Remote Sensing and Modeling of Savannas: The State of the *Dis*-Union

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Abstract – Tree-grass systems occupy nearly a quarter of the terrestrial surface (27 million km^2). They face an uncertain future given pressures from land use change and climate change. Serious systems analysis, modeling, scenario development and ecosystems futures assessment for savannas is needed to avoid past mistakes in land management. Integration of measurement from field and remote sensing with multi-scale modeling is required to realize this. This paper summarizes the state of knowledge, key issues and capacity for savanna systems modeling using remote sensing. The authors contributed to a NASA workshop on remote sensing and modeling savannas.

Keywords: savanna, remote sensing, structure, grass, tree, model, scale, pattern

1. INTRODUCTION

Global savannas are spatially and temporally complex systems in which woody vegetation (trees, shrubs) and herbaceous vegetation (grasses, forbs) both contribute significantly to system level functions such as primary production, carbon, water and nutrient cycling. Savanna regions are also subject to directional changes in the balance between woody and herbaceous cover (shrub encroachment) that remain poorly understood and can have large impacts on land surface-atmosphere interactions and system biogeochemistry. The production of the herbaceous layer, which naturally consists largely of grasses, has been co-opted by humans in many regions to form vital centers for grain production.

Remote sensing of mixed tree-grass systems remains challenging because of the separation of the vegetation into two distinct layers (woody species of varying cover, density, height, leaf area and biomass, over a herbaceous layer of varying density, cover and leaf area), and because the woody and herbaceous layers can have distinct and contrasting seasonality, physiology and phenology which vary in both space and time. Further, fire dynamics in savannas require not only assessment of the timing, extent, and intensity of fires, but also their impacts on vegetation structure. Without reliable methods to adequately assess vegetation structure in savannas, parameterization of higher order models of vegetation function (primary production, vegetation dynamics, water and energy balance) is difficult and model results unreliable.

Much of the land surface most likely to be converted to agriculture in the coming decades is currently under savannas. Improved data on vegetation structure and dynamics in the world's savanna regions, combined with improved models of vegetation function, carbon, water and energy exchange, is needed to enhance our ability to deliver accurate system level assessments of current states and functions, and predictions of future changes, into the decision-making and policy domains. In this paper, we provide an overview of the state of savanna science and consider the potential for development of capacity for assessment of savanna ecosystem futures using couple measurement, remote sensing and modeling.

2. BIOGEOGRAPHY OF SAVANNAS

Savannas represent a daunting diversity of vegetation associations and arrangements. They span a wet-dry continuum, a tree density continuum from grassland to forest, and contain both uniform tree-grass mixtures and discontinuous arrangements of grassland and woodland at a variety of spatial scales. Their land cover classification is variable: for example, in Asia, vegetation consisting of fire-adapted trees and native grasses is designated as open forest. The open grasslands in savannas are usually associated with edaphic or hydrological conditions unsuitable for trees – poor soils, cracking clays and seasonal flooding. In simple terms, this tree-grass continuum in savannas spans environments that are good for trees to those that are bad for trees for a variety of reasons. Woody cover is known to vary with mean annual precipitation, but is also involved in a major feedback involving open tree cover, grass biomass as fuel, and fire frequency and intensity. This can create sharp boundaries and patch structures, resistant to change up to a tipping point. Plant traits and characteristics differ among species, particularly in terms of drought and fire adaptation, and species composition shifts between savanna and forest. Some key requirements to understanding biogeography of savannas include the tree cover threshold above which grass cover is sharply reduced, reasons for woody thickening and time without fire required to reach a non flammable system. Since savannas are defined by the presence of grasses with trees, there

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is value in developing remote sensing products that are explicit about grass cover and biomass.

3. SAVANNA LANDSCAPES AND ECOLOGY

From an ecological point of view, savannas are a highly dynamic, complex, coupled human-environment system in a world where globalization and global change are imposing a mix of economic, sociological, and biophysical drivers. It is therefore imperative that some key structural elements of this complex ecosystem – spatial extent, biomass, function and biodiversity – are closely monitored. Since human need and associated land use change are inexorable, savanna landscapes will have to be put to better use.

