Landcover Stability: Heating and Drying of Plants and Soils

Progress Report 2025

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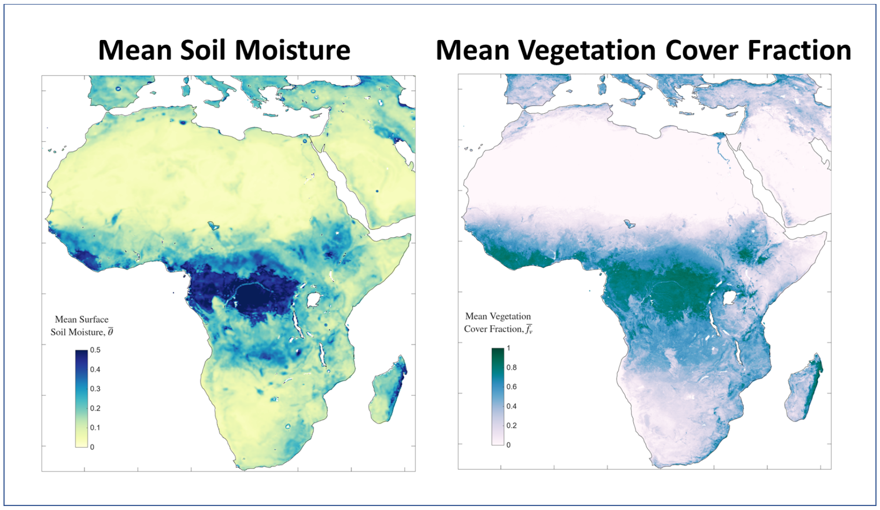
While it may often appear that the climates in which we live are controlled only by clouds and the sun, the bottom kilometer of the atmosphere, where all of humanity and terrestrial ecosystems live, is controlled to a very large degree by the land itself and the water and vegetation integrated into it. Deserts and rainforest are both quasi-stable states that control their own heating and cooling, their absorbed solar radiation, the local weathering and growth of soils, and their own humidities.

The goal of this project is **to map the *processes* and *biophysical interactions*** that form the land surface properties of Africa. Using satellite observations of the land surface, we are 1) Uncovering the behavior of coupled variables which are otherwise unobserved, 2) Determining which land surface characteristics stabilize and de-stabilize the land surface state, 3) Assessing the stability of Africa's local climates, surface characteristics, and vegetated ecosystems.

The first step in this project was the basic **geographical information work**. This involved collecting a number of large data sets and translating them into matching coordinate systems as daily or twice-daily maps of land surface variables over the continent. Our primary analysis variables are soil moisture (SM), vegetation-cover fraction (FV) and land-surface temperature (LST). Making use of two key satellite data streams—the NASA Soil Moisture Active Passive (SMAP) mission and the Satellite Application Facility on Land Surface Analysis (LSA SAF) hosted by the Portuguese Institute for the Sea and Atmosphere (IPMA), all three of these variables are available as time-series of maps on timescales from 15min to multi-annual. The SMAP satellite mission was the source of our SM data, while the FV and LST came from the LSA SAF record. The underlying algorithms to retrieve these data from radiometric measurements were developed by the PI and the Portuguese CoI as science team leads of the respective missions. These data were translated on a shared 9km grid.

We additionally collected two auxiliary variables: vegetation optical depth, also from the SMAP mission, and daily precipitation, from a global reanalysis (ERA5). These were also mapped to the common grid for future co-located analyses.

