

Hydrological and nutrient controls on the structure and function of southern African savannas: A multi-scale approach

Abstract

Understanding and modeling the response of complex ecosystems to change is recognized as a problem that requires understanding of change at multiple scales and involving multiple potential significant and causal phenomena. In this project, we will use EOS remote sensing, *in situ* measurements, and modeling in a multi-scale and modeling approach focused on assessing the feedback and stability of interactions in the complex savanna ecosystems found along a unique aridity gradient in Zambia, Botswana, Namibia, and the Republic of South Africa. The gradient, known as the Kalahari Transect (KT), follows a north-south decline in mean annual rainfall from ~1600 mm/yr to ~250 mm/yr, all on a fairly homogeneous sand formation. Results from our previous IDS and SAFARI 2000 activities in the region have revealed that although the coarse-scale (100s of km) pattern of vegetation cover for the KT savanna is determined by mean annual rainfall and nutrient availability, the small-scale (1- to 100 m) pattern of vegetation structure is highly organized by internal system processes, which operate at local scales. To understand and predict how savanna vegetation dynamics respond to alterations in climate or land-use forcings, it is necessary to observe, characterize and model interactions over these disparate scales. We will address this research goal by conducting a focused field campaign that will support the continued development and application of process-based modeling combined with remotely sensed data. A major goal of the proposed research is to understand how sub-pixel scale local variability is expressed in data from EOS sensors (esp. MODIS, ASTER, MISR) and, in turn, how these sensors may be used to provide synoptic regional-scale information about sub-pixel structure and processes. Thus, we will employ linked field observation, modeling analysis, and remote sensing observations over a set of core sites on which we will anchor our regional parameterizations and models.

The proposed research is responsive to the research goals of NRA-03-OES-03, particularly the question “**How are global ecosystems changing?**” We will employ linked remote sensing, *in situ*, and modeling observations to document and improve understanding of patterns, processes, and changes in terrestrial (savanna) ecosystems at multiple scales.

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1. Goal Statement

In this proposal, we seek to renew an IDS project researching the dynamics of the land surface over Southern Africa. Our project continues to be directly involved with a significant NASA-funded research program called the Southern African Regional Science Initiative (SAFARI 2000) and related NASA funded R&A and EOS validation projects within the Southern African region. These large projects have produced a significant interdisciplinary dataset relevant to the dynamic functioning of southern African savanna ecosystems.

Our initial IDS project had the objective of examining the importance of feedbacks between the atmosphere and land surface in southern African savanna ecosystems. We have shown that although the overall pattern of vegetation cover for the KT savanna is determined by mean annual rainfall and nutrient availability, small-scale patterns of vegetation structure are highly organized by internal processes, which operate at local scales. This conclusion has significant implications for 1) understanding how changes in global climate affect savanna ecosystems, 2) understanding how changes in savanna ecosystems affect the entire Earth system, and 3) monitoring vegetation at different resolutions in time and space, a central issue in the interpretation of remotely-sensed data collection. Therefore, the goal of this IDS renewal is to:

Assess processes that govern the structure and dynamics of savanna ecosystems and the patterns that result at multiple scales.

In pursuit of this goal we shall apply, modify, and further develop local - and regional - scale models of savanna landscapes developed in conjunction with existing NASA-funded studies in southern Africa. These models will be based upon information gained during previous field investigations, and will be supplemented by an additional focused field campaign. Our field efforts will further characterize the multi-scale nature of pattern and process in southern African savannas and provide necessary context to integrate our data and models with both historical and EOS-based remotely-sensed data. We will use this multi-scale approach to understand the impact of global climate change on processes and patterns in soils and vegetation of southern African landscapes.

1.1. Specific research questions

Our previous work (Section 2) has demonstrated that the spatial pattern and temporal dynamics of soil moisture and nutrients are strongly coupled to the regional-scale climatic gradient and patch-scale distribution of vegetation structure in southern African savannas. These findings lead to a number of specific questions regarding how pattern and process of savanna ecosystems are governed by multi-scale interactions between coupled biogeochemical and ecohydrological processes:

- 1) **Pattern:**
 - a. How does the spatial variability of biomass, nutrients, and soil moisture change across the rainfall gradient and how is patch-scale variability expressed on landscape to regional scales?
- 2) **Process:**
 - a. How do local-scale processes explain vegetation, nutrient, and soil moisture patterns at the patch-to-regional scales?
 - b. Are southern African savanna ecosystems open or closed with respect to cycles of water and nitrogen and does the open/closed nature of these cycles vary with differing moisture availability?

3) Prediction:

- a. How will southern African savanna ecosystems and ecosystem processes change under global climate change scenarios, and what implications does this have for local and regional productivity, fire regimes, and global biogeochemistry?
- b. Will expected changes in southern African savanna ecosystems be detectable using current EOS sensors?

2. Scientific Background and Prior Progress

In the past three years, we have conducted intensive research in southern Africa and the Kalahari Transect [NAG5-7956 and NAG5-9357] (cf. Section 3.2). The work associated with our previous IDS study has been synthesized as special issues in the *Journal of Arid Environments*, [Vol 54, Number 2, June 2003] (for initial data archiving and model documentation) and in *Global Change Biology*, [Special Issue, 2003] (for the synthetic products from the field campaign).

The KT follows a north-south decline in mean annual rainfall from ~1000 mm/yr to ~250 mm/yr on homogenous sandy soils deposited during the Pleistocene (Kalahari Sands). The large gradient in both the mean and variation of annual rainfall results in dramatic changes in vegetation structure along the Transect. Vegetation type ranges from partially closed woodlands in the north to open shrub land in the south. Throughout the KT, the mixed life-form composition characteristic of savanna communities is maintained. Thus, the KT is a unique natural laboratory to study landscape processes and assess the impact of global change in savanna ecosystems. Figure 1 indicates the extent of Kalahari Sands in the region, as well as the location of the research sites included in our previous study.

The KT vegetation structure has been extensively characterized [Scholes, *et al.*, 2002; Caylor *et al.*, 2003; Privette *et al.*, 2003]. Structural differences, coupled with the regional rainfall gradient, lead to changes in the relative contribution of trees and grasses to vegetation productivity across the transect [Dowty *et al.*, 2000; Dowty *et al.*, in press; Caylor *et al.*, in press]. Our field investigations into the spatial pattern of woody vegetation across the Kalahari Transect have yielded insights into the ways in which canopy individuals serve to structure the distribution of understory vegetation across the transect [Caylor *et al.*, 2003].

We have explored the functional consequences of observed structural variability in vegetation through detailed model-based characterization of the distributions of simulated productivity for both trees and grasses across the KT [Caylor *et al.*, in press; Caylor *et al.*, in review - b]. Results indicate that models of system productivity in savanna/woodland ecosystems must retain high spatial resolution in order to adequately characterize multi-year structural responses and accurately represent the contribution of grass biomass to overall ecosystem production. Spatial information provided by a large eddy simulation model [Scanlon and Albertson, in press - b] indicates that the spatial distribution of the vegetation fluxes can be highly tied to the distribution of the canopy sublayer air properties, indicating scaling complexity for heterogeneous vegetation associated with highly water-limited conditions.