3.1 Dynamics

Savanna structure (grassy to woody) makes a large difference to carbon stocks and fluxes. Changes in global atmospheric [CO_2] and air temperatures may result in differential responses between C3 trees and C4 grasses due to differences in assimilation rates and NPP at higher [CO_2] and temperatures. Species composition, tree density and the stability or otherwise of woody or grassy systems is affected by the matrix of combinations between high and low plant available nutrients (PAN) and high and low plant available moisture (PAM), and by interactions between mean annual temperature (MAT) and mean annual precipitation (MAP)

Simple models may be one of the better ways to deal with the dynamics of savannas because of scale dependent processes and major state transitions that must be aggregated and scaled-up to regional and global inputs for climate models (Figure 1). A minimalist model might encompass rainfall, trees, grass, demography (recruitment) mediated by disturbance, people, grazers and browsers. Tree clustering/clumping which can be described with remote sensing may in turn define savanna clusters in terms of function. A nested modeling approach with transfer of key aggregates between scales would help land surface coupling, where savannas are not well captured in models. At present, not enough of the diversity in structure and traits is propagated upwards in an appropriate way. A minimal representation of savannas in land-surface-atmosphere models in shown in Figure 2. Within the broad categories given, there is a need to identify plant functional types with particular key physiological traits. Current schemes do not adequately represent the plant functional types, or the characteristic patch structure of savannas.

3.2 Monitoring

The extension of REDD (Reducing Emissions from Deforestation and Degradation) to savanna systems could provide the application context for development of accurate monitoring capacity. For example, a REDD program would need accurate and reproducible aboveground biomass estimates, baseline and change in net forcing and albedo, calculation of emissions from fires, and measures of biodiversity, potential losses, extent of fragmentation, pyro-diversity (variation in burnability and burn properties), and declarations for high biodiversity protection. In order to do this, a range of remote sensing technologies must deliver vegetation floristics, biomass, albedo, burned area, burn intensity, fuel loads, phenology and input to calculation of surface energy and water balances.

3.2 Better Uses for Savanna Landscapes

Since people are such an integral part of savannas, and savannas will be subject to major change, then "smart use" of savanna landscapes is needed. A framework for this could be provided

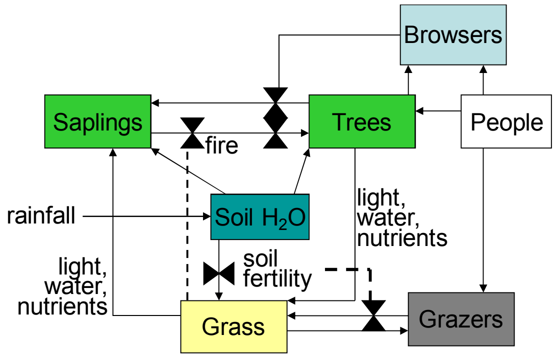

Figure 1. A minimalist model of savanna function.

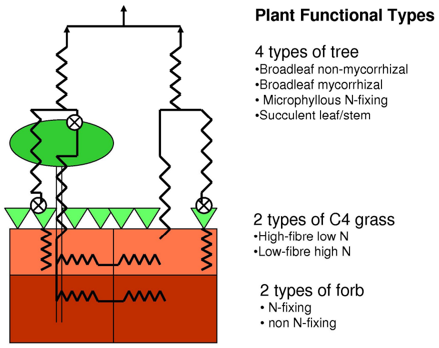

Figure 2. The pathways coupling a savanna land surface to the atmosphere.

Service	Initial	Degraded	Intense	Guided
Forage	2	1	4	2
Fuelwood	4	2	1	4
Craft timber	3	1	0	5
Water	10	4	3	7
Crops	1	3	10	4
Wild fruits	3	1	0	3
Bushmeat	3	1	0	2
Medicinals	3	1	0	2
Tourism	0	0	0	6
C storage	8	2	0	5
Biodiversity	10	3	1	7
Potential	47	19	19	47
Realised	19			

Figure 3. 'Baskets' of ecosystem services delivered by one hypothetical savanna landscape under different development scenarios (values nominally in \$/ha).

by ensuring the flow of ecosystem services in space and time. For this a comprehensive assessment and scenario analysis capability is needed. An example of a service delivery matrix is given in Figure 3. Then the question is "how can we harness measurement, remote sensing and models to deliver the capacity to assess this framework?" Ecosystem services are the outcomes of processes meaning that remote sensing must deliver quantitative measures, or transformable indicators/metrics of process.