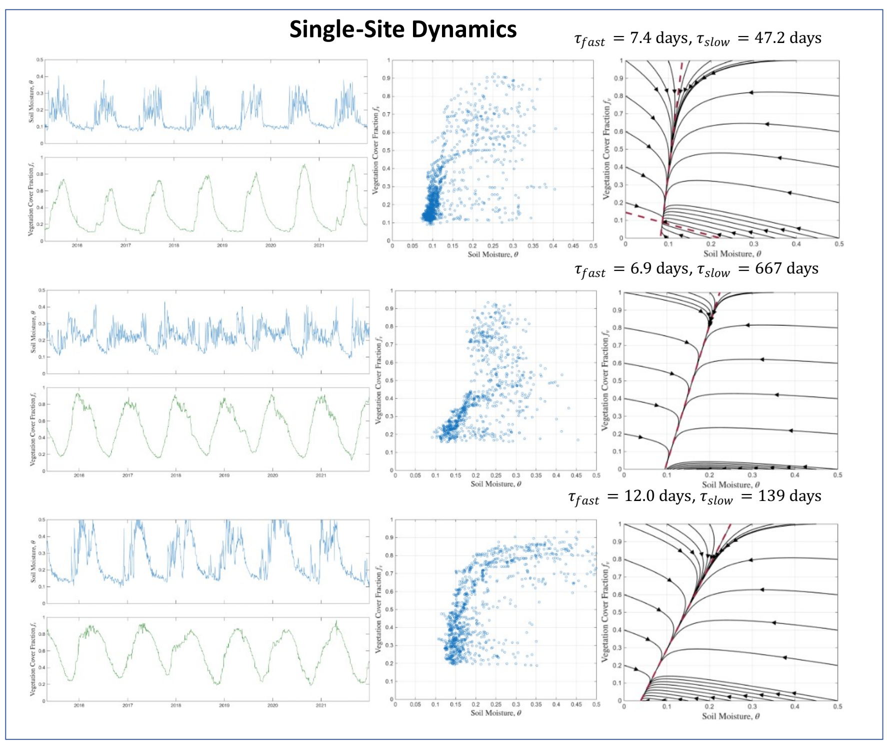
To determine landscape stability characteristics, we are using dynamical systems models which allow all variables to feed-back on one another, and which can determine the ways in which the system state drives its own changes in time. Perhaps most interesting about this is that while interactions between these variables may have been modeled historically through process understanding, their behavior at the



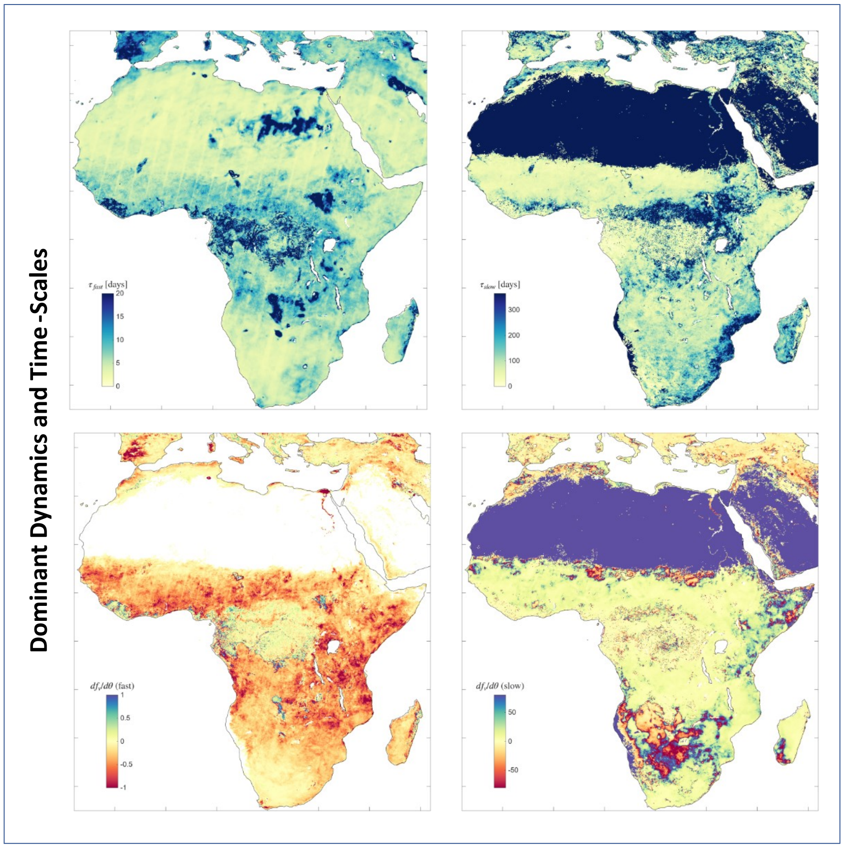
landscape-level is often completely different due to complex scaling relations across millions of trees, soil patches, stones, and puddles. The results of this work will serve as **the first observational benchmarks of these processes and feedbacks** at this scale across Africa.