We have also studied the role of water balance in controlling vegetation structure along the KT using a coupled energy- and water-balance model [Caylor *et al.*, in review - c]. The model indicates pronounced shifts in the yearly water stress experienced by vegetation under and between tree canopies, depending on annual rainfall. By combining multi-temporal AVHRR-NDVI data with theory about the disparate growth response of woody vegetation vs. grasses to the transient status of water availability, Scanlon *et al.* [2002] found a strong relationship between fractional tree cover and mean wet season precipitation. Potential grass cover peaked at

approximately 450 mm of mean wet season precipitation. Above this value, the potential grass area was found to be controlled by the tree cover. Below 450 mm, the potential grass area appeared to be limited by the available rainfall.

To further explore the temporal dynamics of vegetation structure, a soil moisture model was applied to the KT in conjunction with the remotely-sensed fractional cover information [Scanlon and Alberston, in press – c]. The model suggests two distinct regimes of vegetation-rainfall relationships. In the northern portion of the KT, a large portion of the water balance may be accounted for by leakage through the bottom of the root zone in sandy soils, and vegetation may be limited by nutrient availability. However, in the southern portion of the KT, the tree fractional cover is found to be governed by the long-term mean rainfall. These results suggest that the vegetation composition in the water-limited portion of the Transect, over interannual to multi-decadal timescales, can be modeled largely as a function of the mechanistic constraints imposed by the water cycle.

Preliminary analyses of spatial patterns of NDVI show a change in scaling regime between the patch and the landscape scales. This is evidenced by log-log plots variance of NDVI as a function of the scale over which NDVI is averaged (Figure 2). A deviation in this expected linear decrease indicates a change in dominant pattern generating process. In the case of study sites on the Kalahari Transect there is a break in the linearity of the log variance curve that occurs at systematically larger scales as one moves to the wetter end of the Transect (Figure 1). This change in breakpoint appears to be a consequence of plant canopy processes controlling pattern at small scales and other landscape processes then controlling pattern at larger scales. This implies that satellite data collection systems with differing resolutions might monitor the consequences of different processes and that for particular resolutions the same sensors might detect the consequences of different processes in different parts of the same region. Our previous work in the KT has provided some insight into the vegetative, atmospheric, hydrological, and biogeochemical patterns processes that control vegetation cover and structure in the KT. How to integrate detailed patch scale patterns and processes described above to improve understanding of savanna ecosystem functioning and to integrate these insights with observations from EOS instruments is the primary focus of this proposal.

3. Rationale and Significance

3.1 Rationale for proposed research

The rationale for our study stems from the growing evidence of a multi-scale organization of vegetation in southern African savannas. At local to landscape scales, vegetation structure and function is determined by competition-facilitation interactions that are governed by patchy resource distribution in space and time. At landscape to regional scales, climatic gradients affect both hydrologic and biogeochemical cycling, through the action of the southern African gyre and regional patterns of rainfall distribution. Across both of these scales, the distribution and occurrence of fire and herbivory as well as other disturbances exert additional control on vegetation structure and function.

Understanding the response of complex ecosystems to change involves the understanding of change at multiple scales and involving multiple biogeochemical and ecohydrological processes. In this project, we will focus on assessing the patterns and processes that determine landscape structure and predicting how global change will impact savanna ecosystems. In doing so, we will link observations and models at different scales to provide insight into how processes functioning on the leaf and patch scales manifest on the landscape and regional scales.

3.2 Significance of proposed research

Savannas are extensive, seemingly stable mixtures of grasses and trees that cover 20% of the Earth's surface (40% of Africa). They represent an ecological paradox in their shared dominance of plants of radically different life forms. Savannas are not narrow transition vegetation between conditions that favor grasses and conditions that favor trees. Rather, they occupy a substantial part of natural gradient of soil moisture and nutrients. The conspicuously shared dominance of contrasting plant life forms makes savannas inherently interesting from an ecological perspective, while their geographic and socioeconomic importance are underscored by the rapidly growing human populations that depend on savannas for wood products and livestock rangeland.

Owing to their large extent, savannas constitute one of the major global terrestrial carbon pools [Atjay *et al.*, 1979] and are responsible for about 13% of global net primary productivity [Scholes and Hall, 1996]. Savannas have the potential to be either large carbon sinks, or large carbon sources, depending on how they are managed, and the time-scale under consideration. Some savanna areas, especially semi-arid savannas, have experienced distinct and irreversible transitions (in the medium term) that have led to an increase in carbon storage in the form of woody biomass and soil carbon [Walker *et al.*, 1981]. In contrast, many woodlands have experienced a net loss in carbon under grazing pressure and the cutting and burning associated with shifting agriculture and fuelwood harvesting [Lawton, 1978]. Since southern African savannas presently have a moderate degree of anthropogenic disturbance, and since the human population is expected to rise dramatically [Fischer and Helig, 1997; Tarver and Max, 1986], they have the potential to experience a significant change in carbon storage and either contribute to or alleviate the atmospheric carbon load significantly.

By linking remote sensing, *in situ*, and detailed process models in the proposed research, we will provide critical insights into how global change will impact carbon storage and fire emissions in savanna ecosystem.

3.3 Relevance of proposed research to NASA's mission

The proposed research is directly relevant to the research goals of NRA-03-OES-03, particularly the question “**How are global ecosystems changing?**” We will employ linked remote sensing, *in situ*, and modeling observations to document and improve understanding of patterns, processes, and changes in terrestrial (savanna) ecosystems. In particular, we will use this linked study to identify environmental parameters that are important for estimating and understanding changes to these ecosystems. Our research goal is to characterize and explain savanna ecosystem structure and function and provide predictions of ecosystem change under future climate scenarios. This work utilizes existing ecological and biogeochemical models as well as couples biogeochemical, ecohydrological, and vegetation models to create new regionally applicable ecosystem models. In addition, we believe that our approach is highly appropriate to NRA-03-OES-03 which states that “*A particular interest is the linkage of information across different spatial scales to take advantage of data products at the landscape, regional, and continental scales of remote sensing as well as the smaller spatial scales of many in situ ecosystem studies.*”

The proposed research is also directly applicable to NASA's wider ESE research goals, namely:

1) *How is the global Earth system changing (Variability)?* We will study processes in globally-

important savanna ecosystems to determine the processes that govern their temporal and spatial changes.

- 2) *What are the primary forcings of the Earth system (Forcing)?* The proposed research has implications for understanding the causes of land cover change in semiarid regions.
- 3) *How does the Earth system respond to natural and human-induced changes (Response)?* The proposed research will improve understanding of how savanna ecosystems respond to environmental change.
- 4) *What are the consequences of change in the Earth system for human civilization (Consequences)?* We will investigate how southern African savanna ecosystems will change under various future climate scenarios. This will provide direct insight into the suitability and sustainability of land use in southern Africa under altered climate regimes.
- 5) *How well can we predict future changes in the Earth system (Prediction)?* Prediction of the influence of global climate change on southern African savannas is an integral portion of the proposed research, comprising one of our main research questions.

Finally, the proposed research will address the ability of NASA's EOS sensors to capture current and future land cover and structure in savanna ecosystems. These results will have broad implications for planning of future EOS instruments and measurement requirements.