4. SAVANNAS AND GLOBAL EARTH OBSERVATION

Global optical earth observing systems have the virtue of high temporal resolution and the limitation of low spatial (> 250 m minimum), and broad multispectral resolution. Scale is tremendously important in savannas with diversity of phenology and patch structures, disturbance occurring via fine scale shifting agriculture, and agricultural conversion. Within the limitations of the global sensors such as AVHRR (Advanced Very High Resolution Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer), and MERIS (Medium Resolution Imaging Spectrometer), what can currently be measured or inferred about savanna systems from these sensors?

The capability can be described under seven broad topics:
Vegetation structure and dynamics. Time series of NDVI and other indices can describe different vegetation response patterns across the world. They provide the basis to explore links to climate and other factors.
Land use and cover change. Changes in the temporal profiles may indicate major land cover and /or land use change. For example, a progressive decline in NDVI amplitude with no change in rainfall may indicate changed vegetation cover and land use.
Carbon Dynamics. By utilizing the full spectral coverage available from MODIS across land and ocean bands, light use efficiency (LUE) models that derive gross primary production (GPP), and indicate carbon sequestration potential may be enhanced by deriving photochemical reflectance index (PRI) which is correlated with LUE. Burned area products map broad fire extent and frequency, and provide templates for assessment of differential severity and recovery.
Biodiversity. Products such as the Vegetation Continuous Fields (VCF) characterize broad regional fractional cover of trees, herbaceous plants and bare ground. Land cover classifications such as MODIS IGBP (biomes) and MERIS GLOBCOVER (vegetation type and structure) describe land cover differently and reflect different spectral ranges.
Trace Gas and Aerosol Fluxes. Land cover maps identify grazed grassland, wetlands, and seasonally flooded areas which are associated with specific emissions; broad scale indices of soil moisture, and fraction of bare soil assist with water/energy balance estimates; and aerosol clouds and dust can be imaged directly in the dry season.
Climate and Coupled Vegetation Modeling. It is clear that potential for surface description from global earth observing systems to improve surface descriptions in climate models has not yet been realized. However, inclusion of vegetation processes derived from remote sensing into Global Climate Models (GCM) can improve predictions of precipitation (Xue et al., 2010).

For savannas, connecting the temporal processes at coarse spatial resolution, with the nested multi-scale spatial properties and interactions in sub-pixel landscapes is a key need. Upscaling to global imaging systems with high temporal frequency requires nested finer scale remote sensing and ground data collected at appropriate resolution. Importantly, long archives of AVHRR and Landsat provide historical context for current conditions.

5. HYPERSPECTRAL REMOTE SENSING

Hyperspectral remote sensing is currently limited by the lack of global coverage and the signal to noise limitations of the two sensors in orbit, Hyperion and CHRIS (Compact High Resolution Imaging Spectrometer). Much of the cutting edge research has been carried out with airborne systems such as AVIRIS (Airborne Visible/InfraRed Imaging Spectrometer), Hymap, and CASI (Compact Airborne Spectrographic Imager). Methods have been developed for retrieval of quantitative surface and canopy properties such as fractional cover, plant functional types canopy nitrogen, canopy water content and defensive chemicals such as polyphenols (Skidmore et al., 2010). Much of the analytical processing of hyperspectral imagery involves reduction of dimensionality of the data to the key sensitive spectral response regions. Methods have evolved from indices based on reflectance, derivative or continuum removed spectra, through spectral unmixing with end-member signatures, to signal processing and multi-index, multi-scale integrations and transforms seeking multispectral surrogates for hyperspectral index combinations (Guerschmann et al., 2009).

