Quantifying Grassland-to-Woodland Transitions

The Implications for Carbon and Nitrogen Dynamics in the Southwest United States

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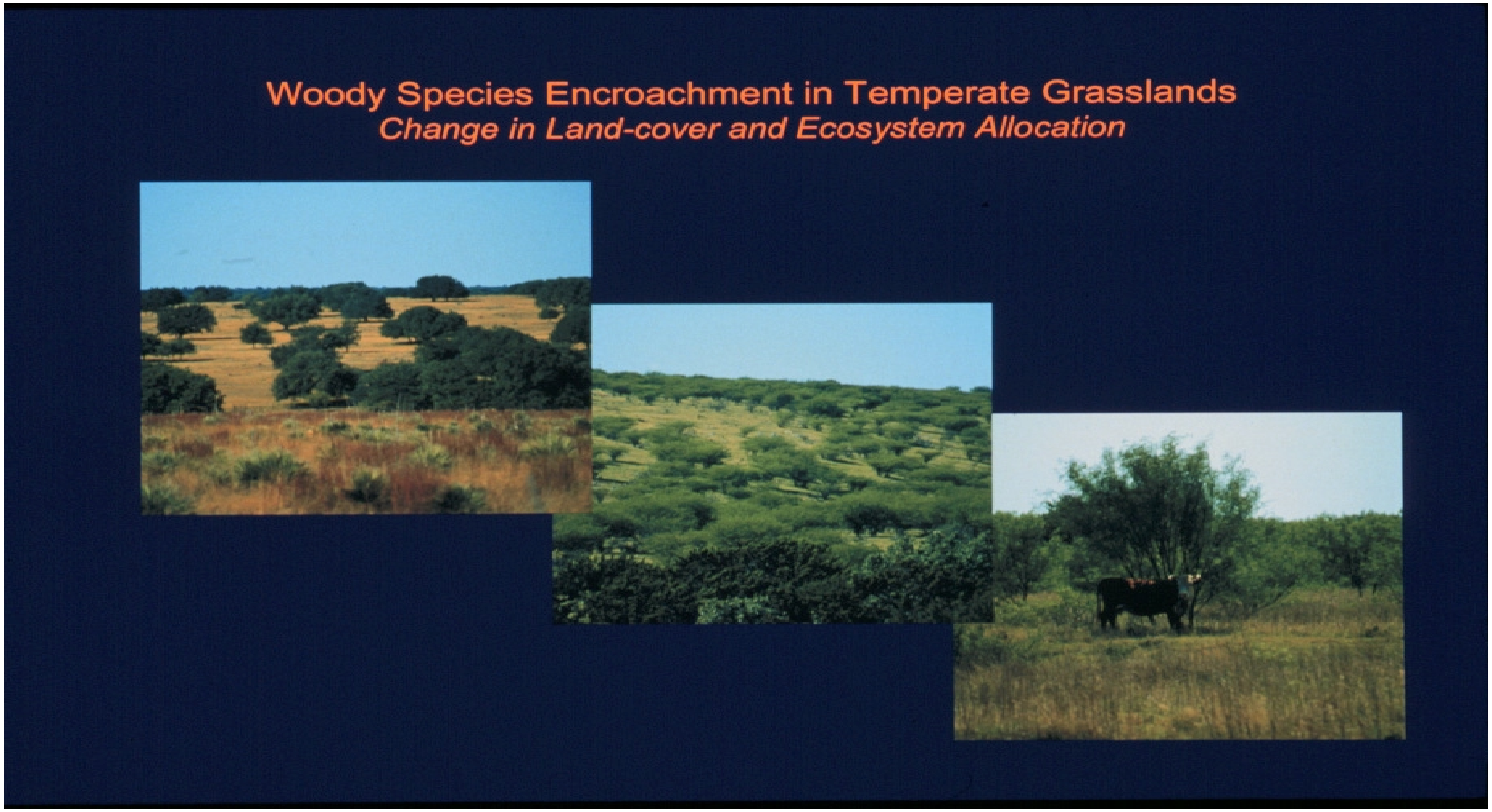


Many dryland ecosytems are mixtures of grasses, shrubs and trees. The balance between these contrasting lifeforms is regulated by complex interactions between climate, soils, herbivory and disturbance. A shift in one or more of these factors can dramatically alter ecosystem structure and function. In many drylands, woody plants have displaced grasses in recent history….

Santa Rita Experimental Range, Arizona
(from Martin 1975)

A desert grassland landscape photographed in 1903...