4. Work Plan

We will address the research questions in Section 1.1 through an integrated set of field, laboratory, modeling, and remote sensing analyses. Our efforts will be concentrated at three sites from the KT – Mongu, Maun, and Upington (Figure 1). A 4-week focused field campaign to all sites will be undertaken during the peak of the rainy season (Feb-Mar) in the first year. *In situ* measurements will be taken and samples collected for later analysis in laboratory facilities at the University of Virginia. Orbital data (ETM+, IKONOS, MODIS, ASTER and MISR) data will be compiled and analyzed to provide insights about the spatial and temporal distribution of green vegetation, non-photosynthetic vegetation, and bare soil. Insights from field, laboratory, and remote sensing analysis will be used to inform modeling efforts that integrate soil moisture, nutrient, and vegetation dynamics.

Products from this work are expected to include models that bridge the gap between large-scale vegetation dynamics that are observable from satellite data and the patch-scale processes that fundamentally define the aggregate behavior. This multi-scale approach will be operative in both directions: satellite-based data will be used to give insight into the savanna compositional dynamics (i.e., tree/grass interaction, sensitivity of vegetation to atmospheric and land-use forcings, nutrient cycling), while knowledge of the vegetation processes will be used to explicate and predict subcontinent-scale observations (i.e., historical variability in vegetation pattern, temporal trends in composition). Results from this proposed research will build upon previous NASA-sponsored research in this region (MODIS/SAVE, SAFARI-2000).

4.1 Pattern Analysis – Multi-scale assessment of savanna complexity

4.1.1 Field Analysis

We have designed a multi-scale geostatistical sampling strategy that will enable quantification of the scales of variability and co-dependence of soil moisture, nutrients, and biomass (Questions 1a and 2a, Section 1.1). Soil nutrient and soil moisture samples will be collected along a transect at each site. Vegetation structure data will be collected within a plot at each site.

Soil Sampling and Analysis

Soil nutrient sampling will be done using standard methods to collect surface soils (0-5 cm depth) [Okin *et al.*, 2001]. While there can be significant variability of soil nutrients with depth in soil profiles, we are most interested in soil resources at the surface because surface condition is most important for seedling establishment and therefore plant recruitment. These samples will be returned to the University of Virginia for analysis of Total C, Total N, nitrate, ammonium, phosphate, chloride, sulfate, and nutrient cations using standard methods [Schlesinger and Pilmanis, 1998]. Samples will be available for isotopic analysis (section 4.2.1). Sample texture will also be analyzed.

Soil Moisture Measurement

Soil moisture will be measured *in situ* using portable hand-held soil moisture probes (Campbell Hydrosense). We will focus our measurements at the depths that represent the vegetation root layer and therefore sample soil moisture at three depths (5 cm, 10 cm, 20 cm). Hand held soil moisture probes are calibrated for sandy soils and therefore produce highly reliable results in the Kalahari Sand that underlie our field sites. Soil moisture decreases during the dry down period after rainfall. Because the geostatistical analysis of soil moisture represents a “snapshot” of this dry down, we will carry out the soil moisture measurements intended for geostatistical analysis as fast as possible, preferably in one morning or afternoon of sampling. We are also interested in the changes in soil moisture through time after precipitation events. Therefore, at the Maun site we will attempt to measure soil moisture repeatedly after a precipitation event at the same locations. If such an event does not happen during the focused wet-season field campaign, we will make arrangements with local personnel at the Harry Oppenheimer Okavango Research Center (University of Botswana) and/or from the University of Witwatersrand – who can monitor local precipitation – to undertake these measurements. This longer-term site will complement the TDR record we initiated during the SAFARI2000 experiment at two core sites at Mongu, Zambia and Skukuza, South Africa (Pinheiro *et al.*, 2001).

Soil Temperature Measurement

To sample the radiometric temperature of the surface we will use hand-held thermal infrared thermometers (Everest and Teletemp). Measurements will be taken over a grid and along the geostatistical sampling transect at each site to determine the spatial variability of this parameter. These measurements will overlap, spatially and temporally, with the soil moisture measurements described above. In addition, a set of infra-red thermocouple transducers (IRTS-P from Apogee), will be deployed at Maun to track the variation of the surface radiometric temperature with soil moisture availability. This site will complement existing radiometric temperature monitoring sites that we have operated at Mongu and Skukuza since Year 2000. These data is expected to aid the scaling process to resolutions commensurable with the remote sensing monitoring.

Sampling Strategy for Geostatistical Analysis

Because the scale of variability varies with water availability along the Kalahari Transect [Caylor *et al.*, in review], the sampling strategy (length of transect and sample density) at each must differ. Total transect length at each site will be set to 2.5 times the patch size (cf. Figure 2, Section 2). This will allow calculation of semivariance and covariance at lags up to 1.25 times the patch size for each site. One hundred equally-spaced sampling locations will be established on this transect. In order to characterize spatial variability at finer scales, we will employ a

nested sampling strategy with high sampling density in portions of the transects. These will comprise 100 additional sampling locations along the transects. Soil moisture measurements and soil nutrient samples will be collected at each location

Detailed Pedological Analysis at each Site

Finally, in order to better understand soil formation processes at each site and differences in soils between each site, soil pits will be dug and characterized. Soil pits will be located to represent major cover types at each site (*e.g.* under tree canopy, under grass canopy, bare soil). The time- and labor-intensive nature of this sort of detailed pedological analysis will limit the number of pits to only a few at each site. Samples from each subsurface horizon will be collected for nutrient and texture analysis. These results will be highly valuable in developing and parameterizing coupled soil moisture – soil nutrient models.

Characterization of vegetation structure

One representative plot will be sampled at each site. Tree basal area and height will be measured in circular quadrats (whose radius varied from 4 to 8 m, depending on the density of the vegetation), distributed in a grid over an area of 250 x 300 m. Tree cover in the same area will be estimated by measuring the length with crown overhead on a line transect 1200 m long, and shrub cover using 300 m of line intercept. Herbaceous species composition will be determined using the dry-weight-rank technique. Measurements of total and tree leaf area indices, leaf photosynthesis and spectral properties will also be made [Privette *et al.*, 2002]. At each site, detailed stem maps will be constructed of the woody vegetation within a smaller intensive sample (1 ha) nested within the landscape-scale sample. All stems greater than 1.5 m in height will be included, and observations of each stem will record species, x-y position, basal area (above basal swelling), heights of top and bottom of crown and canopy spread in two perpendicular dimensions. Heights will be measured either with a range finder or clinometer at 5m or 10m from the base of the stem. Stem density and total basal area will be calculated from the stem map data. Sapling density, litter mass, percent bare soil, and grass biomass will be sampled using a 0.25 m² quadrat with a minimum of 30 samples at each site. Care will be taken to distinguish the spatial variation of sampling density, grass biomass, percent bare soil and litter as between canopies and under canopies of large trees at each site.

4.1.2 Remote Sensing Analysis

In order to connect the proposed field analyses with modeling results and to provide additional estimates of spatial variability of soil moisture and temperature, we will conduct remote sensing-based analyses of these variables at each of our sites.

Data acquisition

We will primarily use data from the EOS Terra and Aqua platforms in the remote sensing portion of the proposed research. MODIS and Global Mode MISR are available from the distributed archives as reflectance products (*e.g.* MOD09A1 and MIL2ASLS). Currently, 200 km x 200 km MODIS land product subsets, Landsat ETM+ scenes, and ASTER scenes for 15 southern Africa sites are available from the LP DAAC. We will request the data from each of these sensors that coincides with the field campaign at each site. We will further request MISR Local Mode (with 275 m resolution compared to 1.1 km for Global Mode) data for each of the sites, coincident with our field campaigns. In addition, we will request composite data from MODIS on a monthly basis from the earliest data available for these instruments (early 2000) to

the end of the proposed research period, as these data become available. Remote sensing data analysis is described below (this section and Sections 4.3.2 & 4.3.3).

