“Savannas in a Changing Earth System”

The NASA Terrestrial Ecology
Tree-Grass Project

Outline for a Coordinated NASA Field Campaign for Earth Observation and Modeling in Mixed Tree-Grass Ecosystems

The NASA Terrestrial Ecology *Tree-Grass* Project

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Foreword

In 2009 the NASA Terrestrial Ecology Program supported a “Scoping Study” entitled “Challenges and Opportunities in Remote Sensing of Global Savannas: A Scoping Study for a New TE Field Campaign”. The initial intent of this project was to develop the case for renewed focus on savannas via a major new field research program in the tradition of the FIFE, BOREAS and LBA series. The Scoping Study made possible a thematic workshop (the “Savanna Remote Sensing Workshop” in Fort Collins, Colorado, March 2010) that gathered some 50 experts from around the world, and an extended consultative process with close to 200 participants, that culminated in the drafting of this White Paper.

Several key realizations emerged during this process that modified our directions, whilst reinforcing our conviction that savannas, and other mixed woody-herbaceous systems, should be the focus of a new TE field program; these realizations now permeate and motivate the recommendations in this white paper.

Firstly, that savanna ecosystems, as generally defined to include woody-herbaceous systems in drought-seasonal areas, are a subset of more widely distributed ‘tree-grass’ vegetation communities worldwide, representing (by our estimates) some 35% of the terrestrial land surface.

Second, that these tree-grass systems, although globally diverse in climatic, biotic, and management characteristics, present similar challenges for earth observation (specifically remote sensing and modeling) because of their fundamental structural similarities (i.e. a discontinuous woody canopy over a more or less continuous herbaceous layer) that transcend the aforementioned differences.

Thirdly, that where remote sensing and modeling of terrestrial vegetation has focused on aggregate retrievals (e.g. total LAI or canopy f_{PAR}) for practical reasons, such historical contingencies need not, and should not, constrain future pathways: should we continue to ignore the horizontal and vertical heterogeneity of vegetated landscapes when our remote sensing and modeling technologies can probably do better?

Fourthly that, while recent TE field projects have greatly advanced earth observation and modeling of vegetation processes, a renewed focus on remote sensing science directed towards the partitioning of woody and herbaceous canopies, could pave the way towards greater structural and functional realism in remote sensing retrievals and associated earth system models.

And finally, that advances in remote sensing and modeling of woody-herbaceous mixtures will provide direct benefits for earth observation in all terrestrial systems where vegetation community structures can generally be considered end-members of the woody-herbaceous continuum.

Summary

In this white paper we develop ideas for a NASA Terrestrial Ecology (TE) field activity that will enhance remote sensing and earth system modeling capabilities in ecosystems characterized by mixtures of woody and herbaceous species ('tree-grass' systems). The *"Tree-Grass"* (*TG*) project will transform our ability to use satellite data and earth system models to assess the current and future role of tree-grass systems in the earth system, and their future in the face of changing climate, changing land use and human population growth. In so doing we will enhance our ability to manage tree-grass ecosystems for sustainability, food security and human wellbeing.

The overarching *TG* science questions are:

1) How are climate change and land-use change altering the structure, function and productivity of tree-grass systems at landscape, regional and global scales? ("Global Change Processes")

2) How will changes in tree-grass structure, function and productivity interact in the earth system and feed-back on the major cycles of carbon, water and nutrients and energy flows? ("Biophysical and Ecological Interactions")

3) How will global change and biophysical interactions in tree-grass systems impact human wellbeing, food security and sustainability into the future? Conversely, what is the potential for global change mitigation, and can human populations in tree-grass regions benefit from this potential? ("Goods and Services")

The coordinated *TG* research activity will focus on a) remote sensing science to realize the potential of airborne and satellite assets to retrieve key parameters describing tree-grass ecosystem state and function; b) development and testing of earth system modeling capabilities suited to the structural and functional characteristics of savannas; c) model-data synthesis (data-assimilation) to integrate new remote sensing and modeling capabilities, and d) extensive education and outreach programs.

TG field activities will adopt a hierarchical sampling approach, with locally intensive field components in North America, linked to globally distributed activities deployed in partnership with international collaborators. We propose a phased implementation for *TG*, with Phase 1 ("Synthesis and Evaluation") concentrating on synthesis and evaluation of existing remote sensing and modeling capabilities in tree-grass systems, Phase 2 ("Field Campaigns') implementing major field, remote sensing and model development activities, and Phase 3 ('Applications') focusing on regional-global scale applications relevant to understanding and management of tree-grass systems.

TG seeks to revolutionize earth observation science through improved consideration of woody and herbaceous functional groups in remote sensing and modeling of terrestrial ecosystems. The *TG* program will entrain and inspire the next generation of earth system scientists and enhance public appreciation of the crucial role NASA remote sensing technologies can play in understanding and managing the earth system.

1. Introduction

1.1. Rationale

Tree-grass systems are globally widespread

Mixed tree-grass and shrub-grass vegetation associations are one of the most spatially extensive and widely distributed forms of terrestrial vegetation on earth. These "savanna" ecosystems (where, for the purposes of this white paper, we use 'savanna' and 'tree-grass' interchangeably to denote any and all mixed woody-herbaceous communities) constitute significant fractions of all continents except Antarctica, and they are found in tropical, subtropical and temperate bioclimatic regions (Figure 1, Table 1). While global tree-grass systems are diverse in their phylogeny, physiology and plant morphology, they share the key structural characteristic of woody plants distributed in the landscape at densities low enough to allow significant growth of herbaceous plants (mostly grasses) underneath and between them (Bourliere and Hadley 1970; Walker et al. 1981; Sarmiento 1984; Mistry 2000; Hill et al. 2011; Lehmann et al. 2011).

Often under-appreciated in global maps

An analysis highlighting tree-grass mixtures derived from the MODIS Vegetation Continuous Fields product (VCF; Hansen et al. 2005) provides estimates of the global importance of tree-grass systems (Figure 1, Table 1). While VCF calibration procedures omit smaller trees (< 5m) and shrubs, the VCF product provides a globally consistent and objective database (albeit potentially underestimating woody cover in some areas because of the shrub omission). Table 1 also shows area estimates from the MODIS Land Cover Land Use product (MOD12; Friedl et al. 2002) representing how 'savannas' are traditionally mapped. Such more traditional savanna definitions significantly underestimate the extent of mixed woody-herbaceous systems assessed from a more inclusive 'tree-grass' perspective. In part this occurs because tree-grass mixtures often arise through human actions reducing woody biomass in dense woodlands and forests or, in some areas, favoring tree and shrub establishment in open grasslands. Since many, perhaps most, biome-mapping approaches are strongly rooted in concepts of 'potential vegetation' they tend to ignore the anthropogenically modified landscapes in defining the biome, where a structural approach (i.e. VCF) does not.

While the estimates of distribution and surface area of tree-grass mixtures in Figure 1 and Table 1 are preliminary, they support a growing realization in the earth observation and modeling communities that tree-grass mixtures are globally far more significant than generally appreciated. For example, many woodlands, including huge areas of temperate woodland and dry deciduous woodland in the tropics, are effectively "managed as savannas" (Hanan and Lehmann 2011), with suppression of trees through fire and wood harvest,

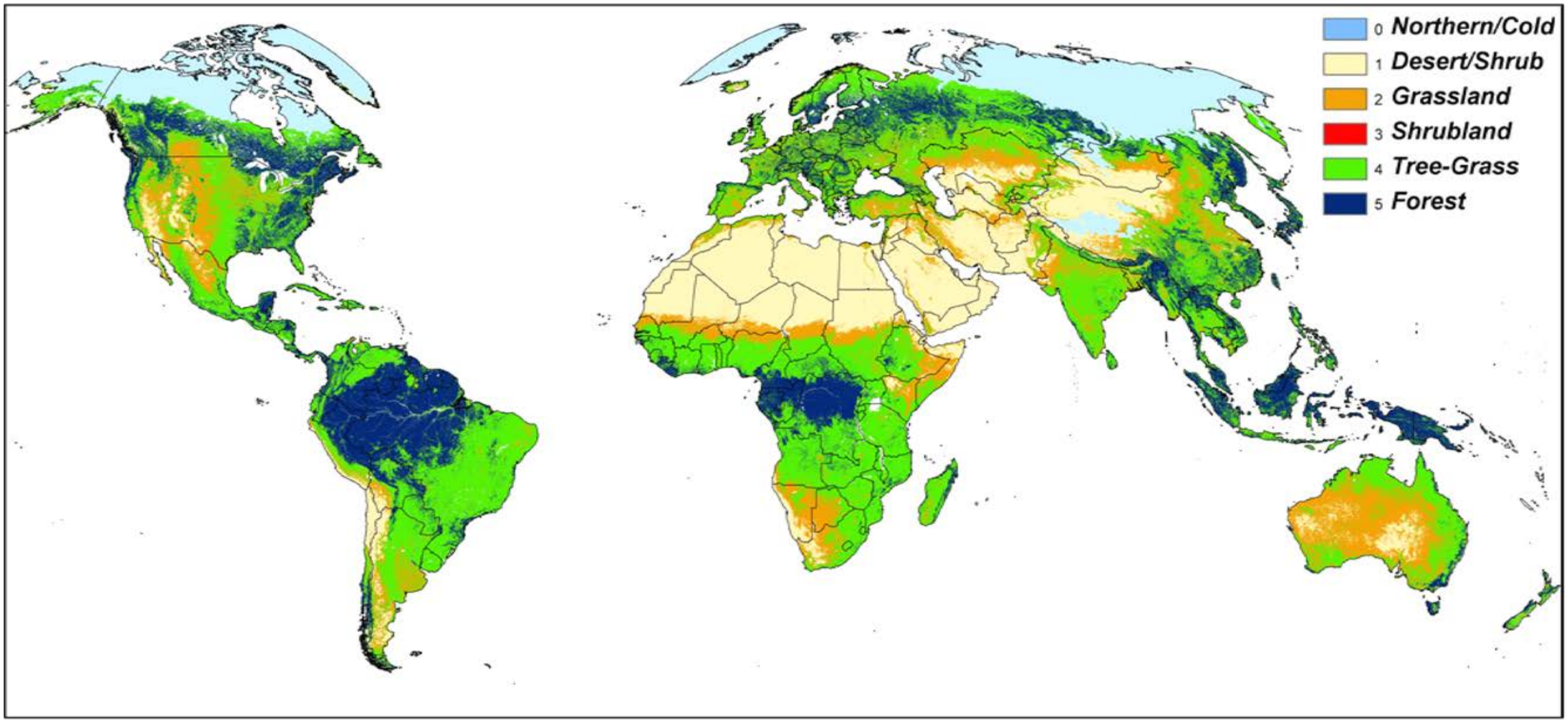


Figure 1. Global distribution of tree-grass mixtures based on classification of MODIS Vegetation Continuous Field (VCF) data. The 'tree-grass' map used the 2005 VCF product (Hansen et al., 2005) which provides relative cover estimates for 'trees', herbaceous' and 'bare soil' components. Tree-grass mixtures were assessed using fixed structural criteria (satisfying 3% < tree cover < 50% and grass cover > 25%). We screened for arctic, taiga, northern boreal, and high mountain regions using a mean annual temperature threshold of -5C (Woodward et al., 2004). The temperature threshold is necessary because, in these colder regions, under-story communities are generally dominated by perennial forbs and sub-shrubs, not grasses, but VCF recognizes them as systems with woody and herbaceous components. Because VCF does not resolve smaller trees and shrubs, the cover of tree-grass mixtures may be underestimated in some areas (e.g. Sahelian Africa and central Australia).

increased grass production and livestock grazing (Figure 2). Furthermore, although industrial-scale arable agriculture tends to suppress trees over large areas, less intensive, subsistence agriculture tends to reduce, but not eliminate, tree-cover. Indeed, less intensive agricultural systems often support persistence of trees for shade, fruit, fuel-wood and other uses, in a patch-work of cleared fields and re-growing fallow. In many parts of the world, therefore, agricultural and pastoral activities promote tree-grass mixtures at patch and landscape scales. As shown using the example in Table 1, more traditional land cover classifications rarely recognize these derived tree-grass mixtures, despite the important differences in structure and function of tree-grass mixtures relative to systems with less structural diversity.

Table 1. Global tree-grass areas (km^2 and % of totals) estimated using structural criteria (tree and grass cover from VCF) and a biome distribution map (MODIS-IGBP)

Continent	Total Land Area	Tree-Grass Area (VCF)	% Tree-Grass (VCF)	% Tree-Grass (MODIS-IGBP)
Africa	29.7 x 10^6	11.1 x 10^6	37.3	30.7
Australia	07.8 x 10^6	02.3 x 10^6	29.2	17.5
Eurasia	54.9 x 10^6	20.2 x 10^6	36.9	8.3
North America	23.3 x 10^6	06.0 x 10^6	25.9	10.8
South America	17.5 x 10^6	08.2 x 10^6	46.8	22.8
Global Land Surface	133.2 x 10^6	47.8 x 10^6	35.9	16.3

Notes: The MODIS Vegetation Continuous Fields dataset (VCF; MOD44B; Hansen et al., 2005) provides 'structurally-based' estimates, with tree-grass mixtures defined when 3% < tree cover < 50% and grass cover > 25%. The MODIS-IGBP area assessment is based on the 'savanna' classes of the MODIS-Land Cover Land Use Classification (MOD12C1; Friedl et al. 2002).

Tree-grass goods and services

Global tree-grass and savanna regions are vital for livestock production, with global annual meat and milk production values exceeding $1.4 trillion (Thornton 2010). In less developed regions grazing systems directly support the livelihoods of more than 600 million poor subsistence pastoralists where food security and livelihoods are vulnerable to climate variability, drought, degradation and famine (Millennium Ecosystem Assessment 2005; Reynolds et al. 2007). In the Continental United States, of the 117 million ha of Public Land managed by the Department of the Interior (DOI), more than 60% are mixed woody-herbaceous savannas and shrubland (NLCD, 2001). More than 80% of Bureau of Land Management (a DOI Bureau) lands are in mixed woody-herbaceous systems, with more than 12 million animal unit months (AUM) licensed to graze on US BLM lands alone.

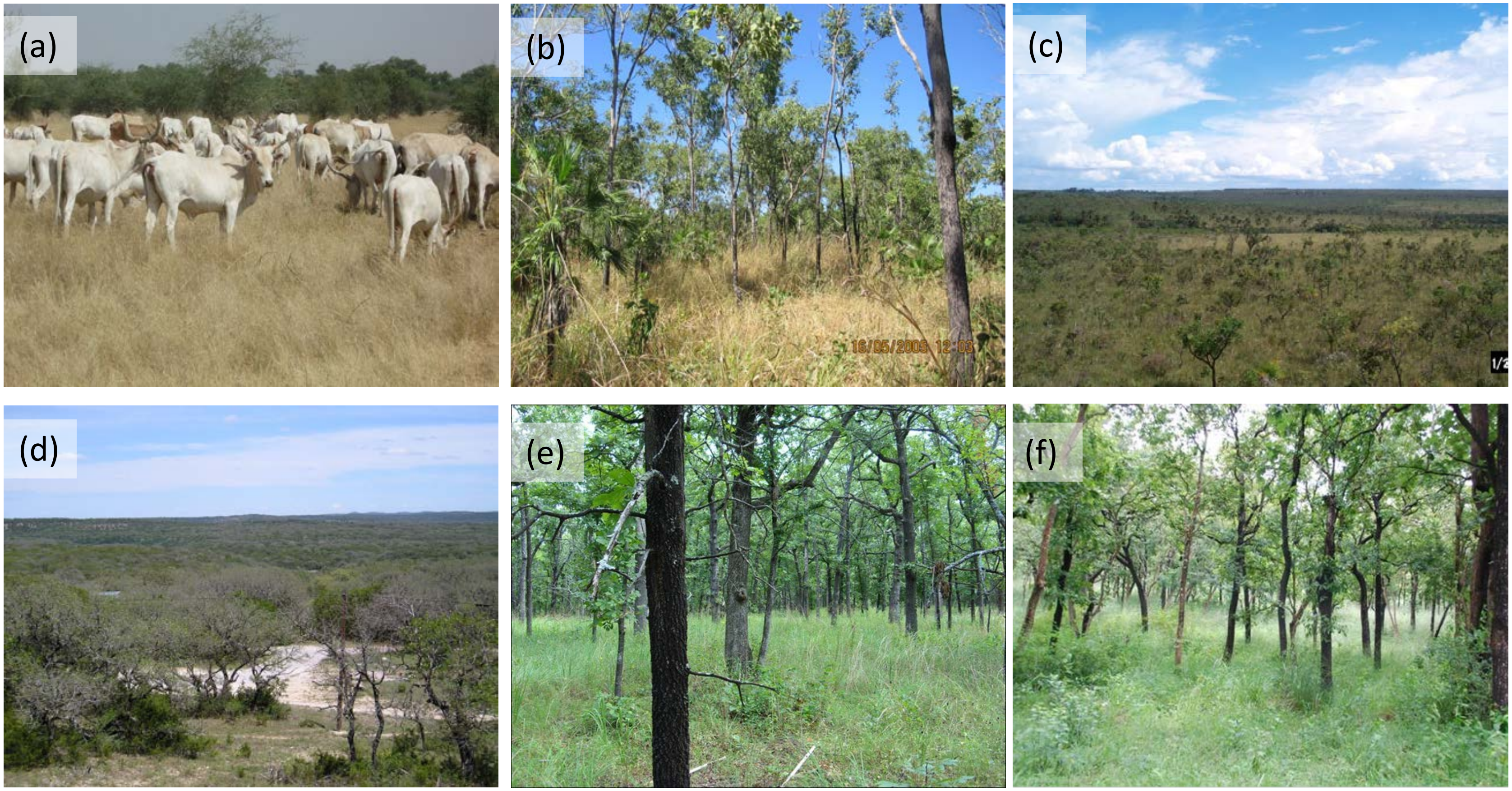


Figure 2. Six examples of globally diverse tree-grass vegetation associations, with regions typically classified as “savanna” in the upper row, and regions typically <u>not</u> classified as savanna in the lower row: (a) Sahel of Mali, West Africa (Photo: F Dembele); (b) Northern Territory savannas, Australia (Photo: A Marks); (c) Cerrado, Brazil (Photo: M Bustamante); (d) Edwards plateau shrublands, Texas (Photo: MJ Hill); (e) Oklahoma oak woodlands (Photo: J Burton); (f) Dry deciduous woodlands of southern Western Ghats, India (Photo: J Ratnam).