… had become a mesquite shrubland by 1941

Project Goal

- To understand how changes in vegetation structure (relative abundance of grass and woody species) associated with human-driven perturbations affects sequestration or liberation of C and N across topoedaphically diverse landscapes

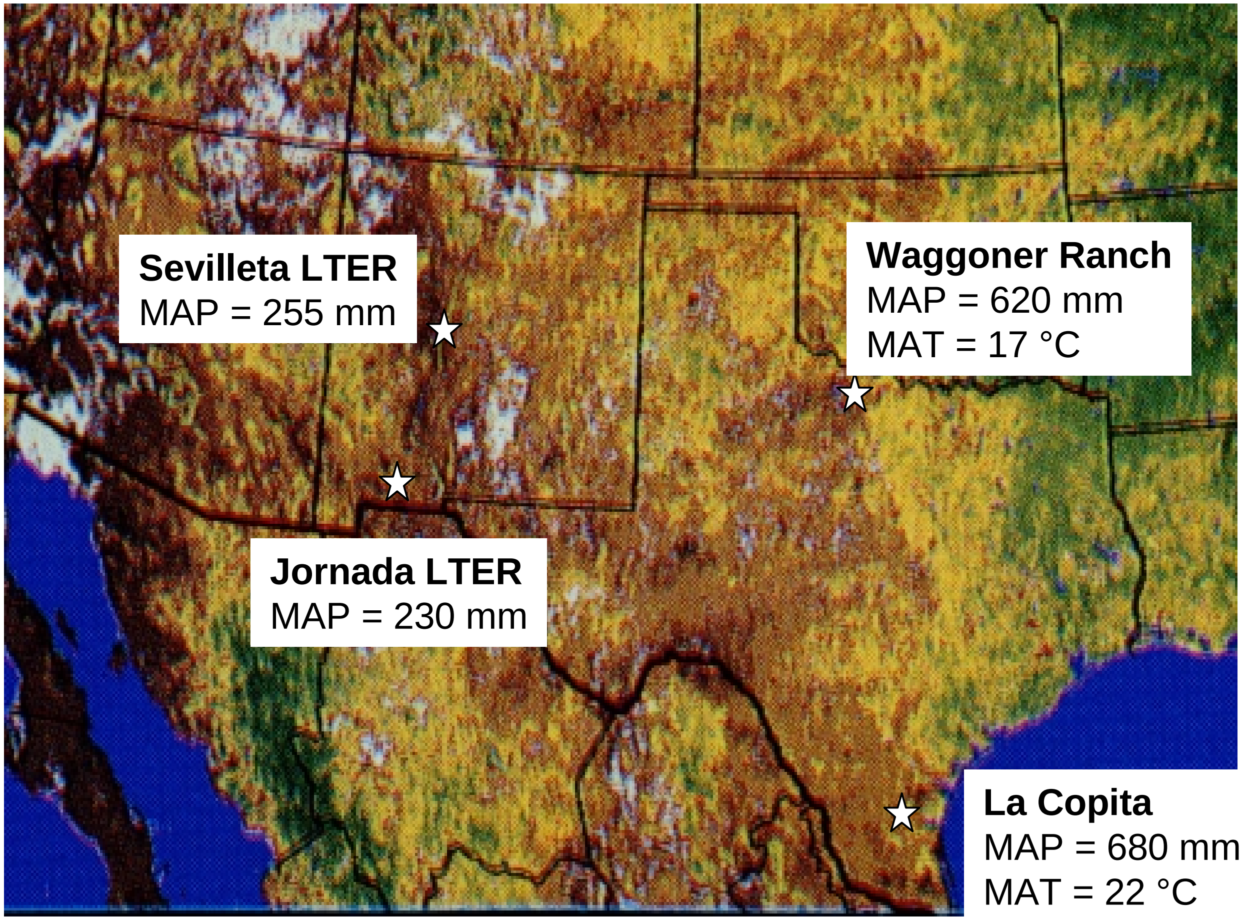
Objectives

- We seek to:
  - Improve our ability to remotely quantify grass and woody plant abundance
  - Generate a comprehensive database on temporal changes in plant and soil C and N for grassland-to-woodland chronosequences
  - Couple remotely-sensed canopy variables with ecosystem simulation models to track biogeochemical dynamics under variable landscape structure and climatological forcings