There are still major challenges associated with application of hyperspectral imaging to savannas. The variably arranged tree/grass structure results in mixed pixels at current and future spaceborne sensor resolutions requiring spectral unmixing. Many of the vegetation responses and biochemical indicators have species and growth-stage specific responses. This means that floristic identification coupled to key plant traits may be essential for calibration. Hence there is a need for a very substantial spectral library of species by growth stage. Only the proposed HyspIRI (Hyperspectral Infrared Imager) sensor would provide global coverage and then only at approximately monthly frequency. Allowing for cloud, this will present problems for fast changing canopy properties needed for model parameterization and initialization. However, site-based sensors such as ENMAP (Environmental Mapping and Analysis Program) could be used to continue scaling and transformation studies between hyperspectral and multi-spectral sensors. It seems likely that until HyspIRI flies, airborne and spaceborne sensors will be needed to characterize fine scale properties and help with scaling to swath coverage from multi-spectral sensors.

6. ACTIVE REMOTE SENSING

Active sensors – radar and LiDAR including terrestrial laser scanners (TLS) – provide considerable promise for description of vegetation. structure considered essential for development of monitoring and futures assessment in savannas. Already, ALOS PALSAR, Radarsat and ICESAT are being used in large scale mapping of forest systems in Amazonia and elsewhere. With the injection of funds in NASA Earth Science by the Obama Administration, The DESDynI (Deformation, Ecosystem Structure and Dynamics of Ice) Lidar and Radar mission is expected to fly in 2017. LiDAR and Radar have already been applied intensively to retrieval of biomass and 3-D tree structure of savannas in field research in Australia (Lucas et al., 2010) and Southern Africa (Asner et al., 2009).

Detailed studies at Injune in Queensland have characterized much of the response domain for LiDAR and Radar in heterogeneous open Eucalypt woodlands. In particular, very detailed research has delineated tree crowns and retrieved vertical profiles on an individual tree basis. Structural attributes retrieved include tree height, crown cover and depth and gap fraction/foliage distribution. Indirectly approaches that combine LiDAR with other data can be used to retrieve basal area, volume, biomass, density and leaf area index (LAI). However, this site has been subject to intensive field sampling over the years and used to calibrate Landsat TM-based foliage cover maps for the region. The role of the intensive calibration of the Landsat-derived measures should not be underestimated. The best relationships between radar and biomass in woodlands have been derived with L-band HV cross polarized data returns. However different structural types and growth stages need to be accounted for, high soil moisture and foliage surface water affects sensitivity and calibration, and maps need integration with LiDAR and optical data for revision and refinement. Backscatter responses are curvilinear and asymptotic, saturating at about 60 Mg ha^{-1} in open woodlands.

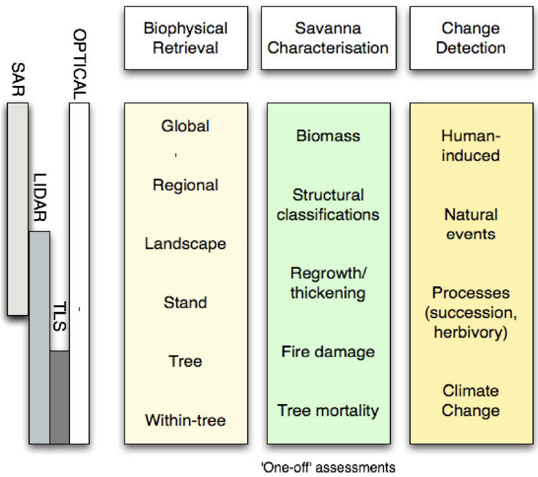

Figure 4. Potential roles for active sensors in savannas

For optimal retrievals, integration across sensors (TLS>Airborne Lidar/optical> Spaceborne SAR/Optical) is recommended (Figure 4). Sampling or transects are needed from airborne systems and spaceborne LiDAR to complement swath coverage with SAR and optical data. Uncertainty can be reduced by better field measurements, using a probabilistic approach to retrieved estimates, and constructing methods for accounting for soil moisture and rainfall-induced variation.