Land use

In many areas, tree-grass systems have already been partially or fully converted to agriculture, and land use pressures are likely to intensify in the coming decades, driven by parallel needs for increased food production to feed growing populations and increased agricultural production to underpin economic development. Since tree-grass mixtures are not fully represented in land surface models, their role in the climate system, and feedbacks with the atmosphere, are not well understood. We therefore have little idea what the consequences of wholesale land cover and land use change will be for ecosystem function, earth system interactions and feedbacks on agricultural and pastoral production systems and human livelihoods.

Fire

Global wildfire occurrence and pyrogenic emissions into the atmosphere are dominated by savanna fires, which represent 80-90% of burned area and >3.5Tg of dry matter combusted each year. These pyrogenic releases have major implications for atmospheric CO_2 source-sink patterns (Randerson et al. 2005; van der Werf and Randerson 2006; Williams et al. 2007). Further, black carbon and trace gases released in savanna fires impact atmospheric radiative transfer, energy dynamics and chemistry (Crutzen and Andreae 1990; Andreae et al. 1996; Scholes et al. 1996; Randerson et al. 2006).

Shrub encroachment

Savannas are also subject to directional changes in the balance between woody and herbaceous cover. At global scales the direction and rates of change, and associated ecosystem impacts, can be variable (Eldridge et al. 2011). The shrub encroachment phenomenon, for example, remains poorly understood but has been attributed to changes in management (grazing and fire suppression) and global change processes (changing temperature and rainfall, and increasing atmospheric CO_2 concentrations; Archer et al. 1995; Brown and Archer 1999; Fredrickson et al. 2006). In other areas (e.g. parts of Australia, South and North America), *loss* of woody plants is associated with invasion of exotic grasses and increasing fire frequency (e.g. Setterfield et al. 2010). Increasing density and cover of trees and shrubs in semi-arid rangelands tends to correlate inversely with capacity for livestock production, and thereby impact livelihoods for both commercial and subsistence cattle farmers. These phenomena are therefore of critical importance for subsistence and commercial management and sustainability of tree-grass systems. They also have profound impacts on land surface-atmosphere interactions, carbon and biogeochemical dynamics (Heisler et al. 2003; Asner and Heidebrecht 2005; Bradley et al. 2006; Knapp et al. 2008).

Earth observation and tree-grass systems

In stark contrast to the importance of tree-grass systems in earth system processes and human well-being, they represent a gap in Earth Observation capabilities, and a serious challenge for the earth observation and modeling science community. Ecosystems characterized by horizontally and vertically complex tree-grass mixtures, and temporal variability related to drought, seasonality, fire, herbivory and land use change, are inherently difficult to measure with remote sensing and represent in ecosystem and earth system models (Hill et al. 2011). However, recent and emerging technologies and instrumentation present opportunities to address these challenges and enhance our remote sensing and modeling abilities in the savannas. These opportunities will facilitate improved understanding of how tree-grass systems interact in the earth system, how they impact and will be impacted by global change, and how they can be managed for the sustainability and welfare of human societies.

To realize this potential, a comprehensive and integrated research program is required that couples remote sensing, field measurements and models at multiple scales. Research activities at local and regional scales have begun the work (e.g. Beringer et al. 2011 in Northern Australia, Shugart et al. 2004 in Southern Africa). This white paper proposes a new concentration and expansion of efforts specifically to improve EO capabilities (remote sensing and modeling) in tree-grass systems, via complementary 'intensive' activities in North America and 'distributed' activities globally. The project aims to transform our ability to use satellite data and earth system models to assess the current and future sustainability of savannas in the face of changing climate, changing land use and human population growth. In so doing we will enhance our ability to manage tree-grass ecosystems for sustainability, food security and economic wellbeing. **For this activity we propose the simple, but directly meaningful, title "*Tree-Grass*" (*TG*).**

NASA Terrestrial Ecology *"Tree-Grass"*

1.2. Scientific Background – tree-grass systems & earth observation

Our conceptual model for tree-grass interactions in the earth-system, with global change and social-ecological systems, is shown in Figure 3.

On geological time-scales the savannas are a young formation. The rapid global expansion of the savannas occurred only 6-8 million years ago (6-8M BP), following the earlier evolution of C_4 grasses 15-35M BP (Sage 2004; Beerling and Osborne 2006). C_4 expansion was associated with changing paleo-climate, increasing evidence of fire in the earth system, and the evolution and numerical expansion of large herbivores specialized to grazing (Pagani et al. 1999; Keeley and Rundel 2005). This included evolution of the ancestors of the animals that humans would later domesticate for meat and dairy production. Changes in climate, atmospheric CO_2 concentration, fire and herbivory were all associated with savanna expansion, and since the last ice age, humans have promoted savanna expansion and persistence through use of fire, wood harvest and grazing (Bond 2008; Hanan and Lehmann 2011). These factors remain critical in determining the modern-day geographic extent of savannas. However, global change processes (land use change and conversion to agriculture, increasing atmospheric CO_2, and changing rainfall patterns) mean that the suite of abiotic, biotic and anthropogenic factors important in savannas is changing. The future function and global distribution of tree-grass systems is therefore highly uncertain (Bond 2008).

Earth System Interactions

Tree-grass systems are significant from many perspectives: as regions that respond rapidly to, and feedback on, climate and climate variability (Charney et al. 1975; Schlesinger et al. 1990; Brovkin et al. 1998; Asner and Heidebrecht 2005; Scott et al. 2006); as areas where land degradation and drought are common (UNEP/ISRIC 1990); as vast stores (actual and potential) of carbon in biomass and soils (Scholes and Hall 1996); as a primary location for livestock and grain production (Kruska et al. 1999; Liu et al. 2008); and a primary location of land use change driven by increasing populations, economic development and globalization (Watson et al. 2000; Houghton and Hackler 2006).

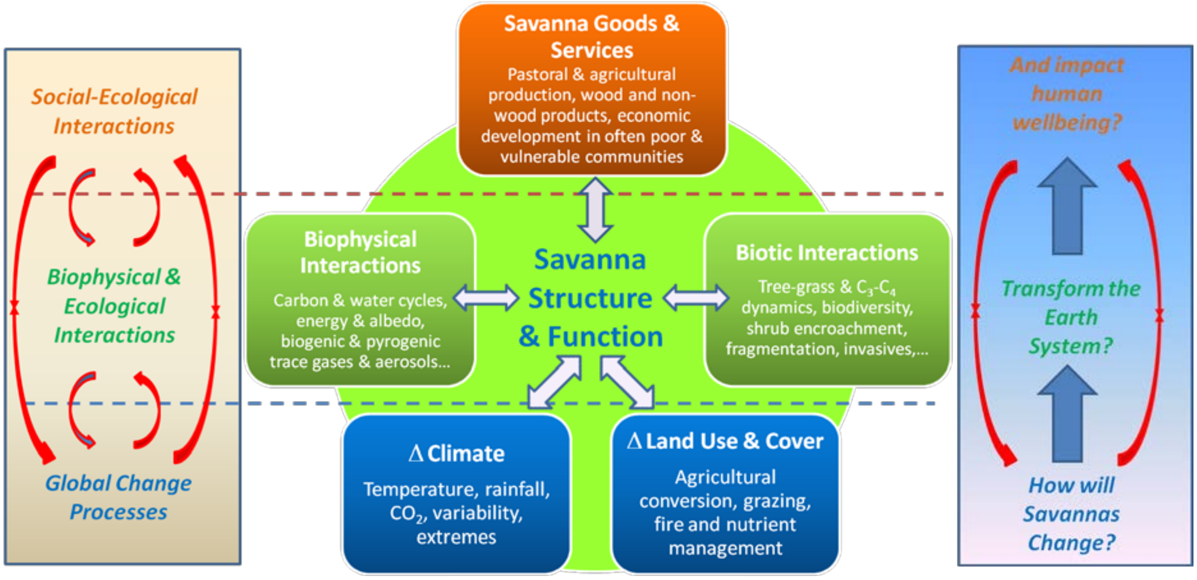


Figure 3: Conceptual diagram for tree-grass and savanna systems, showing drivers of change, ecosystem processes and provision of goods and services (center), interactions between global change, biophysical and social-ecological domains (left), and key science questions for the *Tree-Grass* activity (right).

Fire

Globally, savannas are the most fire prone ecosystems and savanna fires account for 80- 90% of the total global burned area (van der Werf et al. 2003; Mouillot and Field 2005). Estimates suggest that 450-750 million hectares and approximately 3700 Tg of dry matter are burned each year in savanna fires, representing up to 50% of global carbon emissions (Andreae 1991; van der Werf and Randerson 2006). Fires in tree-grass regions also emit a wide range of other chemical species as well as particulate matter, with major implications for atmospheric reducing potential, ozone production, incoming solar radiation and nutrient cycling in terrestrial ecosystems (Crutzen and Andreae 1990).

Desertification feed-backs

The seminal papers of Charney and colleagues (Charney et al. 1975; Charney 1975; Charney et al. 1977) postulated that changes in surface albedo caused by grazing and vegetation degradation in semi-arid grazing lands can impact regional climate by altering precipitation regimes, initiating a positive feedback and increasing degradation. Since then, drought and famine in Africa, in particular, has caused great hardship and many consider the Sahel of Africa as *the* primary location, worldwide, where desertification, overgrazing and global climate change, present serious, and on-going, environmental problems. However, although many empirical and model based studies have examined Charney's hypothesis over the last four decades (Phillips 1993; Nicholson et al. 1998; Asner and Heidebrecht 2005; Giannini et al. 2010) relatively few have demonstrated that local land surface-climate feedbacks have, in reality, been sufficient to impact the global scale processes that generate rainfall variability (see e.g. McAlpine et al. 2007). Indeed, parallel recovery of both rainfall and vegetation in the African Sahel since the droughts of the 1970's and 1980's suggests that this area, at least, is not locked in a downward spiral as originally conceived by Charney (Herrmann and Hutchinson 2005; Olsson et al. 2005; Giannini et al. 2010).

Food security

The susceptibility and sensitivity of savannas to drought and degradation notwithstanding, these regions also play a pivotal role in regional and global food production and food security. In particular, both temperate and tropical savanna regions are important for protein-rich cereal and meat production which, in both more arid and more humid regions, is often limited by water or nutrient availability, pests and diseases. Thus tree-grass regions are extensively used for grazing and agriculture. In many less developed countries tree-grass systems are also important as sources of fuel-wood and charcoal for domestic consumption.

***Tree-Grass* Challenge**

Given the global importance of tree-grass formations it is notable that many, perhaps most, developments in earth observation (EO) systems, and associated earth system modeling, over the past 40 years have been so poorly adapted to the key structural and functional characteristics of savannas. Rarely indeed, do existing EO systems even attempt to separate tree and grass components, and this omission significantly increases uncertainty and potential for bias in assessments of energy, carbon, water and biogeochemical dynamics (Bégué et al. 1996; Hill and Hanan 2011). The failings of satellite remote sensing and models in savanna systems arise in part because of geographical bias towards the economic centers, forests, woodlands, farms and grasslands, of the temperate latitudes. But also reflects the considerable challenge involved in remote assessment of vegetation structure and dynamics in systems characterized by distinct woody and herbaceous functional groups (Table 2).

The separation of trees and grasses in remote measurement of vegetation is a significant challenge, but an even bigger opportunity, for EO systems already

Table 2: Challenges & Opportunities for Earth Observation in Tree-Grass Regions

Challenges for EO in Tree-Grass Systems	Major Scientific Opportunities
1. Remote Sensing (RS)	
Remote Sensing (RS) of land surface properties is difficult in horizontally and vertically complex/heterogeneous canopies	Improving sensor spatial/spectral characteristics, new optical, radar and lidar data should improve our ability to resolve & retrieve vertical and horizontal structure
RS of canopy biophysical variables generally ignores the defining feature of tree-grass systems: that they are composed of separate woody and herbaceous layers	New RS technologies and synergies among sensor types, present opportunities to develop savanna-relevant retrieval techniques for tree-grass structure, biophysical and phenological properties
Methods for remote sensing of biomass and carbon stocks are only recently emerging for forests and not well adapted to low cover and stature savannas	Emerging techniques using optical, radar and lidar to quantify vegetation structure and biomass can be refined and improved for tree-grass systems
RS techniques for canopy physiological and biogeochemical properties and functional rates (fluxes) rarely resolve woody and herbaceous layers	Next generation sensors (hyperspectral, optical, thermal), in synergy with improved structural retrievals, provide opportunities for separation of physiological & biogeochemical properties and functional rates
The central role of disturbance in tree-grass systems (drought, fire, grazing and browsing, wood harvest and agricultural clearance) is difficult to characterize with RS	New and next-generation satellite remote sensing data will provide opportunities for better assessment of soil moisture, fire extent, intensity and emissions, and local changes in vegetation structure related to extraction and conversion
2. Earth System Models and Model-Data Assimilation (MDA)	
Regional & global biophysical/biogeochemical models mostly assume structural homogeneity, with little consideration of vertical & horizontal heterogeneity, mix of functional/physiological types, typical of savannas	Models suited to tree-grass systems are available & can be developed for global applications; improved RS will provide boundary conditions and validation for savanna-appropriate biophysical & biogeochemical models
Dynamic global vegetation models resolve and simulate population dynamics of different plant functional types, but remote sensing retrievals to date have not provided information suited to DGVM validation or optimization	Improved remote sensing retrievals will provide data with which such DGVM models can be parameterized and validated
Despite decades of speculation (since Charney), the role of savannas & tree-grass systems in regional and global climate and biogeochemical cycles, & earth system sensitivity to savanna change, is poorly quantified	Combined field studies & model development provide opportunities for improved modeling of aerodynamic, energy & water balance in heterogeneous tree-grass systems, at local to global scales
Relatively few RS data are routinely used by the land surface modeling community (e.g. global climate and biogeochemistry models), and those that are used are adopted in relatively simple modes for *a priori* parameterization or *post-hoc* comparison and validation	Increasing quality and relevance of RS and modeling capabilities, and developing methodologies for data assimilation, provide opportunities for an expanded role for remote sensing in earth system models, closer model-data integration and improved simulations
Tree-grass systems are inherently 'human' systems where agriculture, grazing, wood harvest and fire management are key drivers of ecosystem processes and land surface-atmosphere interactions, and where ecosystems impact directly human wellbeing and socio-economics	Modeling frameworks for coupled 'social-ecological systems' are evolving, providing new opportunities to couple biophysical and biogeochemical models to social- ecological and agent-based models of human management and decision making processes

Tree-Grass **Opportunity**

available or soon to be deployed and available for regional-to-global scale applications (Table 2). Current and future generation satellite missions (planned by NASA and partner agencies internationally) include significantly improved spectral and spatial resolution optical sensors, alongside new and improved thermal, radar and lidar instruments. These sensors, on their own or in combination, offer much improved capabilities for the characterization, separation and quantification of tree-grass systems. While uncertainties remain in the precise suite of future satellite resources, much can be achieved with existing resources. Furthermore, cutting edge remote sensing research using ground, aircraft and satellite sensors, demonstrating the power of systems already deployed and synergies with and between emerging technologies can and should continue to lay the foundations for future satellite missions. Improved measurements of savannas worldwide will contribute immensely to our ability to diagnose the status and dynamics of the major biogeochemical cycles of carbon, water, and nutrients, and ecosystem energy flows; contribute to fundamental understanding of the ecology of the earth system; and improve options for sustainable management as savannas are exposed to increasing climatic and anthropogenic stress.