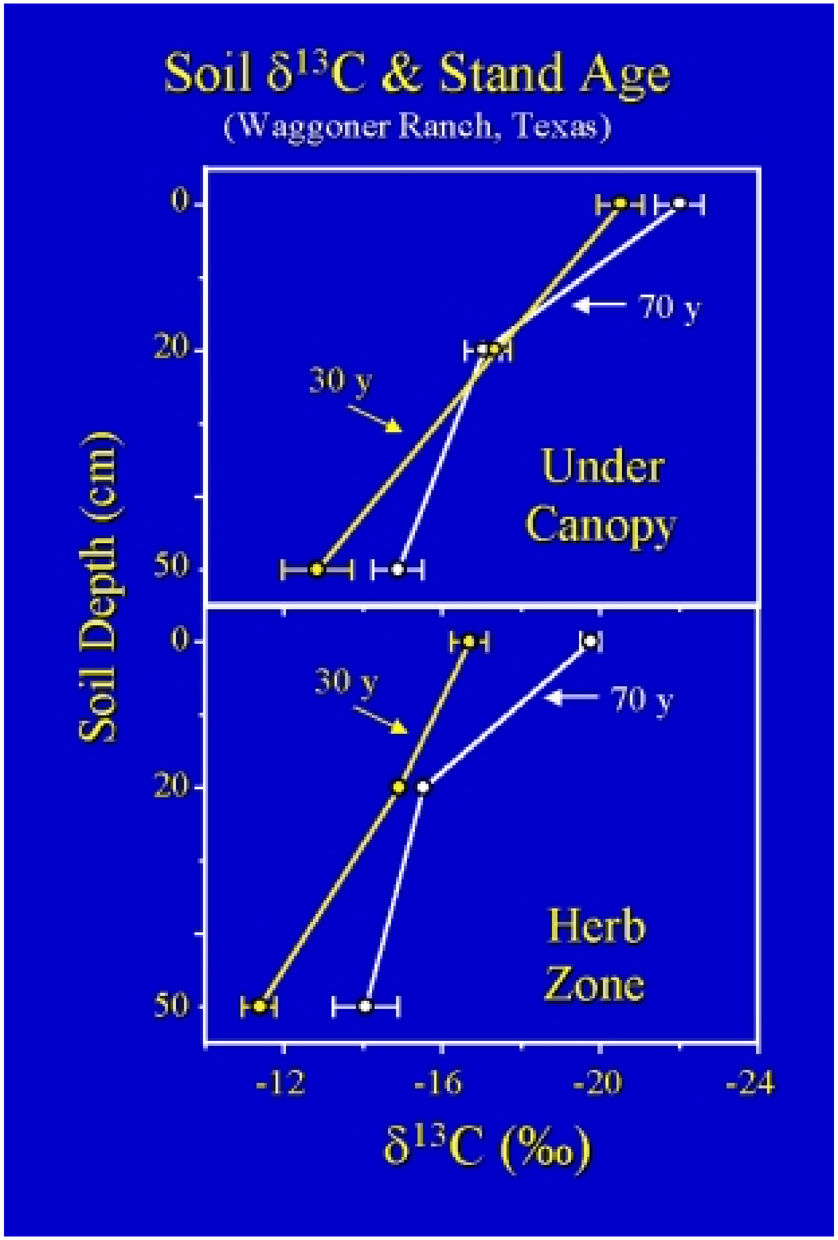
Project Methods

- Two primary components:
  - – Develop remote sensing capability to measure spatial distribution and biophysical characteristics of semi-arid rangeland vegetation at regional level, but at high spatial resolution
  - – Develop link between remotely sensed information and ecosystem models to gain understanding of regional-level biogeochemistry associated w/ natural variability and human-driven land use pressure (grazing, fire)

Study Sites



MAP = Mean Annual Precipitation   MAT = Mean Annual Temperature



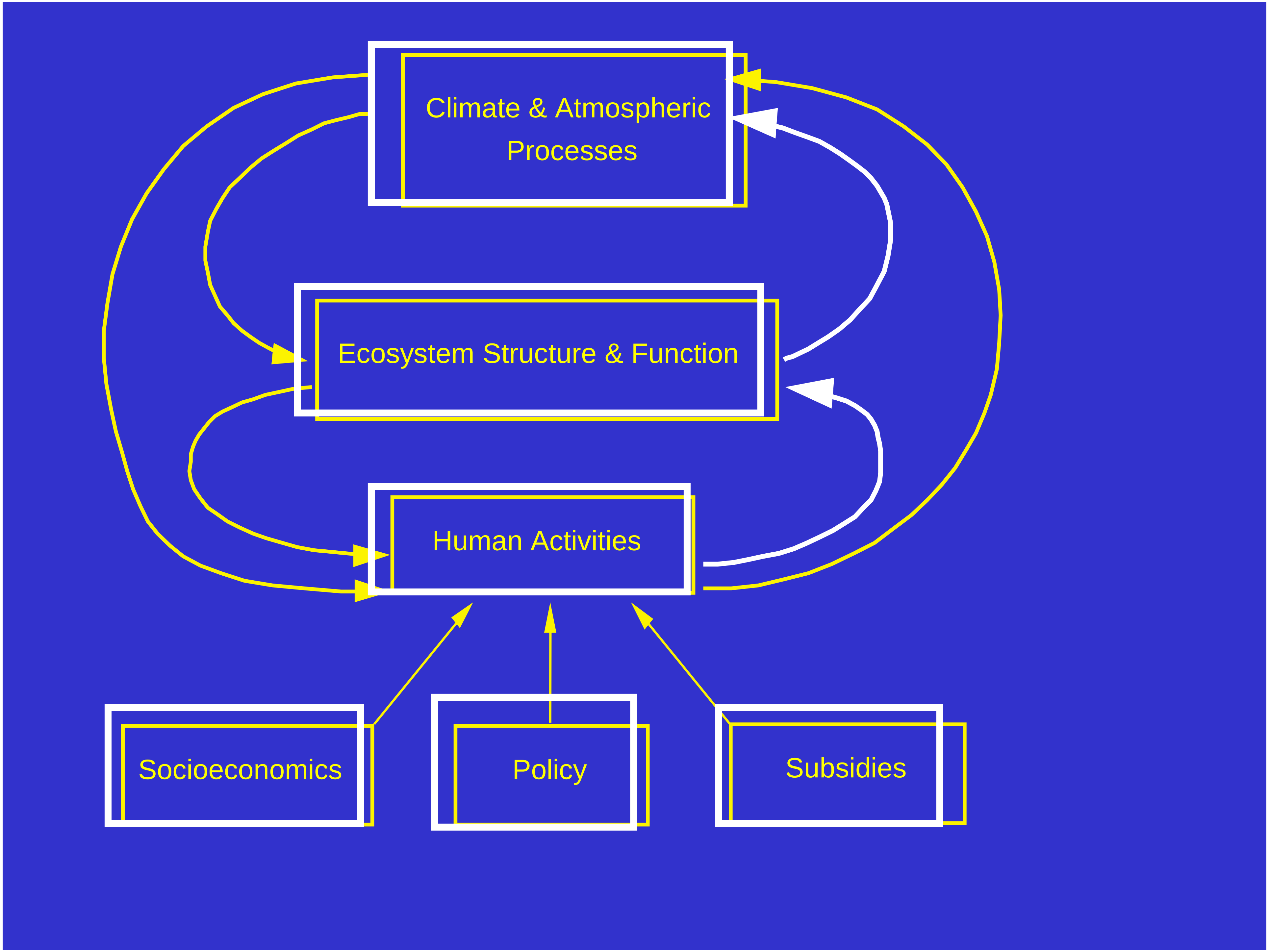
On sites where vegetation history is Not known, $^{13}C/^{12}C$ ratios provide direct, spatially explicit evidence that C_3 shrubs have displaced C_4 grasses.