7. A PHOTON'S VIEW OF SAVANNAS

From the viewpoint of a photon, structure is the first order effect with interaction from each layer and between layers. For radiative transfer in a two layer, tree-grass system, the simpler you make things, the more effects of LAI, leaf angle distribution, clumping, gap fractions are lost, making it difficult to relate ground measures to earth observations. Therefore, how much detail is enough, and do we need to fully explore the detail and examine the physical responses in order to retain the critical structural properties in a simplification? Many simplified radiative transfer approaches, such as clumping index, have been explored in savannas (e.g. Hill et al., 2008) but at coarse pixel resolution, variation in shadow, and sunlit proportion and arrangement, and clumping and vertical and canopy structure are such that the same simplified signal is retrieved from many different structural combinations. So Monte Carlo ray-tracing models can be used to examine leaf level detail. More recently the concept of spectral invariants has improved models of canopy reflectance and transmittance, enabling separation of structure and chemistry. Multiple scattering of a photon in a canopy is a function of the recollision probability and this is independent of wavelength and a function of structure only (Figure 5). With diverse savanna vegetation morphology, invariants may greatly improve plant functional type (PFT) specifications.

There are a variety of other new possibilities. Since, there is important information in the visible and short wave infrared, multispectral LiDAR may give structure and physiology information. Geostationary sensors such as SEVIRI provide very high frequency sampling at low spatial resolution and diurnal fire patterns for Africa. The complexity of the photon's view may be correctly simplified by applying data assimilation to reflectances with the RT models and observations to retrieve an ecosystem model state vector that incorporates structure.

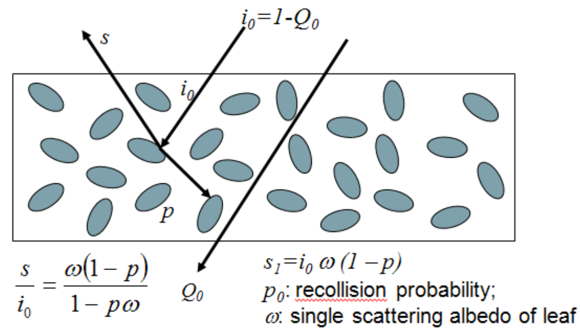

Figure 5. Recollision probability. The signal detected by an optical satellite (s) is a function of number, arrangement and quantity of leaves in the canopy.

8. DYNAMIC GLOBAL VEGETATION MODELS

8.1 Surface-Atmosphere Transfer

Representation of savannas in global models is currently unsatisfactory (compare Figure 6 with Figure 2). Most Dynamic Global Vegetation Models (DGVM) simulate an "either-or" dominant class system. For example the land-surface scheme in the Simple Biosphere Model (SiB) treats savannas as a grassland with no trees, whilst the Community Land Model (CLM) allocates plant functional type tiles within each pixel. Neglecting trees affects the seasonality and magnitude of carbon fluxes, latent and sensible heat fluxes and turbulent exchange between surface and atmosphere is not correctly represented. Patch models like CLM that disaggregate woody and grass vegetation separate soil moisture removal and smooth overall roughness. A better approach would incorporate multiple physiology and continuous and coincident fractional cover of grass and trees. At the scale of these DGVMs, the MODIS Vegetation Continuous Fields Product would readily provide more accurate surface structural representation. Methods using MODIS vegetation indices for disaggregating tree and under storey greenness signals (e.g. Gill et al., 2009) could be combined with fractional cover retrievals (Guerschman et al., 2008) to separate grass and woody phenology. These dynamic assessments could be combined with well validated static assessments based on Landsat TM data (e.g. foliage projected cover; Armston et al., 2009) However, because savanna ecosystem function may be very sensitive to vegetation state transitions, to landscape scale spatial structures and to species level eco-physiological plant traits, particularly in relation to flooded and droughted systems, there is a need to determine the influence of these variables on generalized two layer vegetation descriptions passed to DGVMs and GCMs.

8.2 Woody-Herbaceous Systems

From the point of view of vegetation dynamics, modeling of savannas in DGVMs is aimed at:

1) Understanding what drives woody vs grass competition, particularly differences in water access and disturbance effects of woody cover.
2) Examining the effect of heat and drought stress in concert with CO_2 fertilization on the C_3/C_4 mix and carbon balance of the ecosystem.
3) Climate/chemistry interactions, particularly past, present and future fire dynamics and emissions.