Tree-Grass **White Paper**

In this white paper we develop ideas for a NASA Terrestrial Ecology Program (TE) field activity that will enhance remote sensing and earth system modeling capabilities for tree-grass systems. Our plan breaks the mold of previous TE field campaigns in proposing a hierarchical sampling methodology, with locally intensive field components in North America, linked with globally distributed activities deployed in partnership with international collaborators. The coordinated activity will focus on 1) remote sensing science to realize the potential of new airborne and satellite assets to retrieve key parameters describing tree-grass ecosystem state and function; 2) development and testing of earth system modeling capabilities suited to the structural and functional characteristics of savannas; 3) model-data synthesis (data-assimilation) to integrate new remote sensing and modeling capabilities, and 4) extensive educational and outreach programs to entrain and inspire the next generation of earth system scientists and enhance public appreciation of the crucial role NASA remote sensing technologies can play in understanding and managing the earth system.

1.3. Motivations for the *Tree-Grass* activity

Why tree-grass and savanna systems?

- Given that savannas are sensitive to climate change and centers of land-use change: *global savannas are changing rapidly and will likely be radically transformed in the coming decades*.

Why *tree-grass?*

- Because tree-grass systems occupy regionally and globally significant land area and have strong earth system interactions: *tree-grass transformation will significantly impact the earth system, via changes in energy flows, hydrological and biogeochemical cycles.*
- Because tree-grass regions are vital centers of livestock and grain production for more than 600 million often poor and marginalized people: *tree-grass change will significantly impact human livelihoods, food security, economic and ecological sustainability.*
- Since mixed tree-grass and savanna systems are structurally and functionally more complex than other biomes, capabilities developed in the savannas will be transferable to other terrestrial systems.

Why NASA?

Why *NASA?*

- NASA research must aim to develop and improve remote sensing methodologies in tree-grass regions to capitalize on the convergence of current and next generation satellite instruments and developing computational opportunities now emerging.
- The full engagement of NASA assets, including field, airborne and satellite instrumentation, as well as the NASA research community and partners both nationally and internationally, is the most effective (and perhaps the only) way to advance the necessary research at this crucial moment in time.
- NASA research is needed to realize potential synergies in remote sensing and modeling of the tree-grass biome for future transfer to applications and management.
- NASA has the reputation and prestige needed to entrain researchers in the USA and internationally in a research program that will redefine earth observation approaches in the savannas and more broadly for terrestrial systems.

Why now?

Why *Now?*

- Existing and planned satellite-borne earth observation instruments have capabilities and synergies far exceeding those with which we have become familiar: renewed concentration on remote sensing science in this field campaign will allow us to realize the potential of these instruments, not only in tree-grass ecosystems but in other (structurally less complex) ecosystems worldwide
- Data assimilation methodologies are maturing rapidly, providing new opportunities for the intensive use of improved remote sensing information content: this confluence of opportunities opens the door for the transformation of our ability to monitor and model terrestrial ecosystem

dynamics, biogeochemical cycles and the earth system. Now is the time to make this happen!

- Improved remote sensing, modeling and data assimilation capabilities will enable improved science support to those charged with the sustainable management of savannas at local, regional and international scales in this critical time of global change, population growth, globalization and changing economic and political aspirations.
- **We need to know now how climate and land use changes in savannas and global tree-grass ecosystems will impact the earth system and human wellbeing in the coming decades.**

1.4 *Tree-Grass*: Key Science Questions

Tree-Grass **Science Questions**

Overarching science questions driving the *Tree-Grass* activity are (Figure 3):

1) How are climate change and land-use change altering the structure, function and productivity of tree-grass systems at landscape, regional and global scales? ("Global Change Processes" – blue boxes)
2) How will changes in tree-grass structure, function and productivity interact in the earth system and feed-back on the major cycles of carbon, water and nutrients and energy flows? ("Biophysical and Ecological Interactions" - green boxes)
3) How will global change and biophysical interactions in tree-grass systems impact human wellbeing, food security and sustainability into the future? Conversely, what is the potential of savannas for global change mitigation, and can human populations in savanna regions benefit from this potential? ("Savanna Goods and Services" – orange box)

2. *Tree-Grass* Framework and Science Themes

Tree-Grass **Framework**

Tree-Grass (*TG*) program activities (Figure 4) will be organized to address the Overarching Questions (Section 1.4), via a series of *TG* Science Themes (Section 2.1) and *TG* Earth Observation Focal Areas (Section 2.2). Progress in the areas outlined within the Science Themes and associated EO Focal Areas will allow us to develop improved EO applications directed towards improved understanding and management of global tree-grass systems (*Tree-Grass* Interdisciplinary Applications, Section 2.3). Within the proposed 10-year time-frame, *TG* will build remote sensing and earth observation capabilities that will contribute meaningful and timely information to enhance human wellbeing, livelihoods and sustainable management of the world's savanna regions.

2.1. *Tree-Grass* Science Themes

***Tree-Grass* Science Themes**

The overarching questions posed in Section 1.4 embody some of the most pressing societal problems of the coming century relating to human modification of the earth system and our ability to manage the planet for sustainability and human wellbeing. Within *Tree-Grass* we identify five interdisciplinary (and overlapping) Science Themes where savanna and tree-grass systems are globally significant (Figure 4). Given the inevitable, but uncertain, template of global change processes in the savannas (see Figure 3), these Science Themes will explore how the continuum of biophysical and ecological Interactions, and social-ecological interactions in the savannas will respond to, and feedback on, the earth system and societal wellbeing.

The primary research questions for the *TG* Science Themes are detailed below. *TG* Science Themes are deliberately broad to allow individual and team proposals to the *Tree-Grass* activity the flexibility to define their own priorities, approach and methodologies, with only minimal coordination and direction from above to ensure program coherence.

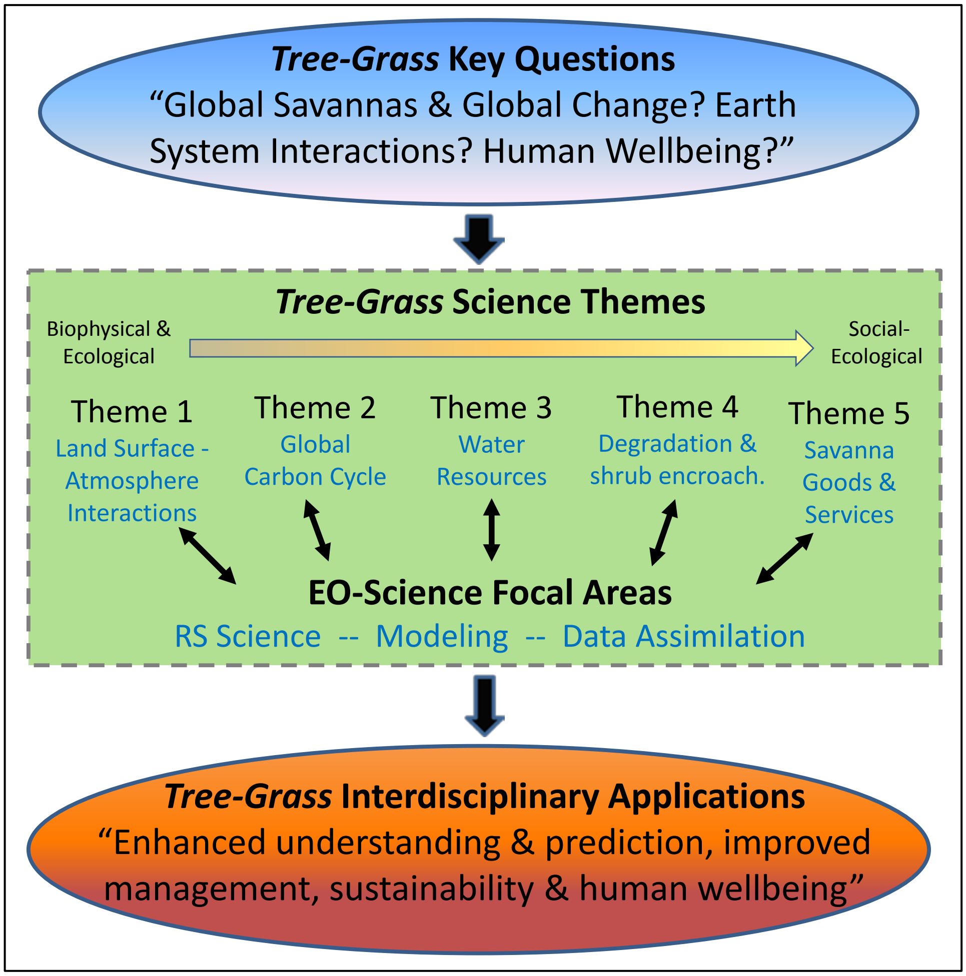


Figure 4: The *Tree-Grass* Science Framework.

2.1.1. TG Science Theme 1: Land surface-atmosphere interactions

Science Theme # 1

- What is the current role of global tree-grass and savanna systems in the earth system via energy and mass exchange at the land surface-atmosphere interface?
- What role do savannas play in atmospheric chemistry via pyrogenic and trace gas emissions, and in atmospheric radiative transfer and energy balance via dust and aerosol emissions?
- How will changes in climate and land use impact the distribution, structure and function of savannas in future decades?
- How will these climate and land use-driven changes in savanna distribution, structure and function feedback on the earth system via changes in energy balance, carbon, trace gas, dust and aerosol dynamics?

2.1.2. TG Science Theme 2: Global Carbon Cycle

Science Theme # 2

- What are the actual stocks and source-sink patterns for carbon in the global savannas?
- What is, and what will be, the role of climate variability, climate change, agricultural conversion, fire and grazing in determining carbon source-sink relationships in global savannas?
- How can savanna and tree-grass systems be managed to increase carbon sequestration while safeguarding provision of savanna goods and services (grazing, fuel-wood, non-wood products, etc.)?

2.1.3. TG Science Theme 3: Water Resources

Science Theme # 3

- In a world with increasing scarcity of clean water for human consumption, irrigation and livestock consumption, and in tree-grass and savanna systems limited by water availability and drought, how will climate change alter vegetation dynamics, and the partitioning of rainfall between vegetation growth, evaporation, runoff and deep drainage?
- How is rainfall partitioning impacted by changing surface conditions (vegetation and soil) related to savanna management (fire, grazing and wood harvest) and conversion to agriculture?
- How can tree-grass and savanna watersheds be best managed to meet demands for vegetation productivity, surface and deep water resources?

2.1.4. TG Science Theme 4: Degradation and Shrub Encroachment

Science Theme # 4

- How are the processes of tree and shrub encroachment and loss, and invasive species expansion, impacted by changing climate, grazing, fire and agriculture at regional and continental scales?

- How, and at what spatial and temporal scales, do degradation and desertification in tree-grass regions alter land surface-climate interactions and global climate patterns via positive feedbacks?
- How do degradation, landscape-scale fragmentation and loss of vegetation cover alter hydrological processes in the savannas?
- How do changes in management and climate impact susceptibility of savanna landscapes to dust generation and erosion?

2.1.5. TG Science Theme 5: Tree-Grass and Savanna Goods & Services

Science Theme # 5

- Can advances in remote sensing and modeling in the savannas improve our ability to quantify, monitor and value savanna natural capital (wood mass, grass cover, forage biomass, water, wildlife, biodiversity and non-wood savanna products, and carbon storage)
- How are climate and land use changes impacting the provision of goods and services in the savannas?
- What are the indicators of human wellbeing in savannas and can these be assessed with remote sensing and modeling approaches?
- What are the tradeoffs inherent in management to maximize one or a suite of goods and services relative to others, and how can optimal management strategies be devised?

2.2. *Tree-Grass* Earth Observation Focal Areas

Goals for Earth Observation (EO) Science within the *Tree-Grass* project are to enhance EO measurement capabilities in the savannas (remote sensing, modeling & applications), address key questions relating to current and future function of savannas and their role in the earth system, contribute to sound management, sustainability and improved human wellbeing. Three EO Science Focal Areas are proposed that cut across the Science Themes:

2.2.1. EO Focal Area 1: Tree-Grass Remote Sensing

EO Focal Area # 1

Objective: Optimize remote sensing retrievals related to vegetation structure, physiology and biogeochemistry, specific to horizontally and vertically heterogeneous tree-grass systems:

- New sensor developments, airborne and future satellite missions and sensor synergies provide new opportunities for much improved RS-retrievals in the savannas. In particular *TG* will explore:
  - New and advanced methods to retrieve and separate tree-grass vegetation structure (e.g. tree population parameters, leaf area and light interception parameters for woody and herbaceous components, aerodynamic parameters) using passive optical (broad-band and

  - hyperspectral, BRDF), active optical (LIDAR), passive and active microwave radar,
  - Improved estimation of tree-grass community physiological status (e.g. photosynthetic quantum yield, nutrient, pigment and enzyme concentrations, canopy stomatal and hydraulic properties) using broad-band and hyperspectral optical, dual or multispectral LIDAR,.,
  - Methods to improve retrievals of vegetation function (e.g. biogeochemical and energy fluxes) in tree-grass systems, either directly (e.g. thermal estimation of energy balance), or via models based on structural and physiological parameters,
  - New and improved methods to estimate environmental boundary conditions that are critical in tree-grass systems, such as soil moisture (microwave, gravity), temperature and relative humidity (thermal, optical),
  - Methods to detect and quantify management and disturbance in the savannas, including fire occurrence, coverage and intensity (thermal, optical, microwave), wood harvest, agricultural clearance, grazing, and invasive species, and the impacts of those processes on tree-grass ecosystem processes and emissions to the atmosphere,

  (Note that, although some remote sensing retrieval methodologies can be stand-alone, many are closely associated with (and will rely on) tree-grass models discussed in Section 2.2.2).

- ➢ New and/or logistically easier field measurement technologies provide new opportunities to measure vegetation structure and function, increasing our ability to develop and parameterize RS retrievals,
- ➢ *Tree-Grass* will capitalize on these emerging sensor and field-based opportunities (that were not available during earlier NASA field experiments) to make real advances in remote sensing of vegetation structure and function.

2.2.2. EO Focal Area 2: Tree-Grass Modeling

EO Focal Area # 2

Objective: Model the ecological, biophysical, biogeochemical and anthropogenic interactions in heterogeneous tree-grass systems:

- ➢ Develop and evaluate tree-grass-specific models (i.e. models that resolve tree & grass dynamics in appropriate detail) to extend and improve existing model capabilities across four primary model classes:
  - Tree-Grass Dynamic Vegetation Models (TGDVM) that simulate vegetation dynamics, tree-grass interactions and ecological responses to climate, fire, herbivory and human management
  - Tree-Grass Land Surface Models (TGLSM) that simulate land surface-atmosphere exchanges of mass (carbon, water), energy and momentum as lower boundary conditions for atmospheric circulation models

- Tree-Grass Biogeochemical Models (TGBGC) that simulate the biogeochemical cycles in vegetation and soils of carbon, nitrogen and other elements, including carbon and trace gas dynamics

Table 3. Relationships between earth system model classes and *TG* Science Themes
(X / + symbols indicate primary / secondary importance of a model class in a TG Theme)

		Class of *TG* Model				
		LSM	DVM	BGC	SIM	G&S
TG Science Theme	Land Surface-Atmosphere	X	+	+	+	
	Global Carbon Cycle	X	X	X	+	+
	Water Resources	X	+	+	X	+
	Degradation and Shrub Encroachment	+	X	+	X	+
	Savanna Goods and Services		+	+	+	X

Model Classes : *TG*-LSM = Land surface models adapted for tree-grass systems; *TG*-DVM = Dynamic vegetation models; *TG*-BGC = Biogeochemical cycle models; *TG*-SIM = Spatially interactive models; *TG*-G&S = Goods and services models.

- Tree-Grass Spatially Interactive Models (TGSIM) that simulate processes, such as surface hydrology and runoff, fire spread, herbivore movements and seed dispersal, where spatial interactions control key aspects of ecosystem function
- Tree-Grass Goods and Services Models (TGG&S) that simulate the coupled social-ecological dynamics of production, harvest and valuation of key products used by local communities (wood, charcoal, forage, food and fiber) and/or the production and value of indirect ‘goods and services (carbon sequestration, water-conservation and purification, greenhouse gas mitigation, and additional social and cultural values offered by savanna landscapes).