Current vegetation at this site is dominated by C_3 woody plants.

Soil carbon at depth, indicates past domination of the site by C_4 grasses

Causes for Woody Encroachment ?

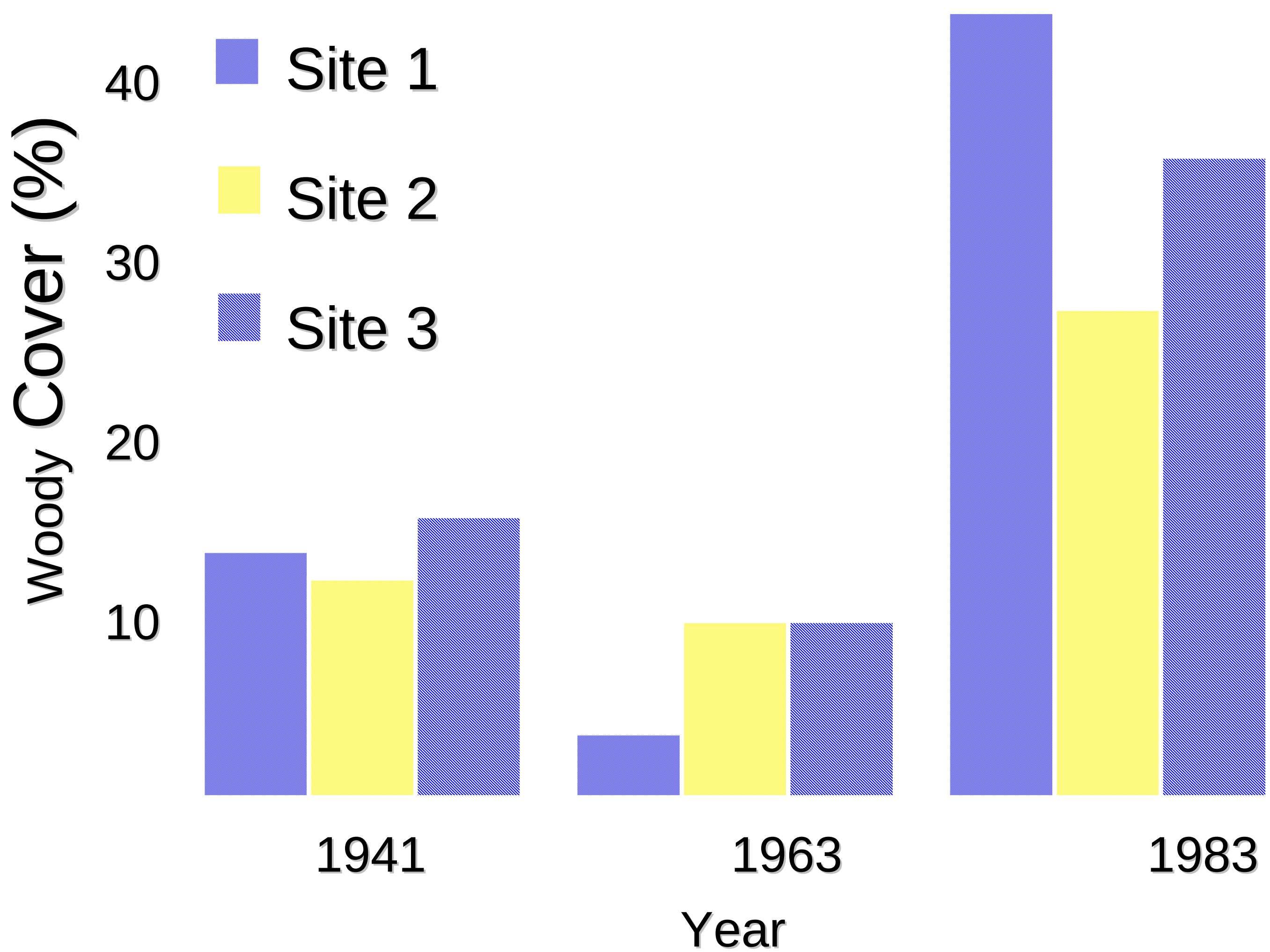
- Natural
  - Climate Change
  - Changes in native herbivore (browser vs. grazer) populations
- Anthropogenic
  - Species introductions
  - Species eradications
  - Atmospheric CO_2 enrichment
  - Altered fire regime
  - Altered grazing regime
- Interactions
- Necessary and Sufficient Conditions



Climate & Atmospheric Processes
Ecosystem Structure & Function
Human Activities
Socioeconomics
Policy
Subsidies

Rates/Dynamics of Change?