We will purchase new IKONOS and Landsat 7 ETM+ data for each of the sites, as close as possible to the time of our field campaigns. These data will be used to supplement relatively coarse MODIS and MISR data and provide high-resolution views of the field sites.

All remote sensing data acquired in the course of the proposed research will complement the existing archive of remote sensing data already acquired during the SAFARI 2000 and our previous IDS effort.

Soil moisture and temperature

A promising source of high-resolution soil moisture fields is the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) onboard Aqua. Unfortunately, soil moisture is not an official product and although it can be inferred from the brightness temperature measurements, the product is not validated or publicly available. If these data become available during the timeframe of this study, we will test their applicability.

Soil moisture retrieved through microwave brightness temperature inversions only describes the surface soil moisture. However, in this study, we must determine the soil moisture availability at the root zone, i.e. at deeper layers. Land surface temperature (LST) variability within a diurnal cycle is closely related with the soil moisture availability at the root zone for vegetated surfaces, and the surface soil moisture for bare surfaces (Jackson et al., 1981). Therefore, we will attempt to understand the relationship between LST and soil moisture at multiple scales so that LST can be used as a proxy for soil moisture, and ultimately for water stress of vegetation. To accomplish this, we will tune the parameterization relating root-depth soil moisture and LST for the model presented in Section 4.2.2 using field data collected at our study sites. We will then scale the point level LST to coarser scales using LST measurements from ASTER (90 m) and AVHRR/MODIS (~1-8 km).

In addition to develop a long-term data record of soil moisture, we will apply the resulting LST-soil moisture relationship to the 20+ year record of AVHRR LST, using bias corrections developed by Pinheiro *et al.*, [2002]. We propose to assess the need for such correction in this study.

Vegetation Analyses

In the proposed research, we will use several independent measures of vegetation cover (Table 1). The Normalized Difference Vegetation Index (NDVI) will be used to assess vegetation greenness. Because NDVI is not sensitive to nonphotosynthetic vegetation (NPV: woody and senescent vegetation), we will use spectral mixture analysis (SMA) to assess the fractional cover of green vegetation (GV), NPV, and bare soil. SMA yields a more complete picture of the land surface than NDVI by allowing quantification of total vegetation cover, as well as the fraction of vegetation cover that is not green (e.g. nonphotosynthetic). Thus, SMA provides a means to separate trees from grasses and to quantify changes in plant phenology. Field spectra collected during the field campaign will also allow estimation of fractional cover of trees, grasses, and bare soil in the selected field areas and further afield, during the field campaign.

A modification of basic SMA will be used to assess the fractional cover of ground components (*i.e.* GV, NPV, and bare ground or trees, grass, and bare ground) [Adams *et al.*, 1993; Gillespie *et al.*, 1990; Settle and Drake, 1993; Shimabukuro and Smith, 1991; Smith *et al.*, 1990]. Multiple endmember spectral mixture analysis is simply a linear spectral mixture analysis

(SMA) technique in which endmembers are allowed to vary between pixels (MESMA: *Roberts et al.*, 1998). MESMA requires a library of soil and vegetation spectral endmembers, which will be compiled from field spectra collected during the focused field campaign at each site. Consistency of soils and vegetation along the KT will enable use of spectral libraries compiled at our field sites to be used for regional MESMA modeling of vegetation cover. Because cellulose and lignin absorptions of NPV are evident in the short-wave infrared, attempts to separate GV from NPV require instruments with spectral bands in this region. Therefore, MESMA will be run at each site on both MODIS MOD43 nadir-view normalized reflectances and Landsat ETM+ data for the field sites. Derived fractional cover will be validated using both cover information derived from detailed data on vegetation structure obtained during the field campaign (Section 4.1.1) and tree cover estimated from high-resolution IKONOS imagery [*Caylor et al.*, in review; *Caylor*, 1999]. Regional-scale fractional cover data (500 m resolution from MODIS) will be obtained from Hansen et al. (2003b).

Spatial Analysis

Our remote sensing analysis strategy is designed to provide NDVI and fractional cover information at multiple scales and multiple times (Table 1). Data on vegetation cover at multiple scales will allow us to understand the impacts of fine-scale variability on coarse-scale orbital land surface retrievals, and to define inherent scales of organization along the KT. Identification of inherent scales of organization within savanna ecosystems allows inference of landscape processes. Understanding how scales of organization are expressed in remote sensing provides insight into the applicability of these data to sense the land surface at relevant scales, and to infer land surface changes.

Following *Caylor et al.* [in review], we will examine the variability of NDVI and fractional cover at different levels of spatial aggregation. We will analyze the relationships between variability and scale of aggregation for NDVI derived from IKONOS, ETM+, and MODIS. Our new analyses of fractional cover of GV, NPV, and bare ground and trees, grasses, and bare ground will allow us to perform similar analyses on these results from ETM+ and MODIS. Unfortunately, fine-resolution remote sensing (~1 – 5 m) data with spectral response in the short-wave infrared, which would allow fractional cover estimates at resolution greater than Landsat ETM+, is not available operationally.

We will also use geostatistical analysis to understand the scales of spatial variability of NDVI and fractional cover at our field sites. For each data product (Table 1) we will calculate and model omnidirectional and unidirectional (from 0° to 360° at 15° intervals) variograms. These results will be useful for direct comparisons with geostatistical analyses of biomass, soil nutrients, and soil moisture from the field data. In addition, they will 1) provide insight about the isotropic/anisotropic nature of vegetation distribution and 2) provide insight into the scale of spatial autocorrelation and organization at sites along the soil moisture transect in southern African Savannas.

Temporal Analysis

Analysis by *Scanlon et al.* [2002] and *Peters et al.*, [1997] has indicated that in savanna ecosystems, spatial variability is reflected in observable interseasonal temporal variability. In savanna ecosystems, this effect is due to the different phenological phases and schedules of different lifeforms (*e.g.* trees and grasses). We will use multitemporal (once-monthly) analysis of MODIS-derived NDVI and fractional vegetation cover (from MESMA) to understand how vegetation cover and phenology changes along the Kalahari Transect. Multitemporal NDVI

analysis will be supplemented by the NASA Pathfinder NDVI dataset. Changes in temporal patterns will be related to different proportions of trees, grasses, and bare soil and thus differences in vegetation structure.

Regional Remote Sensing

Our analyses will concentrate primarily on the three field sites that are the focus of the proposed field campaign. At these sites, we will validate remote sensing products and compare insights from spatial and temporal analysis of remote sensing data with *in situ* data and model results. Detailed field, modeling, and remote sensing at these sites thus will be integrated to understand scales and patterns dominant along the Kalahari Transect. In order to understand how the patterns and processes illuminated by this integrated analysis are distributed across the region, we will extend spatial and temporal NDVI and MESMA analysis of MODIS and NASA Pathfinder data for the entire southern African savanna system.