(note that hybrid models combining one or several aspects of the above model-classes are appropriate and expected as part of EO Focal Area 2)

- ➢ models that use improved remote sensing-based ‘savanna retrievals’
- ➢ and models that are purposefully designed to be ‘data-assimilation-ready’ (i.e. with model structures and computational ability to use new and emerging remote sensing products),
- ➢ *Tree-Grass* must facilitate development and testing of savanna models, assessment of errors using conventional and savanna-specific models, and determine the level of detail required to simulate savanna function at

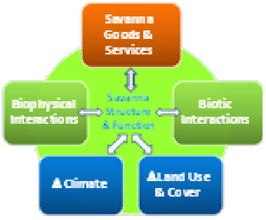
precisions appropriate to earth system modeling needs and *Tree-Grass* Science Themes (Figure 4).

2.2.3. EO Focal Area 3: Data Assimilation

EO Focal Area # 3

Objective: Capitalize on emerging model-data-assimilation (MDA) methodologies, and improving tree-grass remote sensing retrievals, to further the assimilation of diverse EO data streams into earth system models, improve model performance, and provide fully integrated EO solutions that will be valuable for monitoring and managing terrestrial ecosystems.

- Constrain earth system models with spatially and temporally resolved remote sensing and field based data. In particular *TG* will focus on:
  - Enhancing adoption of remote sensing data into tree-grass models via formal MDA (e.g. Barrett et al. 2005); this capability is currently more advanced in certain Land Surface Models (Kaminski et al. 2002; Renzullo et al. 2008) and Hydrological Models (Franks and Beven 1000; Freer et al. 1996), but relatively undeveloped for other model classes or in formulations appropriate to tree-grass systems
  - Exploring the reformulation of MDA from the common situation of "temporally rich-spatially poor" (e.g. climate model assimilation of meteorological station data) to the "temporally poor-spatially rich" situation appropriate for longer-term vegetation community and ecosystem processes
- New data assimilation and model-data fusion approaches provide opportunities (not available during earlier NASA field campaigns) to more closely integrate earth system models with geospatial datasets (Luo et al. 2011)
- *Tree-Grass* will capitalize on the emerging and convergent opportunities provided by improved data assimilation and remote sensing technologies to realize the full potential of remote sensing in earth system models and improve our ability to monitor, diagnose and predict earth system dynamics



2.3 *Tree-Grass* Interdisciplinary Applications: Human Wellbeing and Sustainability

NASA has long sought to develop remote sensing products and earth observation systems that can be applied for management of the earth system to the benefit of mankind. This aim is particularly pertinent in the global savannas and tree-grass systems that often support economically and politically marginalized rural communities.

Goals for *Tree-Grass* Interdisciplinary Applications are to enhance understanding and prediction, and contribute to improved sustainability and human wellbeing. *Tree-Grass* research will provide opportunities to:

- monitor trends in savanna health, sustainability, resilience and vulnerability;
- provide integrated predictions of how the role of savannas in the earth system (carbon, water, energy, atmospheric chemistry and dynamics) will change with changing climate and land use on ;
- assess the likely impacts and trade-offs in provision of goods and services with changing climate and land use;
- contribute to local, national and international management of savannas;
- benefit the often poor and vulnerable human populations that rely on global tree-grass and savanna ecosystems.

3. *Tree-Grass* Research Strategy

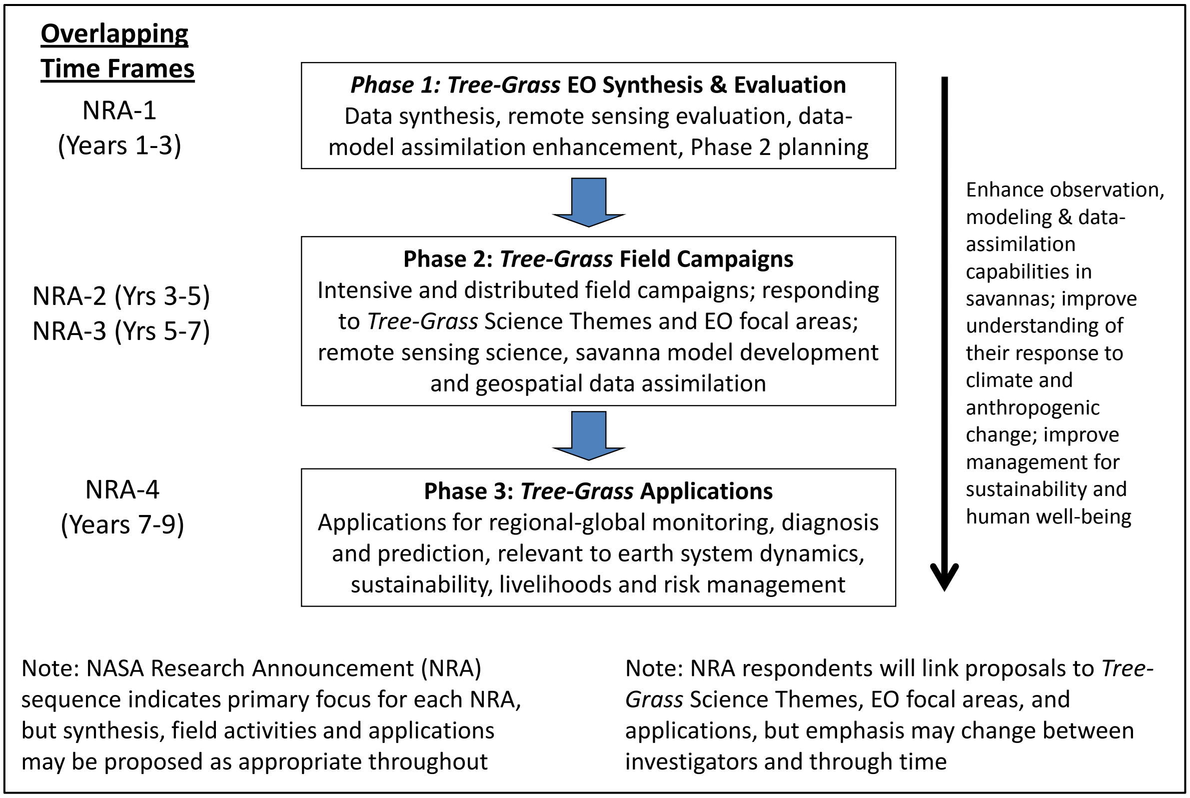
3.1 Overall Approach

Tree-Grass Approach

The *TG* Science Framework presented in Section 2 (Figure 4) outlines the Overarching Questions, Science Themes and EO Science Focal Areas for the *Tree-Grass* activity. In this section we detail strategies and research priorities for a phased implementation of the *TG* research program (Figure 5).

Research funds in Phase 1 will concentrate (primarily, but not exclusively) on synthesis and evaluation of remote sensing, modeling and data assimilation technologies in the savannas and more detailed planning of field, remote sensing and modeling activities in Phases 2 and 3. Phase 2 will focus on intensive and extensive field research to improve remote sensing, model and data assimilation technologies (i.e. the EO Focal Area) across the five *TG* Science Themes, and activities in Phase 3 will focus on development of applications relevant to monitoring and prediction, and on-the-ground management for sustainability and livelihoods in the world's savanna regions (*TG* Interdisciplinary Applications). Education and outreach programs will be implemented throughout the *TG* program and will be designed not only to help develop next generation EO scientists, but will also focus on transfer of knowledge and ready-to-implement applications for practitioners and managers in the USA and internationally (Section 4).

The *TG* program will be highly interdisciplinary across multiple Science Themes, Earth Observation Focal Areas and field activities. *TG* will be a proposal-driven activity in which compelling individual and team proposals will determine the research portfolio emerging, with coordination from NASA and *TG* project managers to ensure program coherence.



Note: NASA Research Announcement (NRA) sequence indicates primary focus for each NRA, but synthesis, field activities and applications may be proposed as appropriate throughout

Note: NRA respondents will link proposals to *Tree-Grass* Science Themes, EO focal areas, and applications, but emphasis may change between investigators and through time

Figure 5. Implementation Strategy for the *Tree-Grass* research program

3.2 Candidate Study Sites and Regions

Field research in *TG* will reflect a strategy for very detailed, geographically focused and comprehensive research at a limited number of "*Intensive*" savanna field sites, in one (or more) regions, with a complementary program of less detailed, more globally representative, research at a larger number of "*Distributed*" field sites (Figure 6). This strategy will promote the synergies and efficiencies inherent in the concentration of resources and cutting edge research in ecosystem function, remote sensing and modeling at *Intensive* sites, while *Distributed* sites will sample the huge range of structural, physiological, bioclimate, edaphic and anthropogenic diversity in the global savannas. Thus, where the *Intensive* sites may be the primary locus of technological advances in remote sensing science and savanna modeling during the *TG* program, the *Distributed* sites will provide opportunities for application, parameterization and validation of new EO technologies across globally diverse tree-grass structural and functional characteristics.

Tree-Grass Intensive Field Sites

***<u>Intensive</u>* <u>Sites:</u>** *Intensive* sites supported by NASA as part of the *TG* program will be located in North America, in key tree-grass ecosystems of the continental USA, with possible addition of sites in Northern Mexico if needed to capture climatic or other environmental or management gradients (Figure 6a). NASA and the *Tree-Grass* program should begin selection of study regions and sites during project planning prior to Phase 1, and complete selection during Phase 1, after appropriate consultation with the community of actual (and potential) lead investigators. *Intensive* study regions will leverage existing sites and infrastructure. Candidate regions suggested here include a north-south transect in oak and pine savannas along the deciduous woodland-prairie boundaries of Wisconsin-Illinois-Missouri-Arkansas-Texas (the “Ecotone Transect”), and an east-west transect from south-western Texas into New Mexico, Arizona and California (mesquite, creosote pinyon-juniper and oak shrublands – the “Southwest Transect” (Figure 6a). In addition to their differences in species composition, shrub/tree morphology and stature, these transects provide contrasting rainfall and temperature climate and seasonality gradients, as well as contrasting physiological (e.g. C3 and C4 physiology of grasses) and functional characteristics (e.g. role of biotic invasions, fire and grazing). Specific sites in these regions could be selected from existing long term study sites (e.g. long-term ecological research sites, Ameriflux, Agricultural Research Service and individually established sites), to benefit from historical data and existing infrastructure. Alternatively, new sites may be developed for more targeted sampling of specific eco-climatic, edaphic or management gradients.

Individual PIs or consortia of PIs will be able to nominate specific sites or a network of sites as primary locations for intensive activities. To avoid dilution of resources and ensure critical mass at the intensive research sites, however, research teams may be requested to move their activities to *TG*-agreed intensive sites rather than implement proposed activities at other locations.

Tree-Grass Distributed Field Sites

<u>Distributed</u> **<u>Sites:</u>** *TG Distributed* site selection (and planning for the types and extent of activities that will be carried out on these sites), will begin prior to, and be finalized during, Phase 1, in consultation with the *TG* and international science community. *Distributed* sites will likely include already-established field sites in tree-grass and savanna locations in North America and world-wide, and new locations selected to improve spatial sampling of tree-grass structural and functional variability. Data from many already-established sites would be compiled for the *TG* database in Phase 1 (Figure 6b).

TG activities at *Distributed* sites will concentrate on measurements of ecosystem structure and function of value to the larger *TG* program in provision of geographically, climatically and ecologically distributed data for parameterization and validation of remote sensing retrievals and model simulations. The type, frequency and duration of research that may be proposed at the *Distributed* sites will depend on the science needs of each proposal, but should reflect the ‘large number of sites sampled at low intensity’ strategy of these sites. Given the potential number and global distribution of *Distributed* sites, a minimal

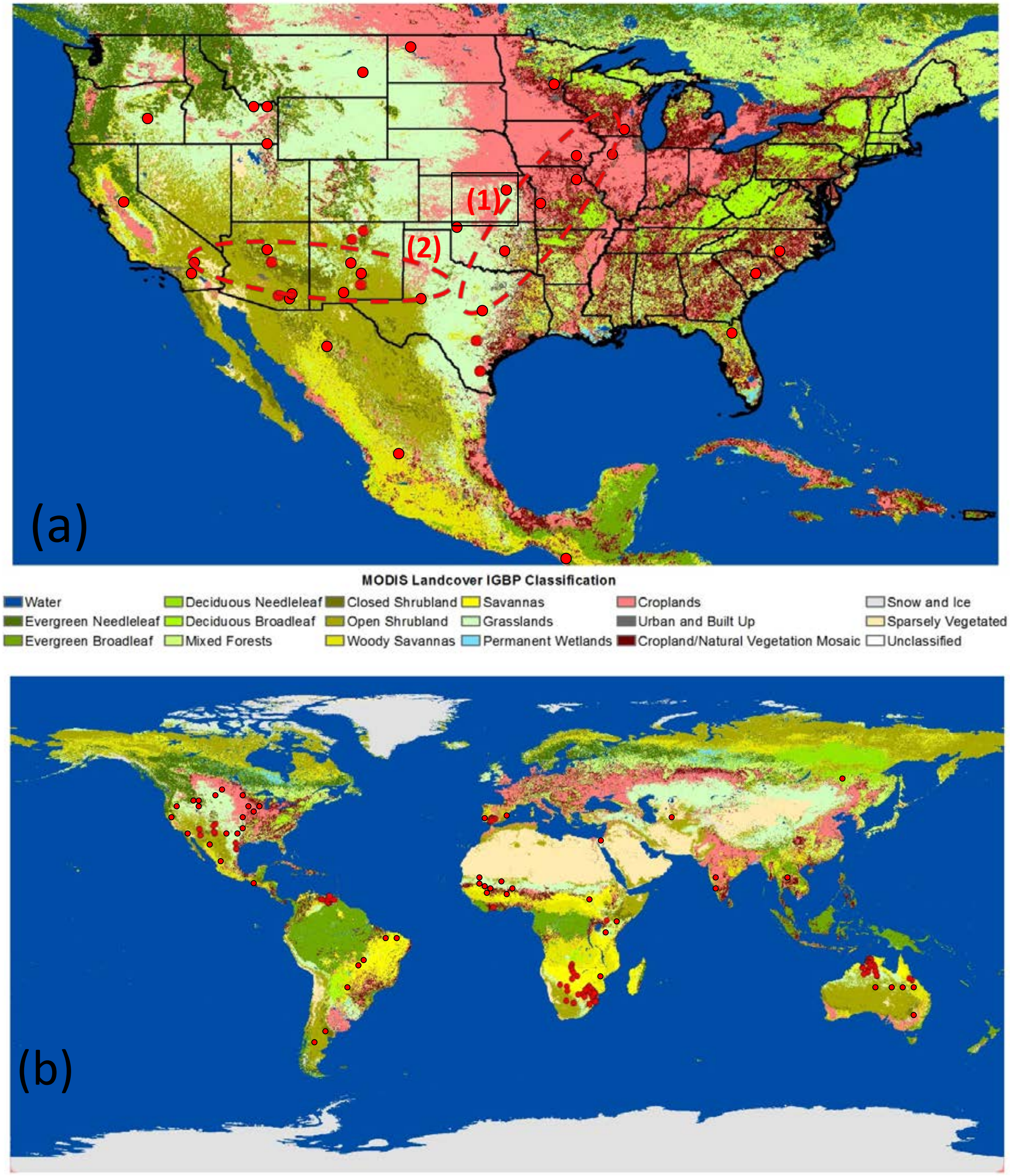


Figure 6: Distribution of potential *TG Intensive* and *Distributed* field sites in the Continental USA and globally. (a) candidate intensive study regions (red ellipses) in the continental USA, and location of established historical and active study sites (red circles) that could contribute to *TG* as *Intensive* or *Distributed* field sites, (b) locations of established field sites in global tree-grass systems (red circles) that could serve as *TG Distributed* Field or, in some cases, be developed as *International Intensives* by international partners (e.g. the Northern Australian Tropical Transect in Australia).

measurement set could involve high resolution remote sensing assessments of vegetation parameters that can be used to calibrate or validate coarser resolution remote sensing or model-based assessments, with little or no field component, or could involve single or infrequent visits with rapid assessment of selected key parameters. To facilitate international collaborations in *TG,* and reduce travel costs, activities at international *Distributed* sites should involve local collaborators, in so far as is possible given local sources of funding and NASA regulations regarding support for international participants.

3.3 Phase 1: *Tree-Grass* EO Synthesis and Evaluation

3.3.1 Phase 1 Strategy

Tree-Grass
Phase 1 Strategy

Phase 1 of *TG* will focus on the synthesis and evaluation of existing global datasets, remote sensing technologies and modeling capabilities as currently applied to tree-grass systems. Studies will be organized with regard to the five *TG* Science Themes (Figure 3), or combinations thereof, and with regard to the three EO-Science Focal Areas. Field research will not be a priority for Phase 1 projects but might be proposed as an integral component of proposals where limited field measurements or methods development are considered crucial and can be implemented as a minor cost component of the overall project.