Changes in woody plant cover are rapid, non-linear, and may be triggered by extreme environmental events (e.g. drought of 1950s). Data below are from the La Copita site in southern Texas

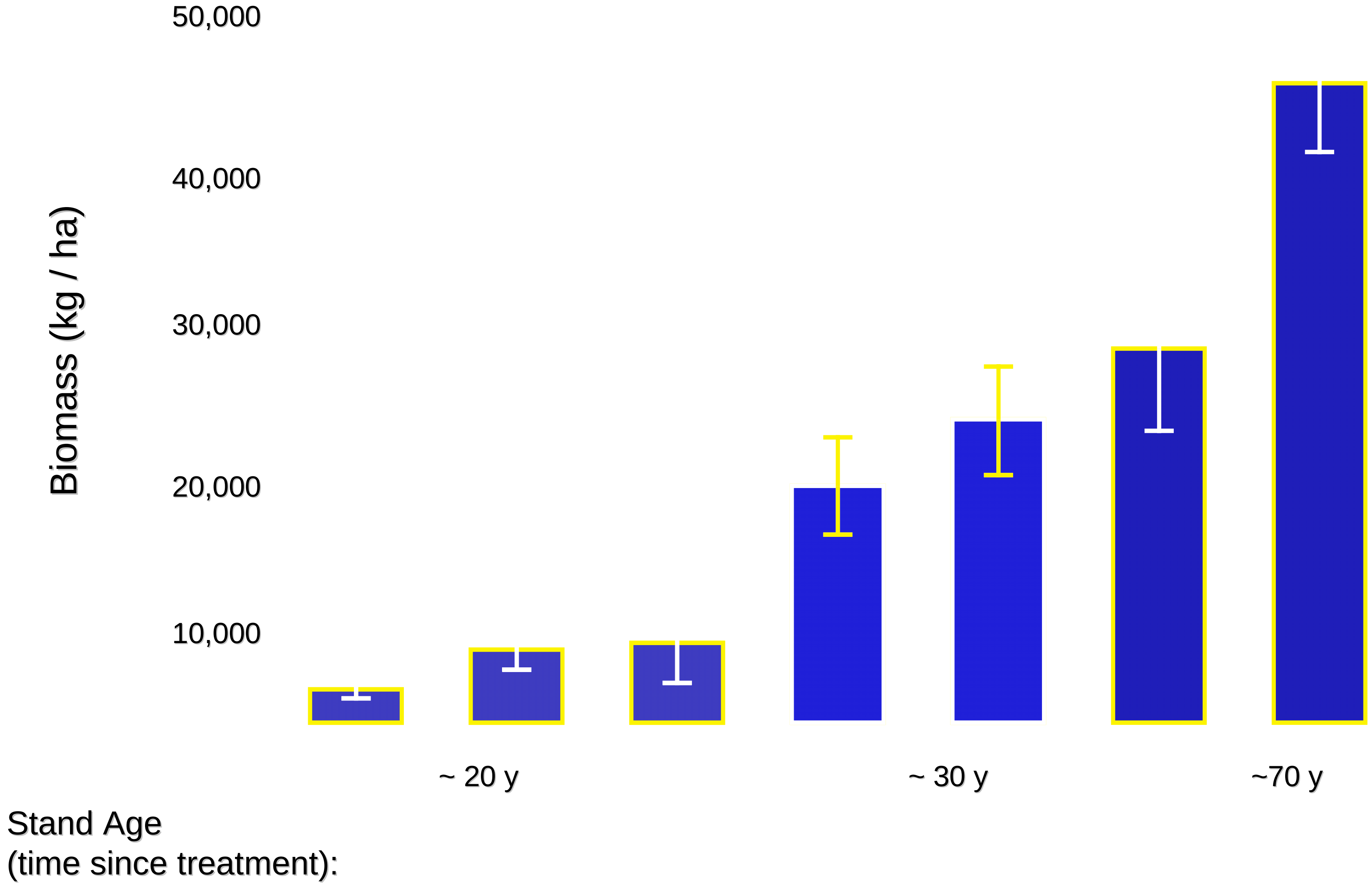


'Brush Management' is critical to sustainable livestock production in many rangelands.