Our first models of the feedbacks at the land surface focused on SM-FVC coupling. To first order, more soil moisture can support more plant growth, and plants tend to dry soils through transpiration. Water, however, changes the total heat capacity of the surface, and cools and moistens the atmospheric boundary layer. Which can change many plant-physiological processes, and trees absorb and reflect solar radiation, which changes the surface energy budget of the landscape.

Our simplest model of SM-FVC interactions is a linear, time-invariant (LTI) dynamical system model, which gives us 1) bivariate system stability, 2) the dominant interaction timescales between the two variables, and 3) the partial derivatives of the variables, indicating their feedback magnitudes and directions. Dynamics for three sites are shown as an example in Figure 2. Despite coming from a large range of bioclimate conditions, all three of these examples have the same stability class: rain shocks the land surface, vegetation grows as soils dry for the first days, and then begin to lose green biomass without further rainfall, ultimately to complete desiccation. This is the most intuitive of the possible feedbacks between the water and carbon cycles on land. Plants grow when given water, and die if left long enough without.



Their exact behavior, however, varies. The wettest ecosystem with the most vegetation can saturate, and barely respond to rain events, and can also go the longest between storms, showing that water supply is controlling the dynamics rather than water demand (evaporative drying). This wettest site is also particularly predictable from either variable; its wet season is its growing season. This is more often true in arid, water-limited locations. Our suspicion is that this seasonally-dominated pattern is more complex than it seems, and our next step is to begin to control for external seasonal forcing using surface energy-balance variables (LST and/or incoming solar radiation) from SEVIRI to separate stability from strong external drivers. This next step extends the system to three coupled differential equations, using a mixture of statistical and physical relationships.



Despite the examples showing rain-driven stability, there are other stability classes in the region. Many of the locations show unstable behavior between rain events, moving away from mean states in all directions, and a number also show complex oscillatory stability, where drying in one dimension leads to growth or wetting in another, only for the variables to switch places and repeat. As we include LST in our future analyses, we will be able to uncover how water, energy, and carbon cycle variables move in sync versus out of phase to counterbalance the others' behaviors.

Maps of the direct dynamic relationships between FVC and SM were **presented by the team at the American Geophysical Union's Fall Meeting** (2025, also Figure 3), with very positive engagement from a large international audience.

These results will be combined with LST to differentiate external drivers from internal feedbacks of landscape stability. This will comprise the first full publication of the project, which should be submitted in the first part of 2026. We expect this to be a long-form article showing the full landscape behaviors for use in future modeling and spatial scaling studies. Any particular surprising results (for example, persistent oscillatory feedbacks) may be worth publishing in short letter-format. Results describing the feedbacks will be published as free-standing data archives as well.

The next step after publishing this study will be to look at the disruptors of landscape-stability: drought, floods, fires, and human interventions. These will build from the results of the first study, finding anomalous behaviors and using major events as case studies. The following stage will determine whether and how Earth System Models represent observed land surface behaviors and how medium-term climate change scenarios will impact the land surface states, their resilience, and their long-term stability.

The proposed project is directly relevant to the overarching goals of MPP2030 by linking research scientists in leadership roles at MIT and within Portugal. The specific topic of the proposal addresses Area 1 (Climate Science & Climate Change) of MPP2030.

References

Short Gianotti, DJ, I Trigo, D Entekhabi (2025). "Stability of biosphere-climate coupling," Biogeosciences 11I-1579, American Geophysical Union Fall Meeting, New Orleans, December 15, 2025.