Priority research in Phase 1 will include integration of existing field and remote sensing data from intensive and *Distributed* field sites worldwide, model assessment, development and benchmarking, and assessment and evaluation of data-assimilation methodologies for tree-grass and savanna models. Proposals in Phase 1 may concentrate on one of these aspects but most will integrate data synthesis activities with one or more of the EO-Science Focal Areas.

An important goal is to test the capacity of field data sets to develop and test robust and scalable methods using remote sensing to measure key structural and functional parameters in tree-grass ecosystems. A prototype set of key variables and parameters for savanna function is listed in Table 4. The activities in Phase 1 will provide a comprehensive survey of current EO capabilities in tree-grass and savanna systems (including field, model and remote sensing resources and capabilities). This will form the basis for detailed planning and preparation for field activities in Phase 2, and ensure that the science of Phases 1 and 2 of the project extend our ability in Phase 3 to contribute to improved management and sustainability of savannas and tree-grass systems worldwide.

Research Priorities: Research funded in Phase 1 will focus on compilation and synthesis of field measurements, airborne and satellite imagery for all sites where data availability indicate they may provide useful contributions to the larger *TG* database, model-based exploration of the errors and uncertainties of current-generation models in simulating *TG* systems, and assessment of model development needs. The *TG* database development will also be a focus of Phase 1 with contributions from individual projects and/or stand-alone data collation activities.

Tree-Grass
Phase 1 Science

3.3.2. Phase 1 Science Components

Field Data: Field data suited to this activity include existing carbon, water and energy flux measurements, vegetation structure (tree, shrub and herbaceous species composition, demography), phenology, productivity, physiological, morphological and biogeochemical plant traits, carbon pools above and below ground, soil depth, texture and hydrological characteristics. Candidate sites include FluxNet sites in semi-arid and Mediterranean temperate climate and the drought seasonal tropics, and potentially large numbers of field sites worldwide where historical and current vegetation structure and dynamics measurements have been made by ecologists, foresters and others for a variety of reasons (e.g. GTOS/GCOS).

Remote Sensing Science: Remote sensing compilations will focus on collection, processing and standardization of a full suite of EO data from airborne and satellite sources in tree-grass regions (coincident with field sites and/or providing coverage of larger regions and/or continents); assessment and inter-comparison of retrievals for model initialization and parameterization. At present two-layered tree grass systems are not effectively described by satellite remote sensing data sets. This component will propose, develop and test improved retrievals of savanna structure and function from remote sensing using historical and current remote sensing data. Remote sensing methods development for anticipated future (satellite or sub-orbital) instruments, using model or instrument simulators, would also be appropriate in Phase 1.

Modeling: Modeling components will focus on development of parameter sets and initialization data for tree-grass-adapted Dynamic Vegetation Models (TGDVM), land surface models (TGLSM), biogeochemical models (TGBGC), spatially interactive models (TGSIM) and Goods and Services models (TGG&S) at landscape and regional scales; testing of models with historical and limited supplementary data; assessment of parameter redundancy, model structural issues, scaling potential and adaptation to ingest remote sensing data. Improvement of the five model classes, or hybrid combinations, to take account of the physiological, structural and biogeochemical heterogeneity of tree-grass systems will improve our ability to simulate tree-grass population dynamics and responses to variations in climate and disturbances (e.g. fire, herbivory, disease and harvest), the fluxes of energy, water, carbon, and momentum for climate model applications, and the major biogeochemical cycles of water, carbon, nitrogen and other elements at a range of scales from patch-scale, to landscape, regional and global.

Data Assimilation: Model-data assimilation research will focus on the use of diverse remote sensing datasets using model-data assimilation frameworks for parameterization and prediction. This may make use of existing or novel MDA frameworks with specific reorientation to efficient assimilation of spatially continuous, but temporally discontinuous remote sensing data that contrasts the more common MDA problem using spatially discontinuous, but temporally frequent, data inputs.

Phase 1 activities will define current state-of-the-art in EO applications (remote sensing, modeling and data assimilation) for the savannas, and build on those assessments to refine priority field, remote sensing and modeling needs for Phase 2. Comprehensive data collation, remote sensing and model assessments in Phase 1 will provide key datasets to avoid duplication of effort and increase the efficiency and productivity of research in Phases 2 and 3 of the Tree-Grass program.

3.4 Phase 2: *Tree-Grass* Field Campaigns

3.4.1 Phase 2 Strategy

Tree-Grass
Phase 2 Strategy

Following the synthesis and recommendations for priority research emerging during Phase 1, projects funded in Phase 2 will focus on novel combinations of field research, tightly integrated with the three EO-Science Focal Areas, and the five *TG* Science Themes (Figure 3). *TG* field activities will combine detailed and comprehensive measurements at a small number of *Intensive* field sites, with relatively lower-intensity field sampling at a larger number of *Distributed* field sites. This combination of *Intensive* and *Distributed* field sites will allow *TG* to emphasize detailed and transformational science at the *Intensive* sites, while recognizing & sampling the huge diversity (in phylogeny, structure, function and management) of tree-grass systems at global scales via the *Distributed* field sites.

TG field research may include both observational and experimental research (i.e. with or without manipulation of abiotic or biotic, “natural” and anthropogenic variables, and with or without replication, as appropriate to the science) as long as observational and manipulative measurement scales are appropriate for the intended remote sensing data and/or model analysis involved. Observational and experimental field work will be designed to explore tree-grass structure and function for key model parameters and key remote sensing retrievals (Table 4; Appendix 4). Field measurements oriented with respect to climatic (e.g. rainfall, temperature) and edaphic (e.g. soil, topography) gradients are appropriate.

Research Priorities: Research funded in Phase 2 will focus on new and innovative field-based research directed at advancing the EO-Science Focal Areas of Remote Sensing Science, Modeling and Data Assimilation in tree-grass and savanna ecosystems. Investigators can propose to work at either or both *Intensive* and *Distributed* field sites. They can propose to do no field work themselves, as long as they make use of data from field sites. Priority projects, however, are likely to include field work well integrated with *TG*-Science Themes and EO-Science Focal Areas. Investigators may propose intensive or *Distributed* field measurements at specific locations, or indicate flexibility to work at sites selected by the larger *TG* program. With particular respect to field activities proposed in Phase 2, measurement programs relevant to multiple *TG* Science Themes (e.g. community and landscape scale vegetation structure and composition measurements; landscape scale soil moisture and hydrology; community and landscape-scale energy, water and carbon fluxes), and multiple EO Science Focal Areas, will be prioritized.

Tree-Grass
Phase 2 Science

3.4.2. Phase 2 Science Components

Field Data: Field measurement programs appropriate in Phase 2 include measurements of vegetation structure (tree, shrub and herbaceous species composition, demography), productivity, physiological, morphological and biogeochemical traits; carbon pools above and below ground; soil depth, texture, biogeochemical and hydrological characteristics; carbon, water, momentum and energy fluxes at plant, stand and landscape scales; and hydrological processes across similar scales (Table 4). Measurements to quantify ecosystem goods and services are appropriate, including direct provision of food, water, fiber, biofuels and other services for humans, and fodder for domestic animals and wildlife, and indirect services relating to ecosystem sources, sinks and storage of carbon, water and trace gases that govern the role of tree-grass systems in climate regulation and change at regional to global scales.

Remote Sensing Science: Remote sensing science programs appropriate in Phase 2 may include detailed field-based radiometry at leaf, canopy and landscape scales, airborne remote sensing using NASA assets, private or commercial platforms, and satellite data acquisitions. Investigator teams may propose research across optical, thermal and microwave domains, including both active and passive systems, as appropriate to their science. Priority will be given to novel remote sensing science proposals, addressing specific tree-grass and savanna remote sensing science issues. Proposals will generally include (but in some cases may benefit from) field measurements at *Intensive* and/or *Distributed TG* field sites to develop, test and validate remote sensing retrievals of tree-grass ecosystem structural and functional parameters.

Table 4. Scale-associated key parameters of structure and function in tree-grass systems

Scale/Category	Properties
Leaf properties	Quantum efficiency, photosynthesis, respiration, transpiration rates; nutrient, chlorophyll, enzyme, pigment and phenolic concentrations; leaf structure; leaf water, temperature and spectral characteristics
Tree and shrub properties	Species; stem density, above- and below-ground canopy architecture, within-canopy LAI; leaf angle distributions; radiative transfer; carbon, water and nutrient pools, fluxes and allocation, functional and physiological traits (N-fixing, fire and herbivore sensitivity and adaptations, reproductive and regenerative strategies)
Herbaceous properties	Species; basal density and cover, above- and below-ground canopy architecture; LAI; leaf angle distributions; radiative transfer; carbon, water and nutrient pools, fluxes and allocation, functional and physiological traits (N-fixing, grass/forb, C3/C4, annual/perennial, fire and herbivore sensitivity and adaptations, reproductive and regenerative strategies); pyro-characteristics (seasonal fuel flammability, intensity and emission properties)
Community/patch properties	Soil characteristics, soil moisture and hydrology; species and functional composition; woody and herbaceous density, cover and biomass; vertical and horizontal heterogeneity and patch metrics; radiative transfer, energy balance, evapotranspiration, carbon and trace gas fluxes; site management and disturbance history
Landscape / watershed properties	Topography and spatial characteristics of soil type, hydrological and ecological properties; landscape/watershed characterization, management and disturbance history; fire history and spatial distribution
Regional properties	Community associations; connectivity and flows of biota, water and nutrients; land use patterns; administrative boundaries; climate gradients and mesoscale interactions

Modeling: Modeling activities in Phase 2 will concentrate on tree-grass model development in the primary model classes (TGDVM, TGLSM, TGBGC, TGSIM and TGG&S; Table 3) appropriate to *TG* Science Themes and the specific research proposed. Proposals will generally include (but in some cases may benefit from) field measurements at *Intensive* and/or *Distributed* TG field sites that will be used to refine parameter sets, adjust and modify model formulation and initialization at community, landscape and regional scales. Studies will evaluate the degree of model complexity necessary for tree-grass applications, iteratively refine models with newly acquired field and remote sensing data, assess model validity, uncertainty, sensitivity and parameter redundancy, and define methodologies for scaling, model-nesting and multi-scale model integration.

Data Assimilation: Model-data assimilation research in Phase 2 will extend MDA activities in Phase 1 to benefit from improved and emerging models and remote sensing retrievals specific to the structural and functional complexities of tree-grass and savanna systems. MDA activities in Phase 2 will likely be linked with model development and remote sensing science activities, as well as to field measurements at *Intensive* and/or *Distributed* field sites. Linked or consortium proposals may be particularly suited to assure the inter-disciplinary integration of field, RSS, model & MDA activities.

Phase 2 activities will redefine and transform EO science (remote sensing, modeling and data assimilation) for tree-grass and savanna systems. It will contribute significant new understanding of how savannas interact in the earth system and the role of human management and societal feedbacks. Comprehensive new remote sensing and modeling capabilities emerging from the integrated field programs in Phase 2 will lay crucial foundations for the Interdisciplinary Applications planned in Phase 3 of the *Tree-Grass* program.

3.5 Phase 3: *Tree-Grass* Applications

Tree-Grass
Phase 3 Strategy

3.5.1 Phase 3 Strategy

Phase 3 of the *Tree-Grass* program will emphasize synthesis of *TG* science and model applications to explore the Overarching Questions (Section 1.5) relating to how tree-grass and savanna biomes will change with climate and land use in future decades, how such changes in the savannas will feedback on the earth system, and how these coupled interactions will impact livelihoods and well-being for the human societies living in, and dependent on, those savanna regions.

Phase 3 will also emphasize the transfer of Earth Observation capabilities and technologies, derived as part of *TG* research, to understanding, prediction and management of the savannas at landscape to global scales. Projects will address key questions and develop solution-based applications relating to *TG* Science Themes (Land Surface-Atmosphere Interactions, Global Carbon Cycle, Water Resources, Degradation and Shrub Encroachment, and Savanna Goods and Services), using the enhanced EO capabilities developed during Phase 2 field campaigns and via the EO-Science Focal Areas (Remote Sensing Science, Modeling and Data Assimilation). Proposals in Phase 3 should include outreach and technology transfer plans with appropriate team membership and allocation of resources.

Field research will not be a priority for Phase 3 projects but might be proposed as an integral component of proposals where limited additional field measurements are considered crucial. Field activities may also be proposed in so far as they contribute to outreach, education and applications, or provide context and opportunity for demonstration of *TG* science to diverse stakeholder communities.

Research Priorities: Research priorities in Phase 3 will emphasize integrated remote sensing and modeling studies that address the questions outlined for the five *TG* Science Themes in Section 2.1. Geographic focus in Phase 3 will be proposal-driven, but research and applications proposals relating to savanna goods and services, management and sustainability of tree-grass systems may focus on the regions associated with *TG Intensive* or *Distributed* field sites. Proposals may also apply models and remote sensing technologies at coarser scales in North America as well as in global tree-grass systems where livelihoods, food security and human wellbeing are closely coupled to savanna dynamics, and where sustainability and productivity are threatened by climate change and degradation. Model studies of tree-grass dynamics under scenarios of future climate and land use change, and how these will impact earth system interactions and provision of goods and services, will be relevant in Phase 3.

4. *Tree-Grass* Education and Outreach

Education and outreach activities will be an integral part of *Tree-Grass*. Emphasis on graduate and undergraduate education, K-12 education, outreach to the general public, and outreach and technology transfer to practitioners and managers, will change during the course of Phases 1-3 (Table 5).

Tree-Grass
Graduate Studies

4.1 Graduate Research Fellowship Program (GRFP)

Graduate student education will be encouraged during all phases of the *Tree-Grass* program. Students will work with individual investigators, funded through inclusion of GRFP costs in PI-led research proposals submitted to biannual NASA Research Announcements. Areas of emphasis for graduate education and research will evolve to reflect changing *TG* emphasis through Phases 1-3. In addition to coursework and dissertation research at home institutions, all GRFP Fellows will participate in GRFP team-building, co-mentoring and enrichment programs organized by an individual or team of PIs funded via a special GRFP co-ordination element in NRA-1 and NRA-3 (see Table x). Competitive GRFP coordination proposals will outline plans to build and strengthen peer networking among GRFP Fellows, via innovative combinations exploiting the power of electronic communication and social-media, supplemented by annual or biannual side-meetings at *TG* workshops and/or major conferences. In Years 3-7 GRFP Fellows will also have opportunities to participate (as students *and* educators) in the E4S Summer Schools (see Section 4.2).

Table 5. ***Tree-grass*** **education and outreach programs (GRFP = Graduate Research Fellowship Program; E4S = Earth System Science Summer Schools; TTAP = Technology Transfer & Adoption Program). * indicates where practitioners and managers will be asked to advise on the long-term research needs and priorities of** ***TG*** **stakeholders.**

Tree-Grass Phase	Year	Graduate Student	K-12	Under-graduate	General Public	Practitioners	Managers
Phase 1	1	X				*	*
	2	X				*	*
Phase 2	3	X	X	X	X	*	*
	4	X	X	X	X		
	5	X	X	X	X		
	6	X	X	X	X		
Phase 3	7	X	X	X	X	X	X
	8	X				X	X
	9	X				X	X

GRFP E4S TTAP

4.2 Earth System Science Summer Schools (E4S)

Tree-Grass Summer Schools

The E4S will be organized by a consortium of *TG* investigators during Years 3-7 of the *TG* program, funded as a stand-alone element of NRA-2 and NRA-3. Summer Schools will be co-located at one or more *Intensive* field sites and could be designed to reach the general public, K-12 school children, undergraduate and graduate students. E4S activities will be organized to leverage opportunities provided by a large and interdisciplinary field-based research program, including field, airborne and satellite instrumentation, and the expertise and enthusiasm of the large number of investigators and students participating. While E4S curricula will draw from *TG* Science and EO Focal Areas, they should also go further to inform target audiences of the broad societal relevance and importance of Earth System Science and Earth Observation.

Competitive E4S coordination proposals will outline novel and exciting plans to educate and engage one or several target audiences. This might include participation in field research for younger students and the general public (potentially including GRFP Fellows as instructors), and introductions to the role of NASA and earth observation technologies in understanding and managing our planet. It could also include advanced theoretical instruction and/or practical experience with remote sensing, modeling and data assimilation for more advanced students (potentially including GRFP fellows as students). Summer schools may be of varying duration with/without a residential component, as appropriate to the target audience.