Fire extent and pattern

We will make use of the MODIS daily 1km Active Fire Products [Justice *et al.* 2002] and the regional southern Africa MODIS burned area product that maps the 500m location and approximate day of burning [Roy *et al.* 2002]. The MODIS burned area product has been validated using independent reference data collected by a substantive GOC Southern Africa Fire Network (SAFNet) validation effort [Roy *et al.*, forthcoming]. We will also use a monthly 1km burned area map of southern Africa produced for 2000 using a decision tree classifier applied to SPOT VEGETATION data [Silva *et al.* forthcoming] and a 1km global 2000 burned area map, GLOBSCAR, produced from ATSR data for the European Space Agency. Evidently there are substantial differences between these data sets that we anticipate will have substantive impacts, although these differences may be mitigated depending on factors such as the fuel load, type and condition. The significance of this finding is that regional emission estimates provided by studies, such as Hely *et al.* [2003b], that used the ESA fire products need to be revisited and the estimates recalculated utilizing the validated MODIS fire products.

The distribution of fire size observed from remote sensing demonstrates robust scaling behavior across a wide range of fire scales in southern Africa. The slopes of the particular scaling relationships observed are dependent on the fuel load, but can also be organized according to tree cover and climate. It can be shown that the population of fuel load values contributing to individual fires is the same for all sizes of fires, so that the total emissions of carbonaceous compounds contributed at each fire scale is a simple linear relationship to total burned area at that fire scale. The absence of bias in burned fuel load distribution across the range of fire scales allows for simple approximations of total emissions from fire at any scale, up to regional estimates from total burned area over the entire subcontinent. Quantifiable differences between the distribution of fuel load values over all of southern Africa, and the distribution of fuel load values actually consumed in fires indicates that it may be possible to generate estimates of emissions over southern Africa from only total burned area and a description of the distribution of potential emissions, which can be derived from the distribution of fuel load. These findings reinforce the need for better quantification of both fuel load and burned area over southern Africa, and should make the rapid assessment of emissions over large areas much more feasible.

4.2 Process Analysis - Coupling spatial pattern to temporal dynamics

In order to answer Questions 2a and 2b of the proposed research concerning processes that govern vegetation cover and structure, soil nutrients and soil moisture, we will conduct biogeochemical and modeling research. This portion of the research will be linked to and use insights/data from *in situ* and remote sensing analyses (section 4.1).

4.2.1 Stable isotope biogeochemistry

Stable isotope compositions can serve as signatures of both the origin of the organic materials, and the specific factors influencing that origin, such as temperature, nutrient levels and productivity. Nitrogen and carbon stable isotope ratios of soils and plants of southern Africa have been correlated with mean annual precipitation, land use change, and frequency of fire [Aranibar *et al.* 2002; 2003]. Several patterns of N cycling have been used to explain the observed isotopic signatures, including temporal and spatial variations of N₂ fixation, gaseous losses, mineralization rates, and tree-grass dynamics. Identification of the chief processes in the field is proposed in this extension. In our previous study, a donor-controlled compartment model that tracked the changes on isotopic composition of soils and plants, was developed to refine hypotheses of N dynamics that could explain the isotopic patterns observed in the Kalahari. Simple patterns of increased ammonia volatilization with aridity and overgrazing, N₂ fixation in humid sites, or export of plant material in overgrazed areas could simulate the overall ¹⁵N enrichment or depletion along rainfall. Cycles of wet and dry years, with corresponding cycles of N mineralization, N₂ fixation, ammonia volatilization and N sources to plants, could simulate the differences on isotopic signatures during wet and dry years. The model also pointed to different chemical forms or timing of N absorbed by trees and grasses. Our previous work indicated the dynamic nature of the system, pointing to high temporal and spatial variability of N cycling processes driven by precipitation, including soil microbial processes and N utilization by trees and grasses. This high and unpredictable variability appears to play an important role on maintaining the co-existence of multiple life forms in savanna ecosystems.

The high complexity of mechanisms involved in the cycle of nitrogen in soils, plants and atmosphere, including high temporal and spatial variability at different scales (hours to decades; meters to subcontinents) makes the interpretation of isotopic signatures difficult [Aranibar *et al.*, 2002; 2003; Aranibar *et al.*, submitted]. However, the striking patterns of ¹⁵N enrichment with aridity, which holds even at a global scale [Handley *et al.*, 1999], indicates the existence of overarching mechanisms, acting beyond that complexity. It is unlikely that all of the different N cycling processes vary independently and are not related to each other in different regions of the world, producing the same pattern of ¹⁵N enrichment with aridity. It is likely that only a few processes, which are modified by climate, can explain most of the variation on isotopic signatures, smoothing the complex web of reactions, isotopic fractionations and temporal variability occurring in ecosystems. Analysis of the N cycling along precipitation gradients over similar soil substrates will provide better insights about N cycling on southern African ecosystems.

4.2.2 Modeling

Our team has developed a set of tools for the process-based modeling of coupled vegetation, nutrient, and soil moisture dynamics at the patch scale. A nitrogen isotope model will be used to analyze the nitrogen cycle and to provide information on nutrient fates and flux rates. The soil moisture model will be driven by precipitation inputs (either from data record or from stochastic simulation). Soil moisture dynamics will force a nitrogen and carbon model which is coupled to a vegetation productivity model through the processes of nitrogen uptake/assimilation

and litterfall/decomposition. The vegetation model provides estimates of fuel load and pyrogenic emissions. The effect fires on the N cycle are modeled as a loss of a portion of standing biomass and soil organic matter and an increase in the rates of mineralization and nitrification [Aranibar, 2002].

Biogeochemical modeling derived from isotopic data

Hobbie et al. [1999] developed the NIFTE (Nitrogen Isotope Fluxes in Terrestrial Ecosystems) model, which simulates measured values of $\delta^{15}\text{N}$ of plants and soils by changing isotopic fractionations. The preliminary model, resulting from our last IDS work, described by *Aranibar* [2002] (NIFTE-Kalahari) was similar in structure to the NIFTE model because it simulated the flux of ^{15}N and ^{14}N in separate submodels to fit the measured $\delta^{15}\text{N}$. The objective of the present research will be to advance the preliminary "savanna-model" by modifying the main processes of N cycling that are thought to explain the ^{15}N abundances, to know which of the postulated hypotheses are reasonable and test them in the field. We will validate our work through intensive analysis at the patch level, and pick a limited number of processes to be evaluated, and extend them across the region for comparison.

Linked soil moisture/nutrient model

In water-limited ecosystems soil water content affects nitrogen cycling, due to the direct or indirect dependence of the processes of decomposition, mineralization, nitrification, denitrification, root uptake, and leaching on soil moisture conditions. Thus, through the soil water balance, the hydrological cycle exerts a significant control on terrestrial ecosystems, in particular in arid and semiarid environments, where the rates of evapotranspiration, nutrient mineralization and nutrient uptake are strongly limited by soil water availability. In order to analyze the role of this hydrologic control on the soil carbon and nitrogen dynamics, we have developed a model with three pools for the dynamics of the soil organic matter (both for carbon and nitrogen components), and two pools for the inorganic nitrogen in the soil (nitrate and ammonium), for a total of eight state variables. The fluxes between these pools (e.g., decomposition, nitrification, uptake, leaching, etc.) have been modeled as dependent on soil moisture conditions [Porporato *et al.*, 2003; D'Odorico *et al.*, 2003]. Through a stochastic mechanistic model of the soil water balance at the daily time scale [Rodriguez-Iturbe *et al.*, 1999] we have related hydrologic processes (including the intermittent stochastic character of precipitation) to soil nitrogen and carbon cycling, and expressed this dependence as a function of the characteristics of climate, soil, and vegetation. The use of daily resolution is crucial in arid/semiarid environments due to the relatively rapid soil dry-down after rainfall occurrences [Noy-Meir, 1973]. This framework will allow for the testing of the hypothesis that savannas along the KT switch from being water limited (more arid sites) to N-limited (moister sites), due to the effect of leaching on soil nitrogen availability. Moreover, this framework will be used to predict the effect of climate variability (modeled through changes in the rainfall and evapotranspiration parameters) on terrestrial plant communities and ecosystems.