Therefore, there are some crucial model features that need improvement: height resolved tree canopies (which could be provided by a DESDynI LiDAR/optical combination); plant fire

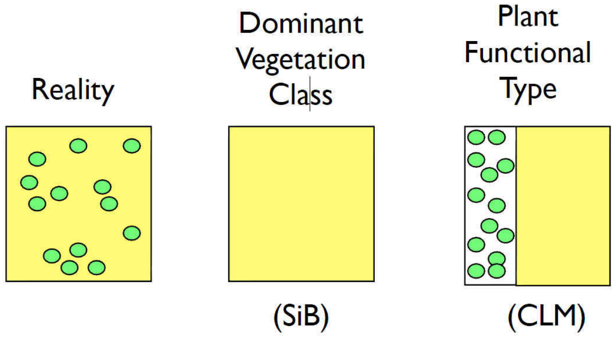

Figure 6. Stylised comparison of reality and representation of savanna in two land surface schemes.

Table 1. Representation of plant traits in DGVMs. LPJ-GUESS is a leading global model, while aDVGM is specifically designed for savannas.

LPJ-Guess (Smith et al., 2001)	aDGVM
Cohort based, each age cohort represented by average individual	Each tree treated as individual
Explicit treatment of establishment, mortality; allocation relatively flexible	Explicit treatment of establishment, mortality; allocation very flexible
Fixed phenology, tropical PFTs specified as raingreen vs. evergreen	Dynamic phenology, seasonal dry environments select for deciduous strategy; plant carbon status is main driver for dormant/active status
Process-based fire model, calculates burnt area, intensity, flame height; kills trees mostly depending on the latter	Semi-empirical fire model, fire spread determined by (random) ignition source, and potential intensity to exceed a certain threshold (wind speed, fuel moisture)
Applicable globally	Applicable in savannas, forests and grasslands

resistance traits that vary with age or growth strategy (link to disturbance and size-related mortality); root/shoot allocation responses to stress; species and ecosystem specific tree phenology (deciduous behavior varies in importance between major savanna systems). Up-scaled individual or cohort modeling is needed for DGVMs to better represent the vegetation and a couple of examples are provided in Table 1. For example, aDVGM simulated basal area with good accuracy along the NATT in Australia, but parameters had to be adjusted from the settings used in Africa.

Better representation of savannas in DGVMs can be aided by remote sensing products that: a) initialize the model with vegetation cover, burned area etc; b) may be used to compare with independent model output from backcasting; and c) provide a mix of good spatial and temporal resolutions that provide quantitative retrievals at multiple scales and enable up- and down-scaling.

9. CRITICAL PARAMETERS

From the preceding sections, we have seen that that highly variable two-layer tree-grass system presents difficulties and must be better described by remote sensing for better global model outcomes. So what are the critical ecological and bio-physical parameters needed.

9.1 Ecology

Landscape scale tree-grass models have explored three concepts:

a) differential rooting depth between trees and grasses (Walter Hypothesis);
b) demographic bottleneck due to differential sensitivity of saplings and trees (e.g. fire);
c) competitive tension from resource competition for water and/or nutrients.

At landscape scale spatially explicit population demography models don't deal with resource dynamics, and heuristic state and transition models may use fire and climate thresholds and drivers, but don't incorporate explicit demography. Simple Lotka-Volterra type models that partition biomass and competition into above and below ground compartments can predict tree biomass (Higgins et al., 2010). There is a need to undertake comprehensive inter-model comparisons in the different global savanna systems – these may reveal the parameter adjustments discussed above. However, given the potential, large, scale-based errors in ground data in savannas due to spatial variability and clumping, use of parameter distributions based on sensitivity analysis, and optimizations of some objective function for inverse fitting of parameter settings is recommended. Models should have their assumptions tested, be benchmarked in the different savanna systems, and modified to utilize existing and near future remote sensing inputs

Therefore, one approach to improve savanna input and feedback to climate change would be to embed a cohort-based vegetation model in a land surface scheme. In order for this to adequately up-scale the demography and critical spatial properties, this might involve three levels including demography at fine scale (provided by LIDAR/optical integrated products), an enhanced DGVM and a GCM. For example, embedding aDGVM in the JSBACH land component of ECHAM (European Centre Hamburg model) will enable consideration of demographic processes in earth system models.