4.3 Technology Transfer and Adoption Program (TTAP)

Tree-Grass Technology Transfer

The TTAP will be a cornerstone of Phase 3, designed to facilitate and enhance the transfer and adoption of EO technologies to and by appropriate stakeholders, practitioners and managers. TTAP will have a 'research-to-applications' and 'communications' focus and could, for example, engage GRFP Fellows, many of whom will be working on *TG* Applications (i.e. Phase 3) projects, in outreach and education. Suitable activities might include web-accessible teaching tools (literature, data and software) and outreach to US teachers on what *TG* products might be used in earth systems science classes, how they can be used, and why it might be of interest and importance to the students. Similarly, short-course Professional Development opportunities might be developed for State, federal, private and/or public land managers to learn state-of-the-art remote sensing and modeling techniques for US and global tree-grass systems. Such activities will require explicit consideration by *TG* investigators not only of the how to make research tools operationally valuable, but also the communication and pedagogical methods that will promote understanding, acceptance and adoption of these new tools by the potential user communities.

TTAP activities will be proposed by an individual or consortium of PI's as a stand-alone element of NRA-4. Mechanisms for outreach and technology transfer may be diverse including direct contact to potential users as well as broad dissemination of results to regional, national and global audiences. TTAP will have dual aims of directly reaching target audiences (managers etc.) via short courses, demonstrations, electronic and print media, whilst also educating *TG* investigators to enhance outreach and communication of key results and technologies developed by individual research teams.

5. *Tree-Grass* Organization and Management

5.1 Scientific Leadership

Tree-Grass Leadership

The *TG* program will be a partnership between NASA and the US Science community, with key international collaborations. Oversight and scientific direction will be provided by a Science Steering Committee (SSC), with representatives from the "tree-grass research" community (academic, Federal, State researchers), and representatives from stakeholder communities (broadly defined as land managers and potential users of improved EO capabilities in tree-grass regions). The SSC should hold regular electronic and teleconference meetings and convene approximately twice-yearly in person for strategic planning and evaluation of *TG* progress. The SSC will be chaired by the *TG*

Project Scientist. The *TG* Project Scientist will be a senior scientist, with experience and interest in *TG* Science and NASA Terrestrial Ecology field programs. This key individual will be selected by NASA from the academic or governmental research community and will be the lead science representative for *TG*. Given the proposed 9-year duration of the *TG* project, the Project Scientist position might be re-selected at approximately 3-year intervals to correspond with Phases 1-3 of the project.

The SSC may also include representatives from international partners. These would be key researchers, or representatives from research funding agencies, participating in *TG* via their field, remote sensing or modeling activities. International representatives will serve to enhance coordination and collaboration between the US based science community and international partners operating International *Distributed* or *Intensive* field sites and participating in regional-to-global remote sensing, modeling and synthesis.

The SCC will delegate the task of detailed planning of *TG* Phases 2-3 to a sub-committee entitled the Science Definition Committee (SDC). The SDC will include member of the SSC, representing the science and programmatic aims of *TG*, and representatives from the *TG* Project Office (see Section 5.2) responsible for the practical and logistical aspects of implementation. The SDC will also consult with Phase 1 PI-led science teams and the wider science community to facilitate dialogue on science directions during *TG* Phases 2 and 3.

5.2 Project Management

Tree-Grass
Management

The *TG* Project Office (Figure 7) will manage day-to-day operations, field and data-related logistics, and liaison between the SSC, SDC and PI-led research teams. The *TG* Project Office will be led by a full-time *TG* Project Manager. The Project Manager will report directly to the Project Scientist and SSC and be tasked with overall management of *TG* implementation plans as agreed with the SSC and SDC. The Project Manager will be assisted by Project Office administrative staff (estimated at 2 FTE) for budget and personnel management. A Science Team Coordinator (1 FTE) will be responsible for liaison between the Project Office and PI's, and coordinate with PI-led Education and Outreach activities. The Project Office will also direct a post-doctoral level researcher (1 FTE) to coordinate "core data products", synthesis and analysis activities (i.e. products of broad *TG* community interest that can be more efficiently generated centrally, using agreed methodologies, than by individual teams).

The Project Office will also include the *TG* Data Team and *TG* Logistics Team (Figure 7) who will report to the Project Manager. Rather than develop new and independent database infrastructure, *TG* will work with one of the existing Distributed Active Archive Centers (DAACs, e.g. Oak Ridge National Laboratory) to archive and serve *TG* data for public access. The *TG* Data Team (2 FTE in

Phases 1-3 of the project), staffed with two data management/technical staff, will coordinate between PI-led science teams and the DAAC to facilitate data flows and quality assurance. In Phase 1 (and as needed in later Phases) the *TG* Data Team will also work with the Project Office postdoc to provide data collation and analysis for "core data products".

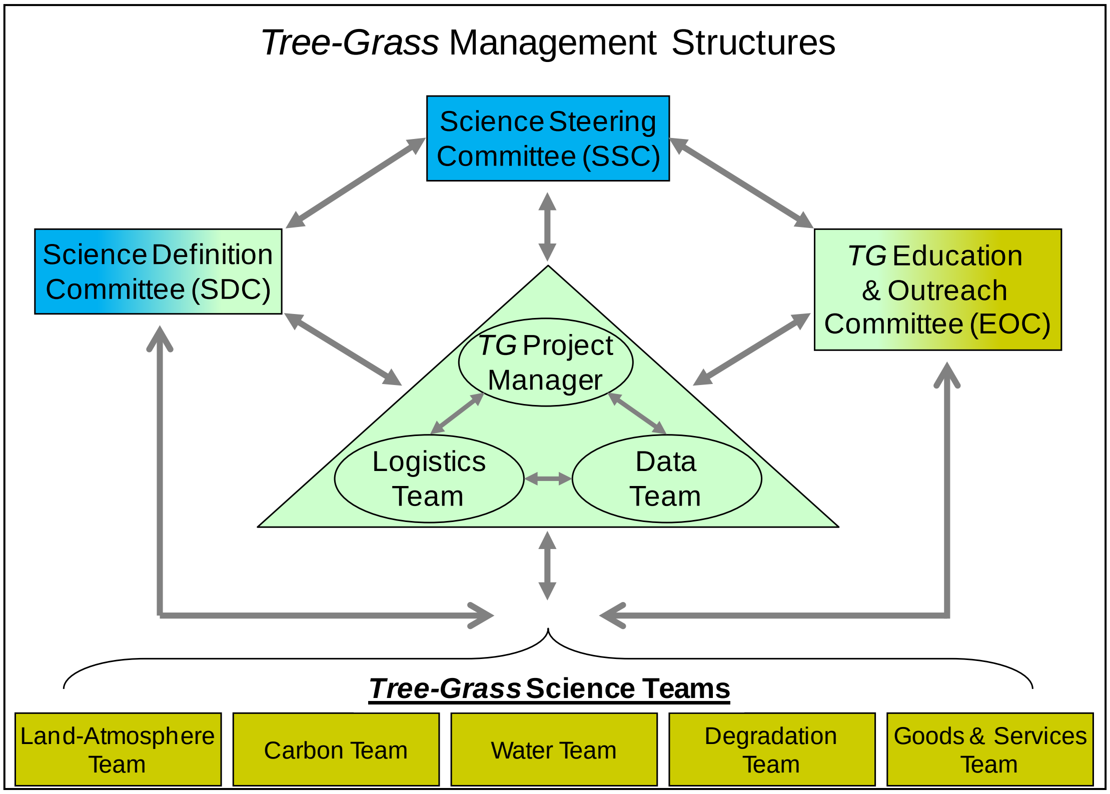


Figure 7. Management and Organizational Structures for *Tree-Grass*, showing scientific oversight (SSC in blue), *TG* Project Office (in green) and PI-led *TG* Science Teams (in yellow) and relationships between them (arrows). The Science Definition and Education and Outreach Committees would be constituted by representatives from Steering Committee, Project Office and PI teams as indicated in colors.

The logistical support team (3 FTE during Phase 2 of the project) will be responsible for critical field infrastructure and any instrumentation or measurements that are assigned to the Project Office as a core service for the PI-led research teams (see Section 5.4). The Data Team and Logistics Team will report to the Project Manager.

The *Tree-Grass* Science Teams will include PI's with research interests in the five *TG* Science Themes (Figure 7) who are supported by NASA as part of *TG* Phases 1 - 3. Membership of the Science Teams may well overlap and will change as the portfolio of PI-led projects changes. Conveners for each Science Team will be selected in consultation with the SSC and the *TG* Project Scientist. The Project Scientist and Project Manager will participate as ex officio members of each

Science Team to ensure communications among and between SSC, Project Office and Science Teams. Science Team activities will be facilitated and coordinated by the Science Team Coordinator (employed in the Project Office) who will assist with organization of Team workshops and communication.

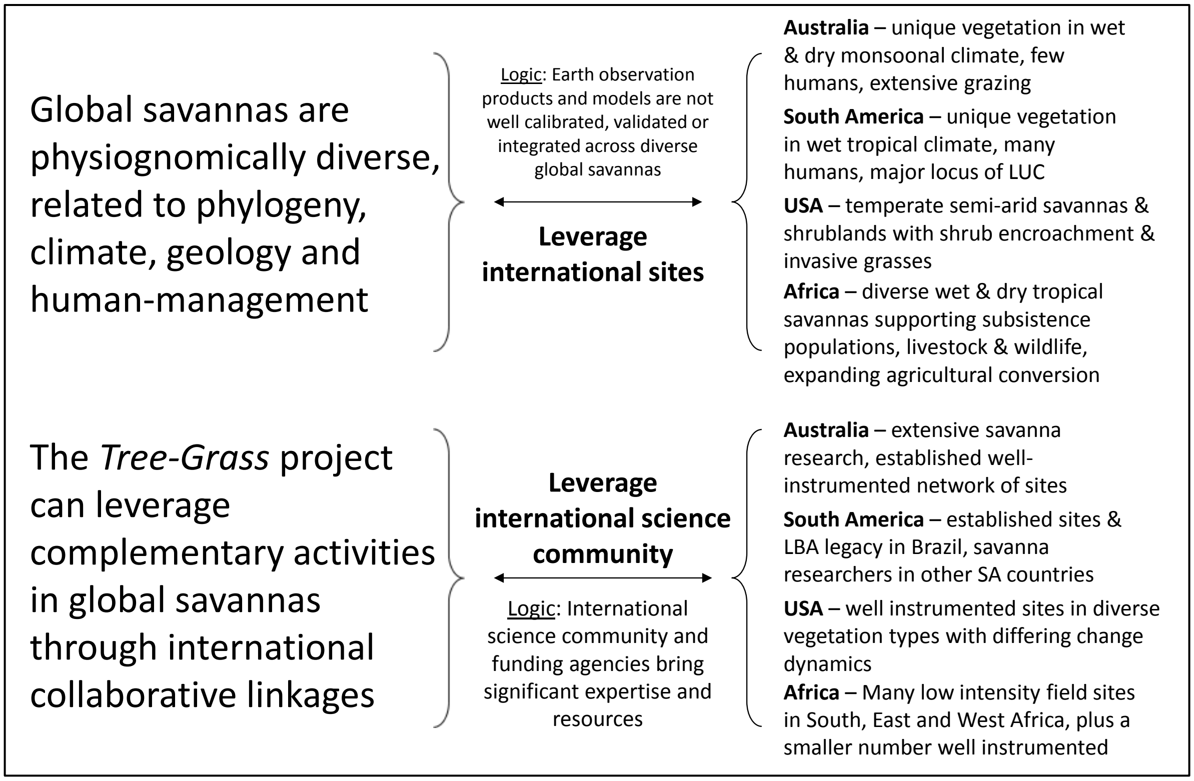
The role of the Science Teams is to coordinate among PI-led projects, and with the Project Office, to ensure coherent progress towards the aims and objectives of the corresponding *TG* Science Themes. This may include discussion and coordination of PI-led research to fill gaps and enhance synergies. It may also include discussions with SDC and SSC on research strategies and priorities, and efforts to ensure collaboration and integration with the other Science Teams and corresponding Science Themes.

Education and Outreach activities during *TG* will be coordinated by individual PI's or consortia of PI's via an independent proposals process (or potentially organized as education supplements to funded research proposals), as part of NRAs 1, 2, and 4. The Project Office, via the Science Team Coordinator, will contribute to and assist with the activities planned as part of the Graduate Research Fellowship Program (GRFP), the Earth System Science Summer Schools (E4S) and the Technology Transfer and Adoption Program (TTAP) (see Table 5).

5.3 Partnerships and Collaborations

Tree-Grass Partners

Within the United States the *Tree-Grass* program is particularly relevant to the research interests and management missions of a large number of academics, researchers, extension officers and managers in universities, State and Federal agencies. In particular, researchers and managers of non-agricultural lands (grazing lands and protected areas) across huge areas of Western and Southern United States, from the Long-leaf pine savannas of Florida, through to the oak and scrub savannas of Texas, New Mexico and Arizona; in the shrublands of the Colorado Plateau and Great Basin; in the Mediterranean savannas of California, and in remnant transition woodlands of Illinois, Iowa, Oklahoma and north-eastern Texas. As such we anticipate keen interest not only from the academic community, but also from Federal agencies, including the Bureau of Land Management, National Park Service, Forest Service, USDA-Agricultural Research Service, Natural Resource Conservation Service and US Geological Service, and their State-level equivalents. Contact with some of these agencies was initiated during the scoping study via participants in the SRS workshop and consultative process. Extensive links are already underway with the relevant research networks, including the Ameriflux (eddy covariance) network, the National Science Foundation Long Term Ecological Research (LTER) network, and the fledgling National Ecological Observatory Network (NEON).



Global savannas are physiognomically diverse, related to phylogeny, climate, geology and human-management

Logic: Earth observation products and models are not well calibrated, validated or integrated across diverse global savannas

Leverage international sites

Australia – unique vegetation in wet & dry monsoonal climate, few humans, extensive grazing

South America – unique vegetation in wet tropical climate, many humans, major locus of LUC

USA – temperate semi-arid savannas & shrublands with shrub encroachment & invasive grasses

Africa – diverse wet & dry tropical savannas supporting subsistence populations, livestock & wildlife, expanding agricultural conversion

The *Tree-Grass* project can leverage complementary activities in global savannas through international collaborative linkages

Leverage international science community

Logic: International science community and funding agencies bring significant expertise and resources

Australia – extensive savanna research, established well-instrumented network of sites

South America – established sites & LBA legacy in Brazil, savanna researchers in other SA countries

USA – well instrumented sites in diverse vegetation types with differing change dynamics

Africa – Many low intensity field sites in South, East and West Africa, plus a smaller number well instrumented

Figure 8. The scientific imperative and collaborative advantages of an international component in the *Tree-Grass* program. The global reach and relevance of *TG* is achieved via proposed 'Distributed sites' (i.e. low intensity sites with broad global coverage) and the possible addition of 'Intensive sites' funded by international partners in countries outside the USA, with science elements similar to the *TG* Intensive sites in North America.

The global extent of savannas with diverse bioclimatic and management characteristics, and contrasting research emphasis in the local science communities, make it essential that *TG* reach out and collaborate with key partners worldwide (Figure 8). From a field science perspective, scientists and their host institutions from Australia, Africa, South America. South and South-East Asia should be partners in this process. In addition, US and international research groups have key and complimentary expertise in tree-grass-related field measurements, savanna modeling, savanna remote sensing and human dimensions that should be included in the development and implementation of *TG*. Thus, in addition to planned *TG*-funded sampling of global tree-grass systems via the 'Distributed' field sites, the concept of "International Intensive Sites" (mirroring activities planned for the US-based Intensive Sites, but primarily funded via local sources) leaves the door open for extensive involvement of those communities in the overall *TG* program. In preparing for *TG,* and during Phase 1 of the project, high-level coordination with international researchers and funding agencies will promote this involvement. Discussions have been initiated with the science communities in Australia, Europe, Africa and South America to explore development of these ‘International Intensives’ that will expand the scope and international reach of the *Tree-Grass* Program.

5.4 Field Operations

Tree-Grass
Field Operations

The proposed strategy of concentrating *TG* field research in North America will reduce cost and logistical difficulties. For example, travel costs to sites in North America for the Project Office and PI-led research groups will be modest relative to costs incurred for international travel. Furthermore, we do not anticipate that it will be necessary to construct accommodation at field sites since suitable accommodation is generally available in the proposed study regions. It might prove necessary for the Project Office (PO) to improve the research infrastructure at intensive field sites, but at relatively modest cost to *TG* (e.g. trailers could be used instead of permanent buildings to provide laboratory space when not already available). The PO would also manage issues of power supply and access to sites, tower construction and other forms of sampling infrastructure, where necessary. The SDC might determine that the PO should conduct core (“service”) measurements at intensive sites in North America and/or at US and International distributed field sites, but most field measurement programs would take place as part of PI-led research projects.

International intensive sites would be funded and managed primarily by international partners, in consultation and coordination with the SSC. NASA-funded activities at these sites might include data acquisition using NASA satellite, sub-orbital and airborne EO resources over international intensive and distributed sites, as well as PI-led research , but NASA expenditures for field activities will likely be concentrated in North American field sites.

