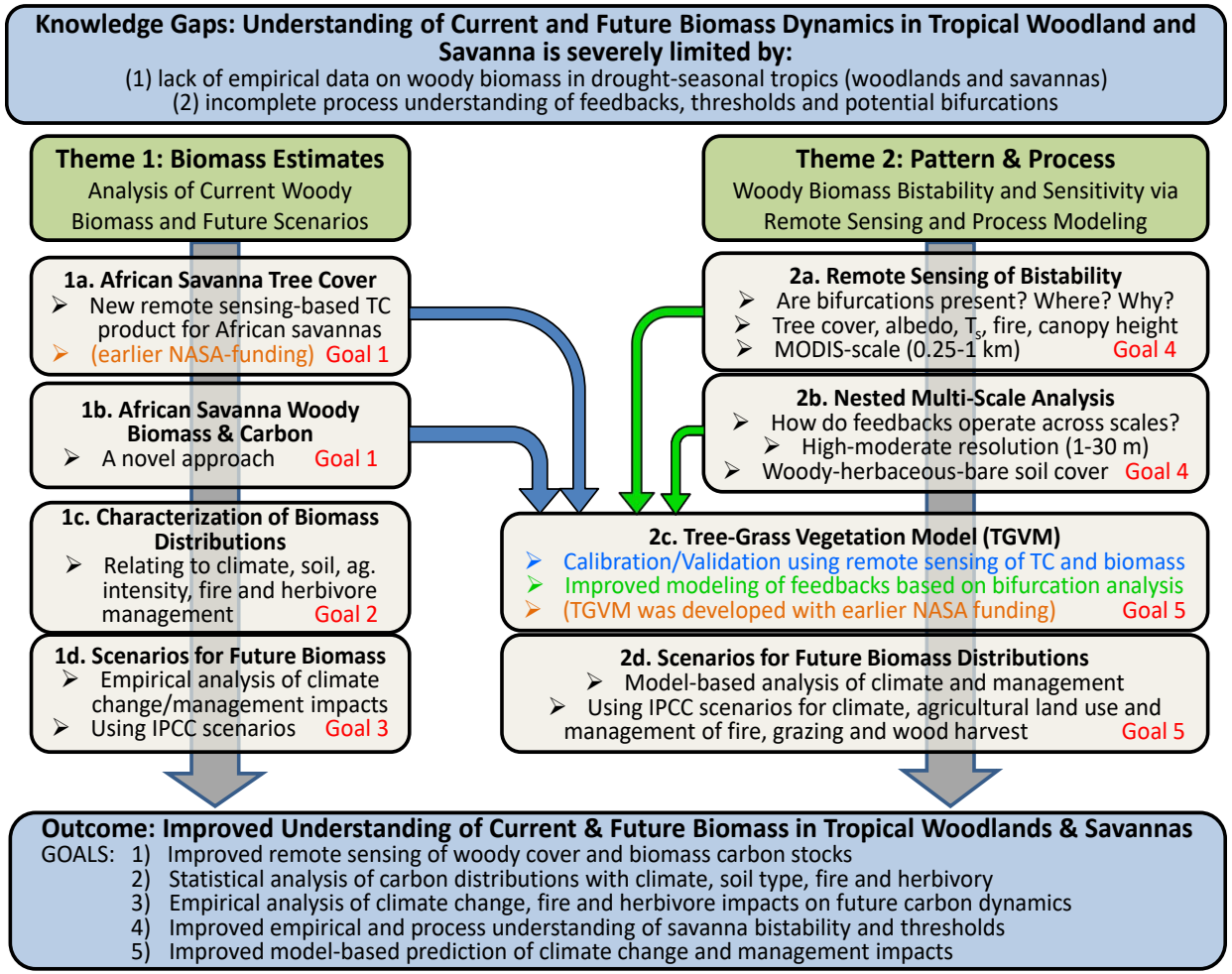
4. Simulating future biomass in tropical savannas – empirical analysis (machine learning):
   - Suggests strong climate and social-ecological influences
   - Continental-scale net changes relatively small, but huge regional differences

5. Simulating future biomass in tropical savannas – process analysis (savanna DGVM) :
   - Climate and social-ecological influences, incorporating amplifying feedbacks, leading to emergent bifurcations
   - Role of forest-savanna bifurcations in tropical woody biomass and carbon sequestration

Bistability and Feedbacks in Tropical Woodlands and Savannas:

Carbon cycle implications of changing climate and management

Thanks to NASA TE (Carbon Cycle Science)!