9.2 Biophysics

Since savannas are vast, highly variable, and sparsely measured, model-data assimilation (MDA) is the best way to measure, model and understand savannas. Remote sensing is essential for water and energy balance simulation. Radiation is partitioned by the canopy, hence the detailed canopy retrievals demonstrated in airborne studies, and promised with future sensors are vital for radiative transfer and subsequent estimations. The MDA scheme can assimilate ground observation, landscape model outputs, and satellite data across scales and eddy covariance measurements where available. Since savannas have high variability in data properties – scales, frequencies, timings, quantitative or heuristics – the MDA can:

1) Quantitatively assess reductions in uncertainty using additional data;
2) Explicitly deal with bias introduced through observations & models;
3) Design & implement 'observing systems' (large data volumes, significant computational overhead) with forecasting capability; and
4) Quantify 'importance' of measured parameters as degree of constraint on models (reduction in prior uncertainty).

In some initial studies (Renzullo et al., 2009), Monte Carlo Markov Chain methods were used to estimate parameters for estimating latent and sensible heat fluxes from a model and remote sensing measures of land surface temperature (MODIS) and soil moisture (Advanced Microwave Scanning radiometer). However, many more datasets could be used to potentially provide constraints on models nested across scales. Given the scale dependence of process in savannas an MDA scheme that can detect bias and redundant parameters or input variables is crucial in establishing an optimal framework. A major question arises as to what architecture of nested models, remote sensing resolutions, and MDA is needed to interface with land surface models feeding GCMs such that transfer of critical, scale dependent information up and down scale is optimized.

10. CRITICAL FIELD MEASUREMENTS: A PROTOTYPE INTEGRATED PROJECT

Remote sensing is a standard component of landscape and functional ecology. This makes robust ground estimation of critical parameters all the more important. Often "ground truthing" lacks rigor and is poorly suited to validation of remote sensing retrievals. Ecology and remote sensing must be closely linked with experimental work and validation work designed in tandem. Often there may be a lot of data, but it may not be well organized. The critical parameters will describe multiple physiologies – under and overstorey dynamics. Soil and below ground processes have to be measured and linked to indicators or calibrate simulation models. Since savanna vegetation and edaphic systems vary widely between the continents, region specific field measurements and local calibration of remote sensing and models is needed.

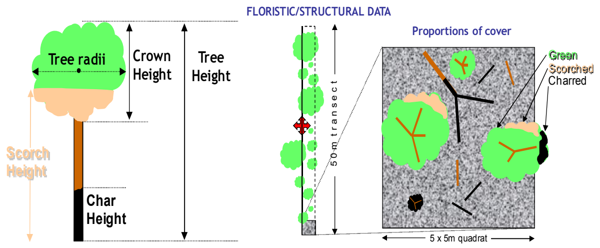

Figure 7. Key measurements of fire effects for combination with a spectral library across severity classes.

SPECIAL (Savanna Patterns of Energy and Carbon Integrated Across the Landscape) is a new integrated project in the Australian tropical savanna. It links ground measurements to remote sensing products. Measurements are taken at a range of spatial scales including leaf and canopy, eddy covariance, airborne mass and energy flux and remote sensing, and satellite products all linked to calibration of CABLE, the CSIRO land system model linked to the Australian GCM. They are evaluating MODIS LAI and GPP products and using tuned remote sensing products for spatial scaling. Particular attention is being paid to fire severity assessment since it has a major affect on carbon stocks and fluxes (Figure 7). MODIS reflectance in the 1640 and 2150 nm bands can be used to discriminate severity classes.

11. CONCLUSIONS

The comprehensive coverage of issues summarized here has enabled us to develop a science framework for improving application of remote sensing and modeling to understanding and management of savanna ecosystems (Hanan and Hill, 2011). With integrated measurement, remote sensing and modeling, the savanna systems can be better described and understood, and this will contribute to better management, support of livelihoods, scenario analysis and futures assessment.

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