5.5 Data Management and Sharing

Tree-Grass
Data Plan

***TG* Phase 1:** In Phase 1 the *TG* Project Office Data Team will develop protocols for standardization and documentation of *TG* data that will facilitate later archive and distribution of datasets originating from PI-led research projects or Project Office core measurements. Data, models and MDA techniques developed as part of Phase 1 activities will be collated and archived for rapid access by other *TG* teams and the wider community in a form and at a scale that can be used to develop and test remote sensing retrievals and various models (Table 6). The *TG* Data team will be work with Investigator teams to ensure that data submissions to the *TG* Database are quality controlled, standardized and in agreed formats, with full documentation and metadata. They will work with an established DAAC (e.g. the ORNL DAAC) to facilitate broad community access to data in a globally accessible archive and distribution facility. The centralized *TG* Database will be made available for Phase 1 synthesis, regional and global data analysis, and increase early access to data during proposal development for Phase 2 projects.

Table 6. Data typology for *TG* Database

Collection Scale

Data Type	Global Synthesis Sites	*TG* Intensive Sites	*TG* Distributed Sites	Internat. Intensive Sites	Regional	Continental	Global	Non-Spatial
Field Measurements	X	X	X	X				
Remote Sensing Imagery	X	X	X	X	X	X	X	
Remote Sensing Value-Added	X	X	X	X	X	X	X	
Model Simulations	X	X	X	X	X	X	X	
Data-Synthesis Datasets					X	X	X	
TG Model Library								X
RS Algorithm Library								X
MDA Code Library								X
TG Literature Database	X	X	X	X	X	X	X	

***TG* Phase 2:** The *TG* Database developed in Phase 1 will continue expansion as an archive and distribution facility for field and remote sensing datasets acquired during Phase 2. Data from *Intensive* and *Distributed* sites will be made available to *TG* investigator teams, and the database will serve as a repository for remote sensing and model simulations for individual sites and for regional and global tree-grass systems (Table 6). *TG* investigators will be required to submit algorithms, model source-code and derived and synthetic products for archive and distribution. Recognizing that advancing the *TG* Science Themes will require interdisciplinary collaboration and access to data among research teams (with different emphasis on field, remote sensing and modeling activities), default *TG* data policies will encourage immediate data submission and sharing, with minimal provision for sole-use periods, but strong provisions to ensure due recognition of intellectual property, data sources and collaboration. The *TG* Database will be available for archive and distribution of data from International Intensive sites if requested by international partners.

***TG* Phase 3:** In Phase 3 the *TG* database will further evolve to provide not only data archive and distribution services, but also public access to *TG* Applications designed for monitoring and management of tree-grass systems. This will include facilitation of the TTAP outreach activities and applications-oriented PI-led science programs. As part of Phase 3 the *TG* Data Team will develop a clearly defined plan for the long-term archive and distribution of *TG* data, including strategies to continue production and distribution of key products and applications of value to *TG* stakeholders.

6. Summary of National and International Research Community Interest in *Tree-Grass*

Tree-Grass and the science community

6.1 *Tree-Grass* science community interest

The NASA call for scoping studies came at a time when many in the savanna remote sensing, ecology and modeling community were considering the current status and future of EO technologies (remote sensing and modeling) as applied in tree-grass around the world. Various groups had, for example, initiated workshops and conference sessions on savanna ecology and methodologies for large scale measurement and modeling. These included a colloquium on savannas at the 2008 AGU Fall Meeting, discussions as part of AMMA and CarboAfrica meetings in Africa and Europe, a workshop on biomass assessment in South Africa following IGARRS (July 2009), and an International Savanna Working Group convened in 2008-2009 with support from the Australian Research Council.

The NASA scoping study provided an ideal opportunity to build on that momentum and gather a larger and more comprehensive community to consider in greater depth the characteristic needs and emerging opportunities for remote sensing and modeling of savanna regions. As part of the Scoping Study we invited 50 leading savanna specialists, from academia and government research laboratories, and from countries in North and South America, Europe, Africa and Australia, to attend the “Savanna Remote Sensing” workshop in Fort Collins in March 2010. The workshop format included 12 invited keynote presentations and breakout sessions organized to define scientific and technological needs and opportunities for a NASA Terrestrial Ecology research program in global tree-grass ecosystems.

The Scoping Study also benefits from contributions from SRS workshop participants and others in the savanna community to a major new book entitled “Ecosystem Function in Savannas: measurement and modeling at landscape to global scales” published by Taylor & Francis/CRC Press (Hill and Hanan 2011). The proposals outlined in this white paper respond to the needs and frustrations of the savanna community, and represent a synthesis of ideas and recommendations emerging from the book, and during the SRS workshop.

Tree-Grass and Federal lands

6.2 Relevance to US Federal and State Agencies

Tree-Grass research will contribute directly to the measurement, modeling, understanding and management of the huge tree-grass areas of South, South-

West and Western USA, many of which are managed by Federal agencies such as the Bureau of Land Management (BLM), Forest Service, Department of Defense and the National Park Service. Extensive tree-grass landscapes in the South-West and West are also managed by a variety of State, local and tribal (Native American) entities. Our intent with *Tree-Grass* is to generate much improved technologies for monitoring and modeling these systems, and to develop tools that will be made available to these diverse stakeholders via the education, outreach and applications activities that are integral to Phases 2 & 3 of the program. We anticipate that stakeholders will be engaged directly during E4S summer schools, via direct contact with TTAP outreach, or as they become increasingly aware of *TG* data and resources made available via electronic media. Given the crucial role that semi-arid tree-grass systems play in the livelihoods of so many subsistence pastoral and agropastoral communities in Africa, Asia, South and Central America, the *TG* program will also be of direct relevance to USAID's new "Feed the Future" initiative.

Tree-Grass and the International Science Agenda

6.3 Relevance to International Global Change and Sustainability Research

Tree-Grass science themes and priorities are consistent with, and will contribute significantly towards, international science frameworks including the Global Earth Observation System of Systems (GEOSS) and the Earth System Science Partnership (ESSP; Diversitas, IGBP, IHDP and WCRP) for whom the USA is a major task leader on many elements. By the time Phase 3 of *Tree-Grass* is ready for implementation (which would be around 2020 based on best estimates), it is likely that land cover and land use change in savannas will have substantially expanded, and some regional impacts of climate change may be starting to be measurable. The IGBP is currently working on a developing a new "grand challenge" agenda to "advance earth system research for meeting global sustainability challenges". The improved EO capabilities generated in *Tree-Grass* will provide a core capability under these frameworks.

We recognize that, in the *Tree-Grass* science context there is great value in additional intensive measurements in the diverse tree-grass systems of the world (e.g. South American, Australian and African savannas, shrublands and dry deciduous woodlands of Central America, Central and South Asia). Based on discussions with the US and international community in preparation of this white paper we recommend that NASA concentrate *Intensive* measurements in North America, but retain a global component in two ways: first through the novel addition of the '*Distributed*' network of sites, and second through the potential that international science communities and funding agencies may leverage their own resources to implement international *Intensives* similar to that which *TG* will deploy in North America, but at little or no cost to NASA (Section 5.3). This strategy will increase the efficiency and cost-effectiveness of NASA's investment, enhance the global relevance of *TG* research, and provide a mechanism for vibrant international collaborations. Initial discussions with partners in Australia, Europe, Africa and South America, suggest strong interest to leverage existing research sites and activities to participate actively in the global *TG* Program. These linkages will be further developed and formalized as the *TG* Program goes forward. We stress, however, that the *TG* strategy to deploy North American *Intensive Sites* **together with** globally *Distributed Sites* means that *TG* will sample, and be relevant to, global tree-grass systems. The addition of *International Intensives* (with support from local funding agencies) will enhance the research program, but *TG* is not dependent on these developments.

7. Resources Needed for *Tree-Grass*

Tree-Grass field infrastructure needs

7.1 Field Infrastructure

Significant infrastructure relevant to *TG* already exists at sites in North America and globally (a sample of potential sites are shown in Figure 6). Potential sites include the densely instrumented sites typical of the *Ameriflux* and *FluxNet* eddy covariance sites (http://ameriflux.ornl.gov and http://www.fluxnet.ornl.gov) in regions and sites with appropriate tree-grass and shrub-grass vegetation communities. They include several long-term ecological research network sites (LTER, http://lternet.edu) and their International equivalents, as well as individual and networked field sites with a range of historical and on-going research into vegetation and ecosystem dynamics (Figure 6).

Where possible and conducive to *TG* science, the *TG* project will leverage and build on existing sites, with addition of infrastructure as necessary, coordinated in some cases by the *TG* Project Office or proposed and organized as part of PI-led research. If necessary to achieve science goals and fully sample across key gradients, the *TG* project should consider adding both *Intensive* and *Distributed* field sites. The Phase 2 suite of field measurements and instrumentation at both *Intensive* and *Distributed* field sites should be finalized during Phase 1 planning modified, where appropriate, by the competitive proposal process and funded PI-led research.

We can, however, anticipate that *TG Intensive* sites will include field measurements directed at addressing knowledge gaps relevant to the 5 Science Themes and the 3 EO Focal Areas. In particular *TG* emphasis on Remote Sensing Science and Process Modeling would indicate the need for dual focus on i) canopy structure and remote sensing technologies for tree-grass retrievals (e.g. functionally resolved canopy structure through a range of traditional (e.g. destructive and non-destructive census methodologies) and non-traditional techniques (e.g. canopy LiDAR, photometric and radiometric techniques) coupled with ground based remote sensing, radiative transfer and algorithm development, and ii) ecosystem function, including soil and canopy physiology and biogeochemistry, energy, water, carbon and trace gas fluxes (e.g. leaf and canopy-level gas and energy exchange measurements via chambers or eddy covariance measurements). The *TG* Project Office might play an important role here in installation of key instrument systems at individual *Intensive* sites including, for example, ground-based canopy LiDAR measurements for characterization of canopy structure, eddy flux measurements of land surface-atmosphere exchanges of energy, water and carbon, and other meteorological and soil physical measurements.

Tree-Grass aircraft needs

7.2 Suborbital platforms and sensors

Aircraft remote sensing will likely play a central role in development and testing of tree-grass retrieval algorithms that benefit from synergies between active, passive, optical, thermal and microwave imaging systems. In proposing candidate sites and transects in North America we envisage an airborne sampling strategy with short-range remote sensing from light aircraft, and long-range and high altitude aircraft able to integrate across the broad regional and continental scale gradients. Both NASA and non-NASA aircraft may be used in this endeavor, with funding for key suites of airborne measurements and instruments (“community remote sensing” determined during Phase 1) routed through the project office. PI’s will likely also propose local or more specialized instrument deployments as part of research proposals.

It is likely that synergies may be obtained with the intensive and extensive airborne imaging planned for the NEON network and continuing activities as part of the North American Carbon Program (NACP). Furthermore, the current model for the NASA DC-8 of intensive multi-instrument missions with dedicated education components through student-proposed science activities could be applied to an airborne campaign around savanna sites in the conterminous USA.

For logistical and cost reasons, aircraft remote sensing over international *Distributed* sites (and the possible *International Intensive* sites added by international collaborators) will occur at lower intensity than over North America. However, NASA investigators (or international collaborators) may propose to ship specific sensors for deployment on local aircraft (for example, the AVIRISNG sensors are small and portable). Or given the proliferation of commercial providers of high spatial and spectral resolution of airborne sensors, *TG* PI’s may contract data acquisitions oversees. *International Intensive* science programs would likely have airborne science components already, as is the case for the Australian NATT Transect for example, that could provide piggy-back opportunities.

Tree-Grass satellite data needs

7.3 Satellite data access and purchase

The suite of currently available and future planned satellites and space-borne sensors changes on a very regular basis (Appendix 4). The global swathe coverage class of optical sensors will provide continuous and free data from MODIS until 2017 and from VIIRS on NPP (launched in October 2011) until the JPSS mission with a second VIIRS on board is launched. Landsat continuity has been compromised for 2012 by the failure of Landsat 5, but it is expected that successful launch of Landsat 8 in early 2013 will ensure access to these data into the future. Given the importance of the seasonal rainfall cycles in tree-grass systems, GPM (Appendix 4), the successor sensor to TRMM, will be a vital source of data for *Tree-Grass* MDA projects. In addition, with the demise of the DESDYNI LiDAR and suspension of the DESDYNI radar until the 2020's, ICESAT-2 capability (Appendix 4), and particularly photon counting within the footprint, may be vital to assist calibration of available optical and SAR imagery in refining structure and biomass estimation in tree-grass systems.

The new Sentinel series sensors planned by the European Space Agency will also be vital for the *Tree-Grass* program. Initial development of *TG* should include formulation of agreements with ESA to image key *Intensive* and *Distributed* study sites, and to regularly acquire swathe coverage of major savanna systems to facilitate scaling up from sites to biome scales.

Access to high resolution optical data is of particular importance for *Tree*-Grass, since capture of spatial properties of savanna landscapes, including tree canopy delineation, shadow patterns, clumping and patch structures is essential for connection of structure with ecosystem function, and disaggregation of sub-pixel signals in EOS MODIS and VIIRS optical data. It is therefore important that an agreement and funding be defined for necessary access to GeoEye-1 and Digital Globe very high resolution optical data.

In the absence of DESDYNI radar, access to both archives and future acquisitions of C-band and L-band SAR will also be very important for the *Tree-Grass* Program. Research on biomass in tree-grass and savanna systems has shown that combination of optical, SAR and LiDAR data is needed to gain effective measurement fidelity for structure and biomass. In the initial stages, the program should obtain full access to archives from the ESA ASAR, and ALOS PALSAR missions, and arrange a close PI relationship with JAXA for the ALOS-2 sensor. These data may be vital for merging with airborne LiDAR acquisitions.

7.4 Approximate Total Cost Estimates for *Tree-Grass*

TG Outline Budget (1)

	Per Year (2)	9 Year Total
Project Scientist (3)		
Project Scientist (0.5 FTE) (4)	96,000	864,000
Research Support Staff (1.5 FTE)	93,600	842,400
Travel, Coordination and Research Supplies	50,000	450,000
Indirect Cost at 25%	59,900	539,100
Project Scientist Total	299,500	2,695,500
Project Office (5)		
TG Project Manager (1 FTE)	120,000	1,080,000
TG Administrative Staff (2 FTE)	144,000	1,296,000
TG Science Team Coordinator (1 FTE)	96,000	864,000
PO-Directed Research Postdoc (1FTE)	96,000	864,000
TG Data Support and DAAC Liaison (2 FTE)	192,000	1,728,000
DAAC Support (Hardware costs etc) (Yrs 1-3)	100,000	300,000
TG Field Crews (3 FTE; Yrs 3-7)	234,000	1,170,000
PO Travel (National, international)	100,000	900,000
Annual Workshop Organization	100,000	900,000
SSC Travel	40,000	360,000
Indirect Cost at 25%	305,500	2,365,500
TG Project Office Total		11,827,500
EO Data & Technology Support (Project Office) (6)		
Airborne Remote Sensing (yrs 3-7)	2,000,000	10,000,000
Satellite Data Purchases (Yrs 1-9)	250,000	2,250,000
High Performance Computer Time (Yrs 1-9)	100,000	900,000
EO Support Total		13,150,000
Field Logistics and Instrumentation Support (Project Office)		
Intensive Site Infrastructure (Yr 3, 4)	600,000	1,200,000
Intensive Site Instrumentation (Yr 3-4 purchases)	400,000	800,000
Distributed Site Instrumentation/Logistics (Yr 3-4 purchases)	100,000	200,000
Field Support Total		2,200,000
Project Office Total (Office, EO and Field)		27,177,500
Education and Outreach Coordination (PI-led)		
GRFP (0.2FTE; workshop costs, travel; yrs 1-9 funded in NRA-1 & 3)	249,000	2,241,000
E4S (8 PI @ 0.15 FTE, 1 FTE, summer school costs; yrs 3-7, funded in NRA-2&3)	843,000	4,215,000
TTAP (8 PI @ 0.15 FTE, 1.0 FTE, outreach activities, yrs 7-9, funded in NRA-4)	843,000	2,529,000
Education & Outreach Total		8,985,000
PI-Led Science		
Phase 1, NRA 1 (~10 projects averaging @750k over 3 yrs)	2,500,000	7,500,000
Phase 2, NRA 2 (~20 projects averaging @750k over 3 yrs)	5,000,000	15,000,000
Phase 2, NRA 3 (~20 projects averaging @750k over 3 yrs)	5,000,000	15,000,000
Phase 3, NRA 4 (~15 projects averaging @750k over 3 yrs)	3,750,000	11,250,000
PI-Led Science Total		48,750,000
PI-led Science + Education & Outreach		57,735,000
***TREE-GRASS* TOTAL ESTIMATED COSTS (9 years)**		87,608,000