Mechanical (top panel) and herbicidal (bottom panel) treatments are expensive; results are often short-lived and may have adverse environmental consequences

Within a region, woody plant cover/ biomass may thus vary, depending on site management history

Aboveground Biomass of *Prosopis* on Sites with Contrasting Brush Management Histories (Gin Pasture, Waggoner Ranch, Texas)



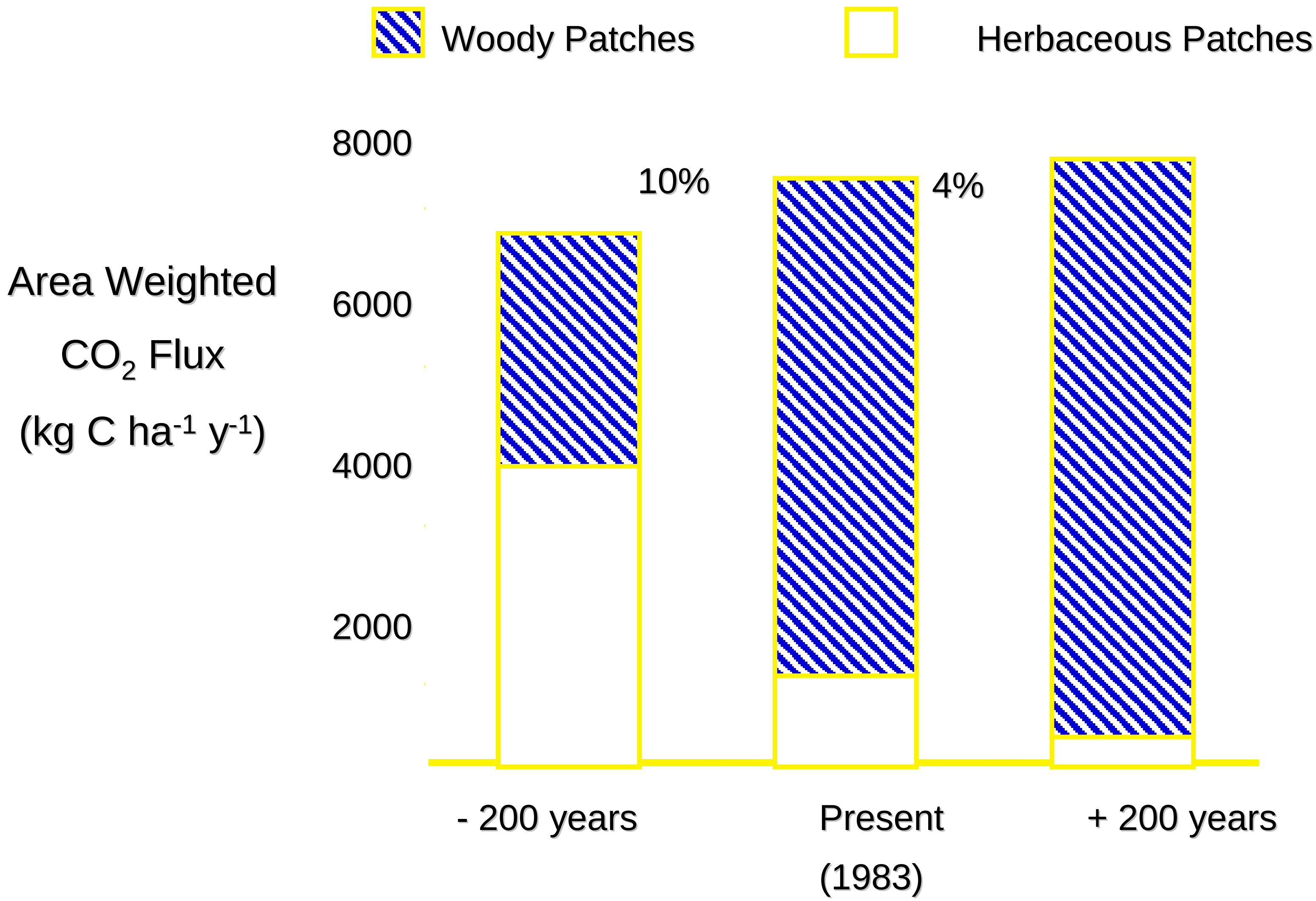
Socioeconomic Implications of Bush Encroachment

* Rural Economies
  ** Commercial Enterprises
  ** Pastoral Societies
* Food, Fiber, Economic Stability
* Sustainability

ECOLOGICAL CONSEQUENCES OF WOODY PLANT INCREASE IN DRYLANDS?

- WOODY PLANTS MODIFY SOILS & MICROCLIMATE
  - • C and N Flux From Soils Increases
  - • C and N Pool Sizes in Plants and Soils Increases

Annual measurements of soil respiration (McCulley 1999) coupled with a successional model of vegetation change (Scanlan & Archer 1991), indicate soil CO_2 flux may have increased ca. 10% subsequent to woody plant encroachment