The soil moisture model is based on a soil water balance for the surface layer (root zone). This model requires daily rainfall and evapotranspiration, rooting depth, and soil properties. We already have access to multidecadal records of daily precipitation and air temperature. Soil properties will be provided by soil sample analyses (Section 4.1.1). The soil moisture model will be tested against field measurements (Section 4.1.1). Land surface temperature will be both directly measured in the field and determined through remote sensing products (Section 4.1.2). The soil carbon and nitrogen model is based on the mass balance of each of the variables. It

requires information on the rates of nitrification, denitrification, uptake, leaching, etc., as well as their dependence on soil water content. These rates will be determined at each site both for grass and tree plots using stable isotope analysis (Section 4.2.1), while the field and lab work outlined in Section 4.1.1 will determine the size of the different pools.

Vegetation productivity model

A regional fuel load model has been developed for the Southern African Region utilizing the regional primary production model developed as part of a related project focusing on the Kalahari Transect [Hély *et al.*, in review]. The model has been used to simulate fuel load over southern Africa for 1999-2000, and validated against independent field estimates of fuel load [Hély *et al.*, 2003b]. In addition, the model has been used to develop regional emission estimates based on remotely-sensed observations of burned area [Hély *et al.*, 2003a]. A structurally explicit patch model is nested within the regional productivity model. The patch model simulates CO₂ uptake by photosynthesis, along with respiration and evapotranspiration on a daily basis. It requires daily rainfall, mean temperature, relative humidity and wind speed as data input. The model has four components: leaf physiology, canopy processes, soil water balance, and leaf phenology. The leaf physiology component includes models for C₃ and C₄ photosynthesis, stomatal conductance and CO₂ and water diffusion through the stomata. Stomatal conductance is calculated with the model of Ball *et al.* [1987] modified to include a response to soil moisture as in Woodward *et al.* [1995]. Nitrogen uptake rate and leaf-level allocation are based on light availability in each canopy layer, and the soil nitrogen content, which can vary over the year of simulation. In this manner, the model can be directly linked to observations and models of nutrient and water dynamics. Leaf level irradiance throughout the canopy is based on a Beer's law attenuation of incident above canopy irradiance [Shugart, 1984]. There is a corresponding vertical root profile for both trees and grass, which have distinct distributions of root mass through a three-layer soil profile. The soil water balance for each soil layer is a simple sum of inputs from rainfall (or drainage from the overlying layer), outputs from plant transpiration (dependent on root mass and available water) and soil evaporation from the top layer only. Because the exact nature of the mechanisms promoting leaf flush and leaf fall in the savannas of southern Africa is unknown, leaf phenology is handled using two distinct modeling approaches. The first approach is deterministic in nature and prescribes leaf flush and leaf fall at the onset and end of the wet season respectively. The second method allows the timing and, to a lesser extent, the rate of leaf flush and leaf fall to depend primarily on the intensity and persistence of available soil moisture conditions.

4.3 Prediction – Synthesizing pattern and process

We are very interested in predicting changes in southern African savanna ecosystems, as well as identifying the effect of expected changes on global biogeochemical cycling (Question 3a). In addition, in order to determine the effectiveness of current and future EOS sensors in sensing variation and change in vegetation structure in southern African savannas, we will investigate forward and inverse modeling of BRDF of canopy structure (Question 3b).

4.3.1 Future Scenarios

GCMs have shown that the projected warming over southern Africa in response to doubled atmospheric CO₂ levels is on the order of 2-3 °C [Hudson, 1997]. Rainfall estimates for such scenarios contain a large degree of uncertainty [Joubert and Tyson, 1996; Joubert and Hewitson, 1997], however it has been suggested that variability in the climate may change, instead of the mean climate, leading to increased intensity and variability in daily rainfall totals

[Joubert and Hewitson, 1997]. Predictions from global-scale models will be used to drive the soil water/nutrient and vegetation productivity models discussed above in order to characterize the implications of changing climate on the vegetation, nutrient, and soil moisture regimes of southern African savanna ecosystems. These results will allow us to predict the consequences of global climate change on fire emissions from and carbon sequestration in savanna ecosystems.

4.3.2 Prediction of fine-scale distribution from large scale (inverse modeling)

Remote multiscale measurement of canopy structure is an evolving science. *Hansen et al.* [2002a, b] developed a regression tree approach to estimate percent canopy cover from both 1 km AVHRR and 500 m MODIS data. However this approach only depicts canopy material above 5 m height, which is considerably higher than much of the woody vegetation in semi-arid southern Africa. Canopy height data is more difficult to obtain, though Pinheiro et al. (2002) recently developed a height map for the continent by merging Hansen's [2002a, b] land cover map with ecosystem height data in the literature. Some new options, such as the Geoscience LASER Altimeter System (GLAS) onboard NASA's IceSAT (launched January 2003), could be used if their vegetation products become operational.

We will test an alternative approach based on reflectance anisotropy (bidirectional reflectance, BRDF) signals. Abundant research has shown that reflectance signatures vary with canopy structure (e.g., *Myneni et al.*, 1997; *Asner et al.*, 2000). Through inversion of physically-based or kernel-driven BRDF models, such as those used operationally in the MODIS and MISR processing systems, parameters may be retrieved which represent or can be correlated with canopy structural information. Alternatively, empirical reflectance relationships (e.g., ratios of reflectance at one angle to another angle) from these models may be correlated with structure. Our baseline approach will be to assess the experimental parameters within the MODIS MOD43 (BRDF) product thought to be correlated with structure [*Schaaf et al.*, 2002]. We will regress these parameters against structural data we collected over the past five years at more than 15 sites in the region (e.g., *Caylor et al.*, 2002; *Privette et al.*, 2002; 2003). Our backup approaches will be to test the BRDF model parameters derived from MISR data processing (e.g., *Gobron et al.*, 2002), or conduct independent BRDF model inversions (e.g., *Li and Strahler*, 1992; *Chopping et al.*, 2002) by constraining the models with available ancillary

4.3.3 Prediction of coarse-scale distribution from fine-scale (forward modeling)

The great potential for remotely detecting ecosystem responses to climate change was recently demonstrated when Myneni et al. (1997) used AVHRR NDVI to show a lengthening of the northern hemisphere growing season. Because canopy structural changes can be expressed in reflectance anisotropy (see above), we will test the potential for detecting savanna changes by parameterizing a physically-based BRDF model (e.g., Myneni et al., 1997) with canopy structure changes predicted by our productivity model. Specifically, we will assess the detectability (signal-to-noise) of the predicted reflectance changes as would be observed by wide field-of-view sensors (e.g., MODIS), multi-angle sensors (e.g., MISR) and fine-resolution sensors (e.g., Landsat-class). If successful, such methods could allow detection of large-scale savanna changes to climate that might be indistinguishable in site-level field measurements (i.e., within the expected site variability).