Notes:

1. All budget estimates to be refined during detailed project planning prior to project initiation
2. Budget items repeat over 9 years unless indicated in item description
3. Project scientist could be from University, NASA Center or other Federal Agency
4. All FTE salary estimates include a 20% fringe benefit component
5. Project Office hosted by NASA Center or University
6. EO flight time and satellite data needs to be refined during pre-planning and Phase 1 of project

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Appendix 1: Critical Requirements for Earth Observation in Tree-Grass Systems

Recommendations from the Savanna Remote Sensing Workshop (March 2-4, 2010)

1. **Key Considerations**
   - Potential future changes in tree-grass regions due to human exploitation and climate change represent a poorly understood and serious threat to both ecosystem function and human well-being through unforeseen feedbacks and irreversible changes.
   - A comprehensive capability for scenario analysis and tree-grass futures assessment is an essential tool for understanding the impacts and feedbacks of global change on hundreds of millions of humans dwelling in, and depending on, these systems.
   - Current remote sensing and modeling is poorly developed for the vertical, horizontal and temporal heterogeneity of woody-herbaceous systems. However, improved remote sensing and modeling capabilities are emerging and should be leveraged for tree-grass systems.
   - An appreciation of current capacity for measurement, remote sensing retrieval, modeling and prediction in tree-grass systems must be obtained to more clearly identify deficiencies, needs, and developments to be targeted by an intensive field campaign.
   - A targeted field and remote sensing research program should support development of new 'tree-grass' remote sensing capabilities as input to improved model and data assimilation frameworks.
   - Refined measurement and modeling systems should contribute to management of vulnerable tree-grass systems worldwide for improved management, sustainability and human well-being.
2. **Measurement**
   - Field measurements of vegetation structure and function should be closely linked with remote sensing and model development, parameterization and validation.
   - Critical parameters describing the multiple physiological, structural and biogeochemical traits and functions in both under- and over-storey dynamics are essential.
   - Scale-related variability of field measurements in highly heterogeneous tree-grass systems should be considered in design of field programs.
   - Soil and below ground processes have to be measured and linked to indicators and/or used to verify and calibrate model simulations.
   - Region specific detailed field measurements and globally distributed calibration and validation of remote sensing retrieval techniques and models is needed.
3. **Biophysical, Biogeochemical and Ecological Modeling**
   - In tree-grass systems models need to encompass climate impacts on tree-grass dynamics, mediated by disturbance, fire, herbivory, wood harvest and clearance (e.g. Higgins et al. 2010).
   - Comprehensive model inter-comparisons are needed to determine the extent to which tree-grass resolving models reduce error and bias in model results at local, regional and global scales
   - 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.
   - Since savannas are vast, highly variable, and sparsely measured, model-data assimilation (MDA) provides the best framework within which to measure, model and understand savannas.

- Given the scale dependence of process in savannas an MDA scheme that can detect bias and redundant parameters is crucial in establishing an optimal framework.
- Representation of tree-grass systems in global models is currently unsatisfactory. However, model schemes do exist to incorporate multiple physiology and vertical/horizontal heterogeneity of tree-grass systems.

4. Remote Sensing

- For savannas, connecting the temporal processes at coarse spatial resolution (e.g. Gill et al., 2009; Xue et al., 2010), with the nested multi-scale spatial properties and interactions in sub-pixel landscapes is a key need.
- For optimal retrievals, integration across sensors including terrestrial laser scanners, airborne lidar/optical sensors, and spaceborne synthetic aperture radar, lidar and optical sensors is recommended in savanna woodlands. Sampling or transects are needed from airborne systems and spaceborne LiDAR to complement swath coverage with SAR and optical data (e.g., Lucas et al., 2011; Armston et al., 2009).
- Since tree-grass systems are defined by the combination of grasses and trees in the landscape, development of remote sensing products that explicitly measure grass cover and biomass, separate from woody biomass and leaf area is important (e.g., Guerschman et al., 2009).
- With diverse savanna vegetation morphology, spectral invariants that enable separation of structure and chemistry in canopies, may greatly improve plant functional type (PFT) specifications.
- Combinations of polar orbiting and geostationary sensors such as SEVIRI may greatly improve retrieval of phenological dynamics, drought progression and fire dynamics.

5. Savanna as Coupled Human Environment Systems

- The extension of REDD (Reducing Emissions from Deforestation and Degradation) to savanna systems could provide the application context for development of accurate monitoring capacity.
- 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.
- 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 through the measurement and modeling of the flow of ecosystem goods and services in space and time.
- Ecosystem goods and services in tree-grass systems are the outcome of complex social-ecological processes: earth observation for tree-grass systems must deliver quantitative measures, or transformable metrics of process, critical inputs to models, and dependable model simulations for now-casting and forecasting tree-grass productivity and sustainability and critical interactions in the earth system

APPENDIX 2: Savanna Remote Sensing Workshop Participants
(March 2-4, 2010, Fort Collins, Colorado)

Family Name	Given Name	Affiliation
Archer	Steve	University of Arizona
Arneth	Almuth	Lund University, Sweden
Baker	Ian	Colorado State University
Baldocchi	Dennis	University of California Berkeley
Barrett	Damian	University of Queensland, Australia
Bruna	Emilio	University of Florida
Bucini *	Gabriela	Colorado State University
Bustamante	Mercedes	University of Brasilia
Coughenour	Michael	Colorado State University
Disney	Mathias	University College London, UK
Dohn *	Justin	Colorado State University
Dubayah	Ralph	University of Maryland
Eamus	Derek	University of Technology Sydney
February	Edmund	University of cape Town
Ferreira	Laerte	LAPIG - UFG
Ferwerda	Jelle	University of Twente, Netherlands
Griffith	Peter	NASA GSFC
Hanan *	Niall	Colorado State University
Herrmann	Stefanie	NASA Goddard Space Flight Center
Higgins	Steve	University of Frankfurt, Germany
Hill *	Michael	University of North Dakota
Hodkinson	Dan	NASA Carbon Cycle and Ecosystem Office
Hoffman	William	North Caroline State University
Hutley	Lindsay	Charles Darwin University, Australia
Lefsky	Mike	Colorado State University
Leisz	Steve	Colorado State University
Litvak	Marcy	University of New Mexico
Lucas	Richard	Aberystwyth University, UK
Neuenschwander	Amy	University of Texas at Austin
Palace	Michael	Complex System Research Center, UNH
Parton	William	Colorado State University
Powell	Rebecca	University of Denver
Prihodko	Lara	Colorado State University
Prince	Steve	University of Maryland
Rahman	Faiz	Indiana Univeristy
Roberts	Dar	University of California Santa Barbara
Saatchi	Sassan	NASA-JPL
Schaaf	Crystal	Boston University
Scholes	Robert	CSIR, South Africa
Sea	William	CSIRO-Canberra
Solorzano	Alexandro	University of Brasilia
Stuart	Neil	University of Edinburgh
Sutton *	Alexandra	Colorado State University
Tieszen	Larry	USGS-EROS
Treddenick *	Andrew	Colorado State University
Washington-Allen	Robert	Texas A&M University
Weber	Keith	ISU GIS Center
Wickland	Diane	NASA-HQ
Williams	Christopher	Clark University
Woodhouse	Iain	University of Edinburgh
Young	Truman	UC Davis; Mpala Research Centre

* organizing committee

APPENDIX 3: Field sites relevant to *Tree-Grass*: site-clusters (some individual sites) with active ecological, biophysical or ecosystem function measurements in mixed tree-grass vegetation

Continent	**Region, State or Country**	**Site or Cluster Name (# of sites)**	**Measurement Type**	**Relevant *TG* Science Theme**	**Initial Point of Contact**
Africa	West Africa	AMMA (>8)	Bg, F, M, Ph, Pr, RS, S	1, 2, 3	Lebel
		SSDE (5)	Bg, Ex, M, Pr, S	2, 4, 5	Hanan
		CarboAfrica (1)	Bg, F, M, RS	1, 2, 3	Valentini
	East Africa	Mpala (>5)	Bg, Ex, Pr, M, S	2, 4, 5	Augustine
		Serengeti	Bg, Ex, M, Pr, S	2, 4, 5	Anderson
	Southern Africa	KNP-Flux (2)	Bg, F, M, Ph, Pr, RS, S	1, 2, 3	Scholes
		KNP-Exp (>5)	Bg, Ex, Pr, Ph, RS, S		Govender
		KNP-RS	R, S	1	Balzter
		Mozambique	Bg, Pr, S	2, 4, 5	Ribiero
		Luangwa Valley	Bg, Pr, S	2, 4, 5	Prince
Australia	New South Wales	UNE (>5)	Ex, Pr, S	2, 4, 5	Kumar
	Northern Territory	NATT (>10)	Bg, F, M, Ph, Pr, RS, S	1, 2, 3	Hutley, Eamus
	Queensland	Injune	Ex, Ph, Pr, RS, S	1, 2, 3	Lucas
	All	AusPlots (>200)	Bg, RS, S	2, 4	White
Europe	Israel	Yatir	Bg, F, M, Ph, Pr, S	1, 2, 3, 4, 5	Yakir
	Portugal	Evora	F, Ph, Pr	1, 2, 3	Pereira
	Spain	El Saler	F, Ph, Pr	1, 2, 3	Sanz
N. America	Arizona	Santa Rita	Bg, F, M, Ph, Pr, RS, S	1,2,3,4	Scott
	California	Tonzi Ranch	Bg, F, M, Ph, Pr, RS, S	1,2,3	Baldocchi
	Idaho	Snake River Flux Network (3)	Bg, Ex, F, M, Ph, Pr, RS, S	1, 2, 3, 4, 5	Germino
	Kansas	Konza Prairie	Bg, Ex, F, M, Ph, Pr, RS, S	1, 2, 3, 4, 5	Briggs
	New Mexico	Upland Flux Network (4)	Bg, F, M, Ph, Pr, RS, S	1,2,3,4	Litvak
	North Carolina	Sandhills & Jones Longleaf Pine (2)	Bg, Ex, M, Ph, Pr, S	2, 4, 5,	Hoffmann
	Texas	Freeman Ranch	Bg, F, Ph, Pr, RS, S	1,2,3,4	Litvak
	Western Rangelands	ARS Network (7)	Bg, F, Ph, Pr, RS, S	1, 2, 3, 4	Svejcar
S. America	Argentina	Bajo Verde Ranch	Bg, Ex, Pr, RS, S	2, 4, 5	Peinetti, Roglich
	Argentina	Chaco Arido (6)	Ex, Pr, RS, S	4, 5	Blanco
	Brazil	LBA (2)	Bg, F, M, Ph, Pr, RS, S	1, 2, 3, 4	Vourlitis, Da Rocha
	Brazil	ComCerrado network (2)	Bg, Ex, F, Ph, Pr, RS, S	2, 3, 4,5	Bustamante

Measurement Types: Bg = soil or plant biogeochemistry; Ex = experimental manipulations (e.g. rainfall, fire or grazing treatments); F = flux measurements (C, H2O, energy); M = modeling (one or more of *TG* model classes); Ph = physiology (leaf level photosynthesis etc); Pr = production; RS = remote sensing; S = vegetation structure and/or demographics;

Note : These are sites that might provide historical and current data for *TG* Phase 1 activities, and might be candidates for new or expanded measurements in *TG* Phase 2. We acknowledge that there are thousands of sites worldwide where some form of ecological or biophysical measurements have been performed. This table does not intend to be an exhaustive list of all sites. It provides an inventory of regions (site clusters or particularly well studied individual sites) with significant on-going research on tree-grass structure and dynamics that will be updated and expanded during TG preparation.

APPENDIX 4: New and next generation satellite missions relevant to *Tree-Grass*

Agency/Platform	Sensor/Spectral Coverage	Revisit	Spatial Resolution	Launch/ Lifetime	Relevant Objective
NASA – NPOESS Preparatory Project (NPP)	VIIRS – 22 bands, 412-865 nm; 1240 – 4050 nm; 10.763-12.013 µm	Daily with 8 and 16 day products	400m/800m	2011/5 years	Operational merger of AVHRR and MODIS capability and continuity
NASA – Landsat Data Continuity Mission (LDCM)	OLI: 9 bands – 433 – 2300 nm; TIRS: 2 bands – 1030-1250 µm	16 days	30m (15 m pan); 100m TIR	2013	Landsat continuity: carbon monitoring; land cover/land use change; burned areas; etc etc
NASA – Soil Moisture Active Passive (SMAP) mission	Radar 1.26 Ghz, VV/HH/HV Radiometer – 1.41 Ghz	3 days (equator); 2 days (boreal)	40 km	2014	Global measurements of soil moisture and its freeze/thaw state.
NASA – Joint Polar satellite System (JPSS-1)	VIIRS – 412-865 nm; 1240 – 4050 nm; 10.763-12.013 µm	Daily with 8 & 16 day products	400m/800m	2016	Operational merger of AVHRR and MODIS capability and continuity
ICESat-II	Laser - 532 nm wavelength	91 day with monthly sub-cycles	70 cm along track sampling	2016	Vegetation canopy height for large scale biomass and biomass change
NASA – JPSS-2	VIIRS – 412-865 nm; 1240 – 4050 nm; 10.763-12.013 µm	Daily with 8 and 16 day products	400m/800m	2019	Operational merger of AVHRR and MODIS capability and continuity
NASA – HyspIRI	Hyperspectral: 218 bands, 380 – 2500 nm TIR: 8 bands, 3.98 – 12.05 µm	19 days/ 3 days with off-nadir 5 days	60 m	2021	Ecosystem function and diversity; volcanoes, wildfires, water use, land surface composition.
DESDynI SAR	L-Band SAR	12-16 days	~10 m	2020's	Vegetation structure
JAXA/NASA – Global Precipitation Measurement (GPM)	Core satellite: dual-frequency precipitation radar (DPR) and microwave radiometer; Constellation: microwave radiometers.	3 hours	DPR 250-500 m footprint	2013	Highly accurate and frequent global rainfall observation (TRMM follow-on)
JAXA – Global Climate Observing Mission – Water (GCOM-W)	Advanced Microwave Scanning Radiometer 2 (AMSR2,); 6 bands, 7 – 89 GHz	Daily	5 – 50 km	TBA;	Precipitation, vapor amounts, ocean winds, sea surface temperature, water levels on land areas, and snow depths
JAXA – Global Climate Observing Mission – Climate (GCOM-C)	Second Generation Global Imager (SGLI) 19 bands, 380nm to 12µm	2-3 days	250 m – 1 km	TBA;	Surface and atmospheric measurements related to the carbon cycle and radiation budget, such as clouds, aerosols, ocean color, vegetation, and snow and ice.
JAXA – Advanced land Observing Satellite-2 (ALOS-2)	L band SAR, 1.2 Ghz	14 days	1 – 3 m spotlight 3 – 10 m swath	TBA; 5-7 yrs	Effective monitoring of cultivated areas; Global monitoring of tropical rain forests to identify carbon sinks.
ESA Sentinel 1	C band SAR; VV +VH;	1-3 days	5 x 5; 5 x	2013/2015;	Mapping of land surfaces;

	HH + HV.		20; 20 x 40;	consumables for 12 years	forest, water and soil, agriculture
ESA Sentinel 2	13 bands: 443-2190 nm	5 days (with 2 satellites)	10, 20 and 60m	2013; consumables for 12 years	Land cover/use, change detection, vegetation properties
ESA Sentinel 3	OLCI-21 bands; 400 – 1020 nm. SLSTR-9 bands; 550 – 12000 nm. MWR-2 bands; 23.5/36.6 Ghz	27 day repeat	300 m 500 m/1 km	2013; consumables for 12 years	Land color (MERIS successor); Land surface temperature; In-land water; Vegetation products
DLR/ENMAP Consortium – Environmental Mapping and Analysis Program (ENMAP)	VNIR: 420 – 1000 nm SWIR: 900 – 2450 nm	4 days using off nadir pointing	30 m	2013: 5 years/ 25 years in lower orbit	Agricultural and forest management; hazard assessment; monitoring inland waters; dryland degradation; mineral exploration
INPE – China-Brazil Earth Resources Satellite series (CBERS 3/4)	PANMUX: 4 bands 510-890 nm MUXCAM: 450-890 nm IRMSS: 0.5-12.5 μm WFI: 450-890 nm	26 days 5 days 26 days 5 days	5 m 20m 40/80m 64m	2011/2013	Vegetation, agriculture, environment, water, geology and soil; surface temperature; regional and national mosaics; monitoring dynamic phenomena

APPENDIX 5: SRS Mailing List

Name	Affiliation	Country
Amiri, R.	Monash U.	Australia
Anderson, D.	USGS	USA
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