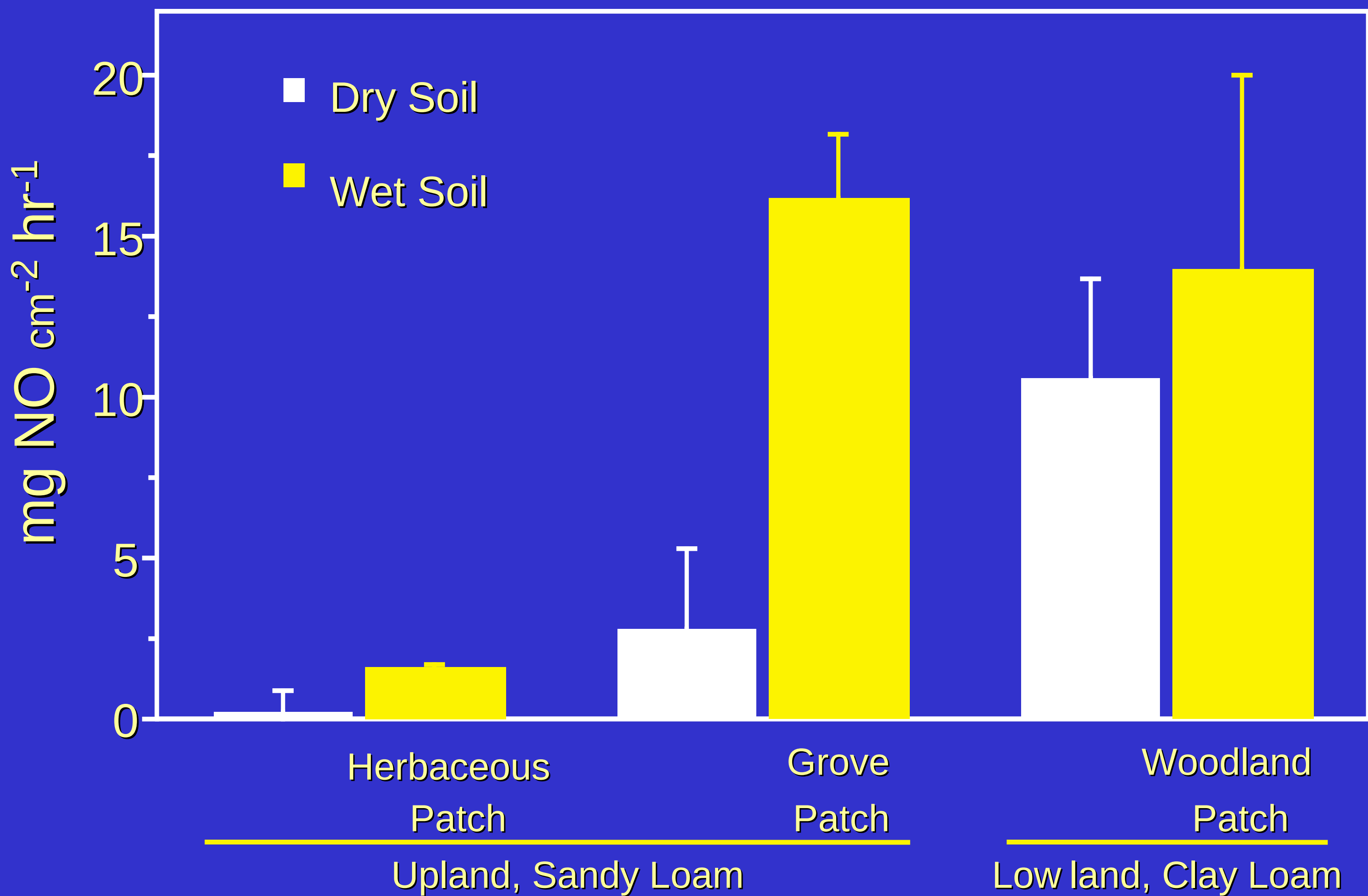
Patch Type	Annual N-Mineralization ($\mu g\ g^{-1}\ y^{-1}$)
Herbaceous	42 $\pm$ 5
Shrub Cluster	200 $\pm$ 18
Grove	137 $\pm$ 16
Woodland	127 $\pm$ 29

Annual nitrogen mineralization rates at the La Copita site in southern Texas are highest in soils associated with woody vegetation known to have developed over the past century

From Hibbard 1995

NITRIC OXIDE FLUXES

La Copita Site, Texas



Vegetation Change

Model

(Scanlan & Archer 1991)

NMHC Emissions

Model

(Guenther et al. 1995)

(Guenther 1997)