5. Benefit to Education, development of human resources, and dissemination of results

The interdisciplinary nature of this proposal makes it especially fruitful for the mentoring of graduate students in the Environmental Science Program at University of Virginia. The project

will fund four postdoctoral research associates and two to four graduate students at University of Virginia who will develop part of the proposed research for their dissertation. Students and postdocs will be included in the writing of articles for peer-reviewed journals. The submission and publication of these articles, as well as the attendance at conferences on matters relevant to this project will represent the main way to disseminate the results and receive a feedback from other scientists

5.1 Outreach and the SAVANA consortium

One of the goals of this project will be to enhance the capacity *of Africa* to solve the challenging health and environmental problems *in Africa*. We see our initiative as a way of utilizing regional expertise, while expanding educational opportunities, and introducing global perspectives to the students in all locations. Thus, the full and equal participation of the institutions in southern Africa will be crucial to the development and implementation of this endeavour. Having said this, it should be noted that this project is built on a previously established foundation of cooperation between participating institutions. In this case, the University of Virginia (UVa) had collaborated with the University of the Witwatersrand (Wits) and the University of Eduardo Mondlane (UEM) to conduct environmental research within the region for nearly 25 years. This collaboration included joint field studies and laboratory work between faculty and students, the integration of technology into our research (e.g. the acquisition and use of satellite imagery and the development of computer based environmental models), and academic exchanges between faculty and staff. Moreover, UVa, Wits, and UEM (and the University of Botswana, the Harry Oppenheimer Okavango Research Centre, and the University of Venda, South Africa) have formalized this commitment for research and educational collaboration through a series of Memoranda of Agreement signed throughout the course of the previous 5 years.

Collaboration among the participating universities was extended to the global classroom via teleducation for the first time during the Fall 2001 semester with a live, real-time, class: ‘*Seminar on the Ecology of African Savannas*’ course taught jointly by UEM, UVa and Wits. These offerings were expanded in the Spring and Summer 2002 sessions and the present academic year, 2002-03, with classes on ‘Ecological Issues in Global Change’, taught at UVa and broadcast to students at Wits, ‘People, Culture and Environment of South Africa’ taught in South Africa to a group of Virginia students, and ‘Modeling of African Human Environmental Interactions’ taught jointly by UVa, the University of Venda and the University of Botswana, using the teleducation technology we piloted in August 2001.

We intend to continue this educational bridge with southern Africa through the development of a joint M.A. degree that will be able to be fulfilled by taking courses at the different institutions affiliated with the SAVANA consortium. These courses include more technical graduate level classes in "Advanced Remote Sensing" (Okin and Swap), "Dryland Eco-Hydrology" (Shugart and D’Odorico) and "Environmental Geochemistry" (Macko) being offered simultaneously in the U.S. and Africa through teleducation technologies. We will also offer an advanced level seminar on the KT. This seminar, will be driven by results and insights from the proposed research: PIs, Co-PIs, Postocs, graduate students, and other colleagues will present a synthesis of the research activities developed on the KT.

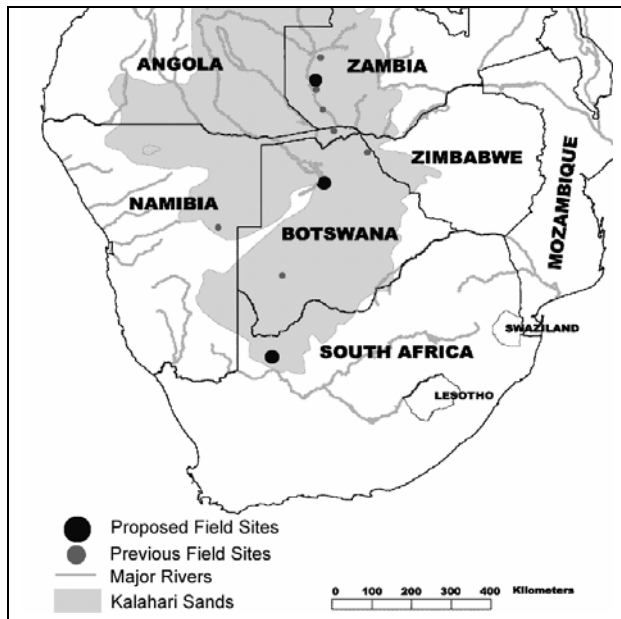


Figure 1 - Distribution of Kalahari sands and major rivers in southern Africa. Locations of all existing Kalahari transect sites are provided. The three KT sites to be used in this study indicated.

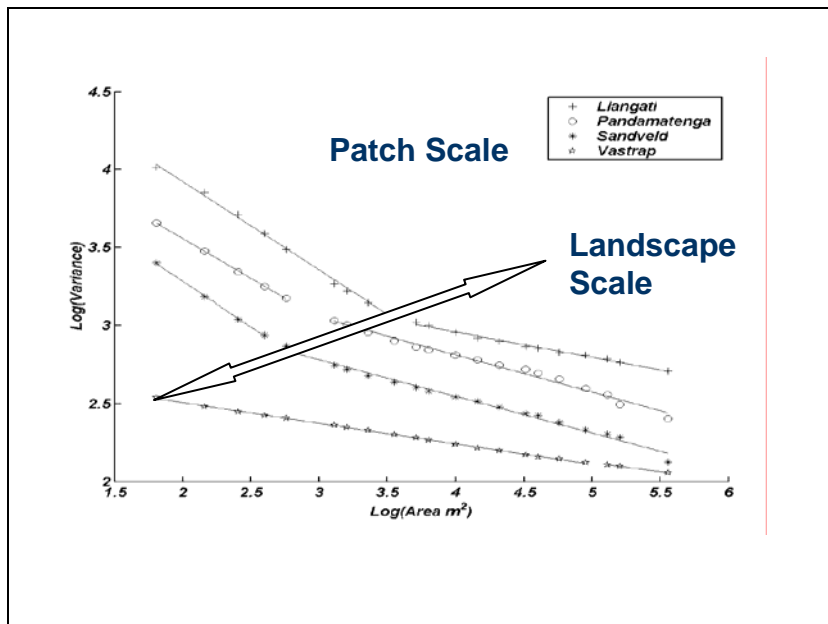


Figure 2 - Realization of the multi-scale nature of savanna ecosystems, depicting the variance of the NDVI field as a function of the area over which the field is averaged. The threshold scales between the distinct patch and landscape regimes are: (3600 m²) Liangati; (576 m²) Pandamatenga; and (400 m²) Sandveld. No threshold scale is observed for the southernmost site, Vastrap. It is likely that the minimum scale of 16 m² is insufficient to resolve the individual-patch scale pattern at the southernmost site, where vegetation is sparse and consists of small shrubs and isolated grass clumps.