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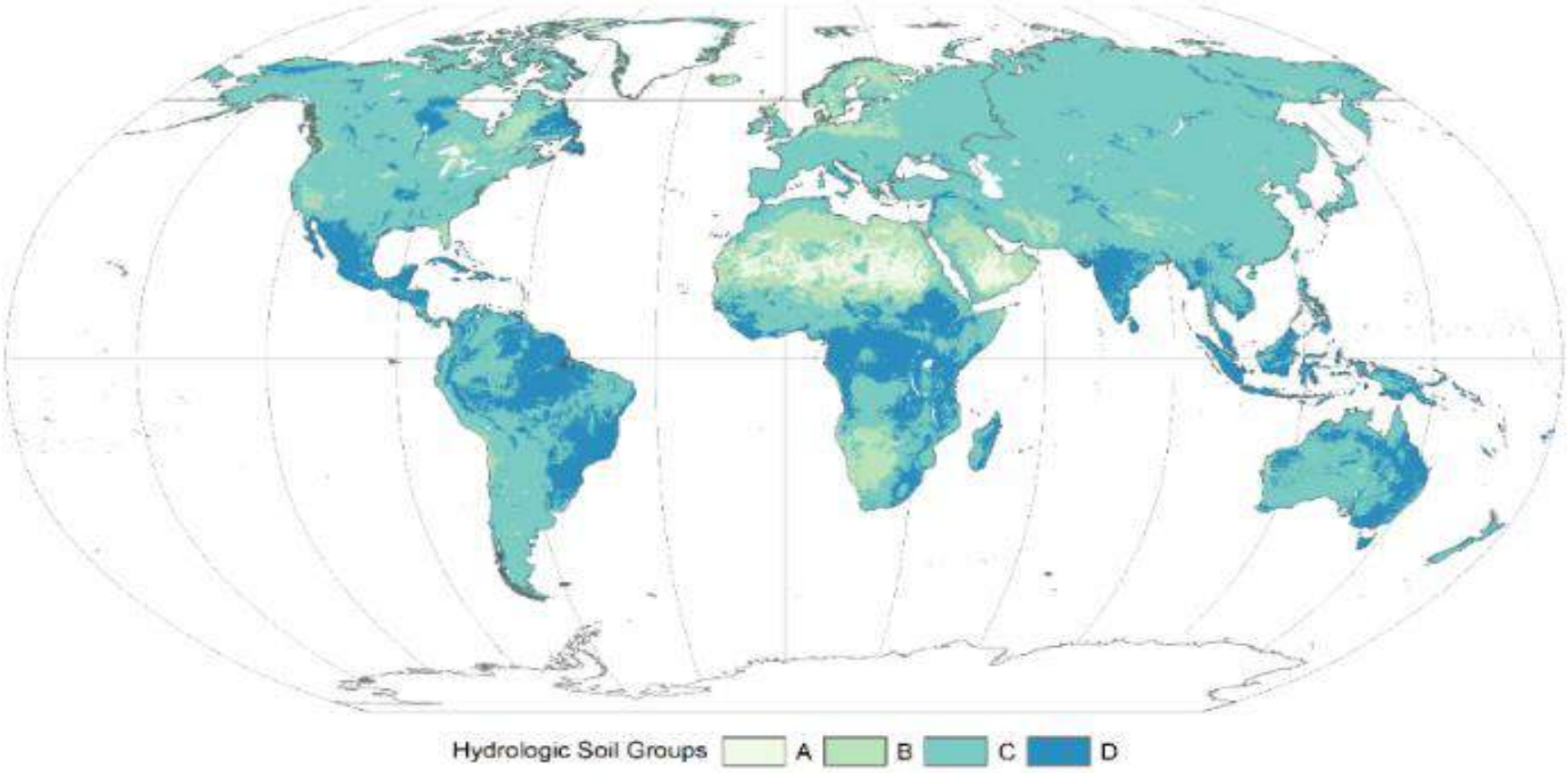
Side-products and publications



Global hydrologic soil groups (HYSOGs; Ross et al. 2018) for curve-number based runoff modeling.

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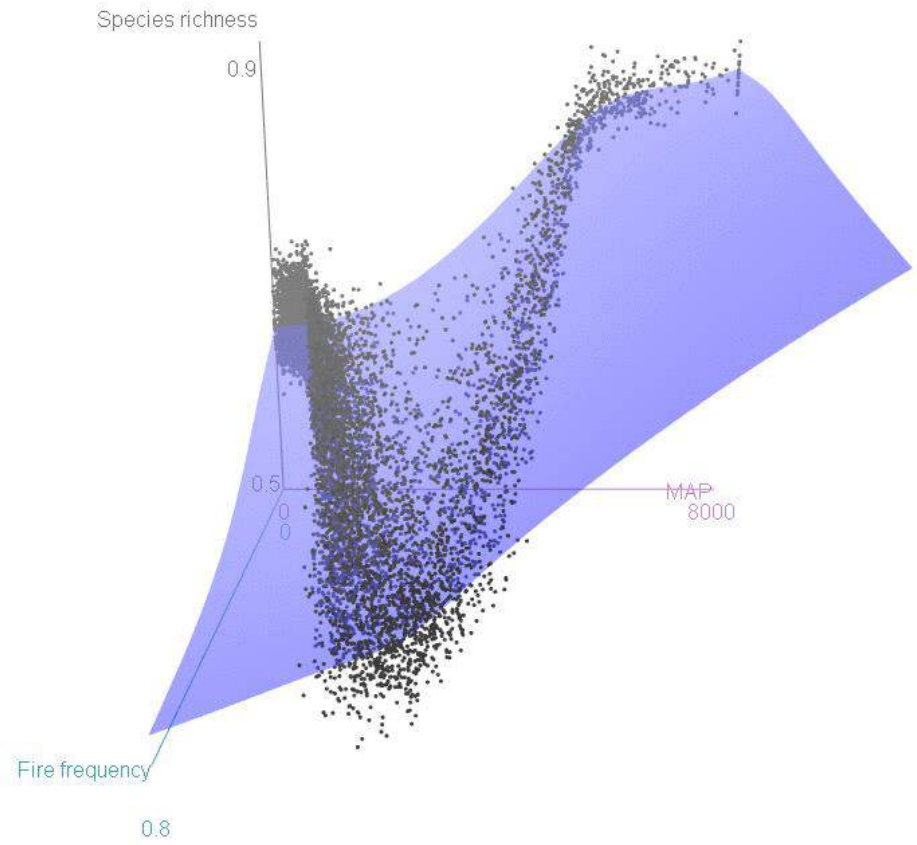

Pseudo-data Experiments

- Global surrogates
  - Re-analysis
- Re-visualization

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Ecological learning from machine learning (Yu et al. 2019, in prep)