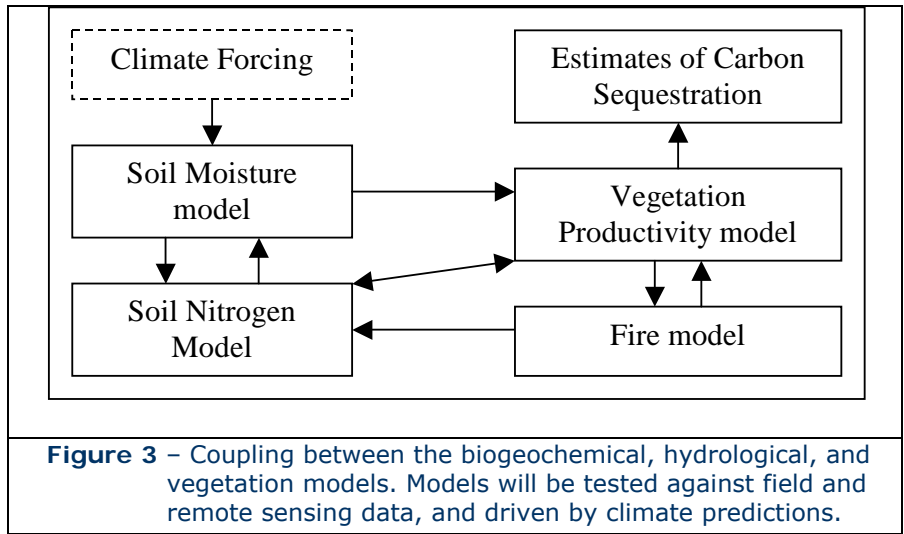


Table 1: Planned analysis of IKONOS, Landsat 7 ETM+, and EOS MODIS 8-day reflectance data.

	IKONOS color infrared	ETM+	MODIS 8-day composite
Resolution	4 m	30 m	500 m
NDVI (one-time)	✓	✓	✓
MESMA (one-time)		✓	✓
NDVI (multitemporal)			✓
MESMA (multitemporal)			✓

6. Management Plan and Schedule

The research team is composed of:

- Hank Shugart, University of Virginia, Principal Investigator, has responsibility for overall project oversight. In particular, he will work on the regional-scale modeling and co-teach a course in “Dryland Ecohydrology”.
- Stephen Macko, Co-Investigator, will coordinate the isotope biogeochemistry portion of the study. He is the manager of the isotope laboratory at the University of Virginia. He will supervise a postdoc who will carry out the field portion of the isotope work, accomplish the isotope analyses and advance the Kalahari -NIFTE model.
- Robert Swap, Co-Investigator, will coordinate the field activity/logistics, contribute to the acquisition and analysis of remote sensing products. Swap will also supervise the prediction runs of the coupled nutrient-cycle/vegetation-productivity model.
- Gregory Okin, Co-Investigator, will oversee the remote sensing analysis (large scale analysis of photosynthetic and non-photosynthetic vegetation) and will supervise a graduate student who will carry out remote sensing analysis. Okin will also teach a course in “Advanced Remote Sensing”.
- Paolo D’Odorico, Co-Investigator, will work (with K. Caylor) on the scaling analysis of vegetation patterns. He will also work (with Ana Pinheiro) on the modeling of soil moisture and nitrogen cycle. D’Odorico will Co-teach the “Dryland Ecohydrology” course.
- Jeff Privette, Co-Investigator, will contribute to the remote-sensing analysis and to the inverse and forward modeling of BRDF.
- Kelly Caylor, Postdoctoral Research Associate, will study the scaling properties of vegetation and fires. He will participate to the field campaign and make measurements of vegetation structure. Caylor will also apply and test the vegetation productivity model and couple it to the soil biogeochemical model.
- Todd Scanlon, Postdoctoral Research Associate, will be in charge of soil moisture and soil temperature measurements. He will compile and analyze remote sensing products for the multidecadal temporal analysis of savanna ecosystems. Scanlon will also relate large-scale patterns of vegetation to mode-derived soil moisture and nitrogen availability along the transect.
- Ana Pinheiro, Postdoctoral Research Associate, will contribute to the remote-sensing analysis (soil moisture and soil temperature) as well as to the application and testing of soil moisture and nitrogen cycle models.
- Graduate students (Environmental Sciences Program at University of Virginia): Funds to support two graduate students are included in the proposed budget. In the past we have been able to leverage external funds to acquire teaching stipends. These additional internal funds would allow us to have a total of three to four graduate students involved with the program.
- Prof. Harold Annegarn, Collaborator, is at the Atmosphere and Energy Research Group, University of the Witwatersrand, Johannesburg, South Africa. He will provide technical and logistic support during the field campaign. The University of the Witwatersrand is a member of the consortium SAVANA (South Africa-Virginia Networks and Associations), a regional consortium for environmental science research and education and policy.

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8. Facilities and Equipment

Computers

The Investigators at University of Virginia and Goddard Space Flight Center have computer labs equipped with high-end workstations and the required software. The University has site licenses for software programs that would be used for this research, including Matlab, Arcview, and IDL. Funds for a large RAID array to house remote sensing data have been included in the proposed budget.

Geochemical Laboratories

Non-isotopic analyses: Okin has all required laboratory facilities for the preparation and storage of samples from the field. He owns or has access to all equipment required for standard biogeochemical/nutrient analysis of soil samples, including a total organic carbon analyzer, an ion chromatograph, and an atomic absorption spectrometer. Funds for required upgrades of the ion chromatograph are included in the proposed budget.

Isotopic analyses: Geochemistry Laboratories in the Department of Environmental Sciences at the University of Virginia house a VG PRISM stable isotope ratio mass spectrometer (MS) capable of light isotope analysis of gases prepared offline for ¹³C, ¹⁵N, ¹⁸O and ³⁴S. Also coupled to the PRISM are an automatic twenty port manifold for the analysis of prepared gas samples and an automated carbonate system. In addition, the facilities include a Fisons Optima stable isotope ratio mass spectrometer to which is coupled a CHNOS (Carlo-Erba) elemental analyzer making the instrument capable of ¹³C, ¹⁵N, ¹⁸O, D and ³⁴S analyses on organic materials and waters. This instrument is a dedicated mass spectrometer for continuous flow measurements. Newly installed is a Micromass ISOPRIME continuous flow stable isotope instrument, which is dedicated to

GC/C/IRMS applications. A HP 5890 GC has been combined to a combustion interface for GC/C/IRMS capability of both ^{13}C and ^{15}N of individual molecular components. Other instrumentation included in these facilities are a HP 5890 GC coupled to a HP 5971A MSD which is capable of both EI and CI analyses. Also present are two automated sampler step gradient amino acid analyzers capable of ion exchange and reverse phase separations. The isotope laboratory also has vacuum lines for the off line isolation of gases for the analysis of oxygen isotopes in water, carbon and oxygen isotopes in shell and nitrogen and carbon isotopes in organic materials. The laboratory also has a LABCONCO Rapidstill II for steam distillation of ammonium and nitrate from water samples for nitrogen isotope analysis and a Thermolyne 30400 programmable furnace for stepped pyrolysis of samples.

Field Spectrometer

Okin owns an Analytical Spectral Devices, Inc. (ASD) Full Range (FR) field spectroradiometer that will be used to collect field spectra of vegetation and soils during the focused field campaign.

“Support facilities” along the KT

The University of Virginia has a long-standing collaboration with University of Botswana and/or from the University of Witswatersrand. The field campaign will be coordinated through these universities and during the field campaign the scientists funded by this project will be housed at the Okavango Research Center (University of Botswana) and at the University of Witswatersrand.