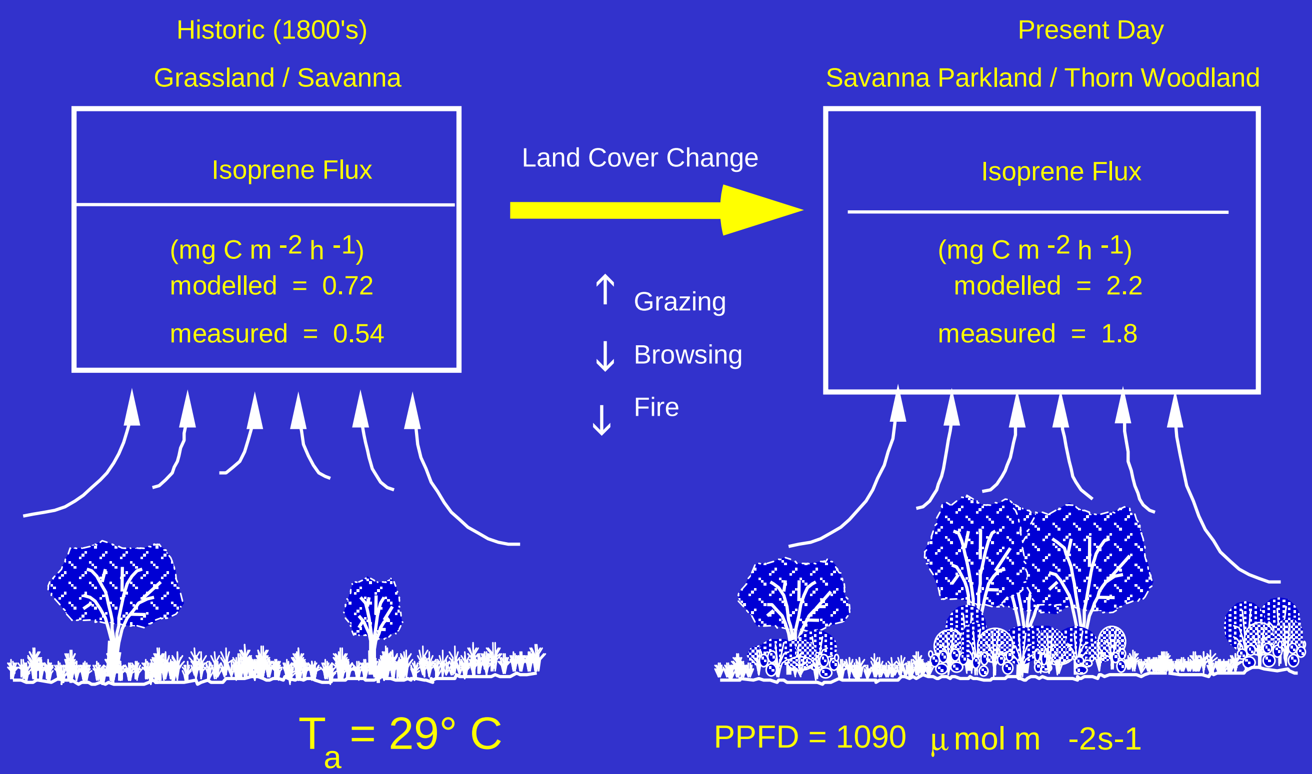
Land Cover Change and NMHC Emissions

in a Subtropical Savanna

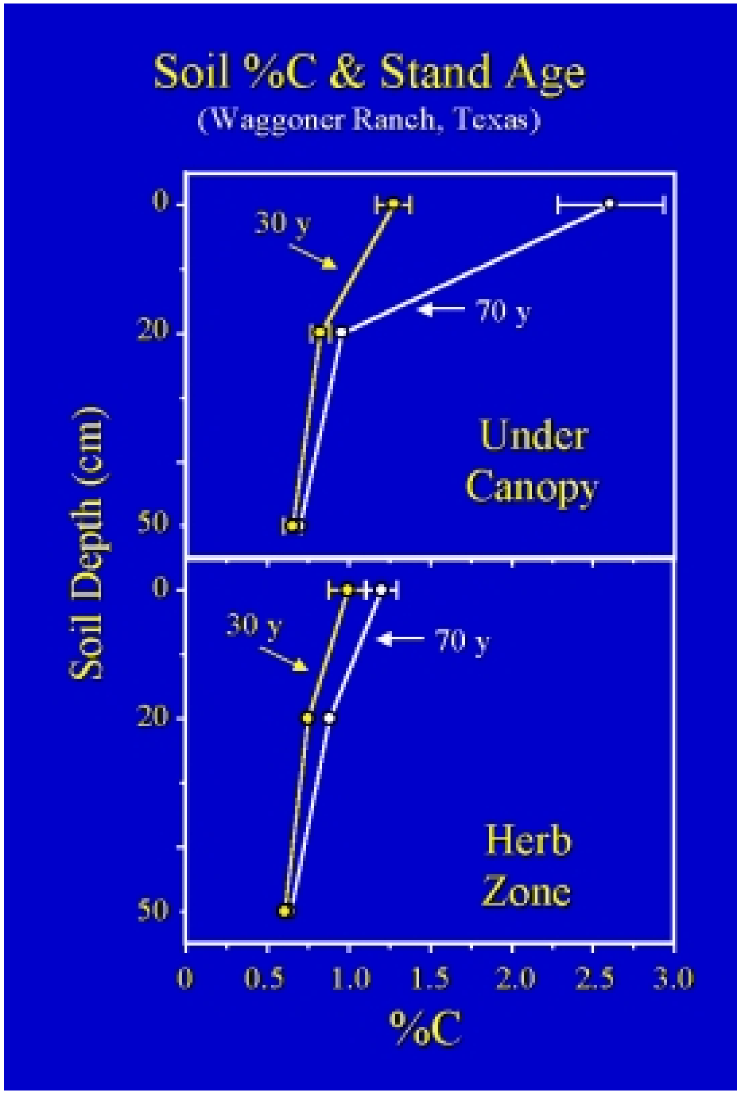
(Guenther et al. 1999)

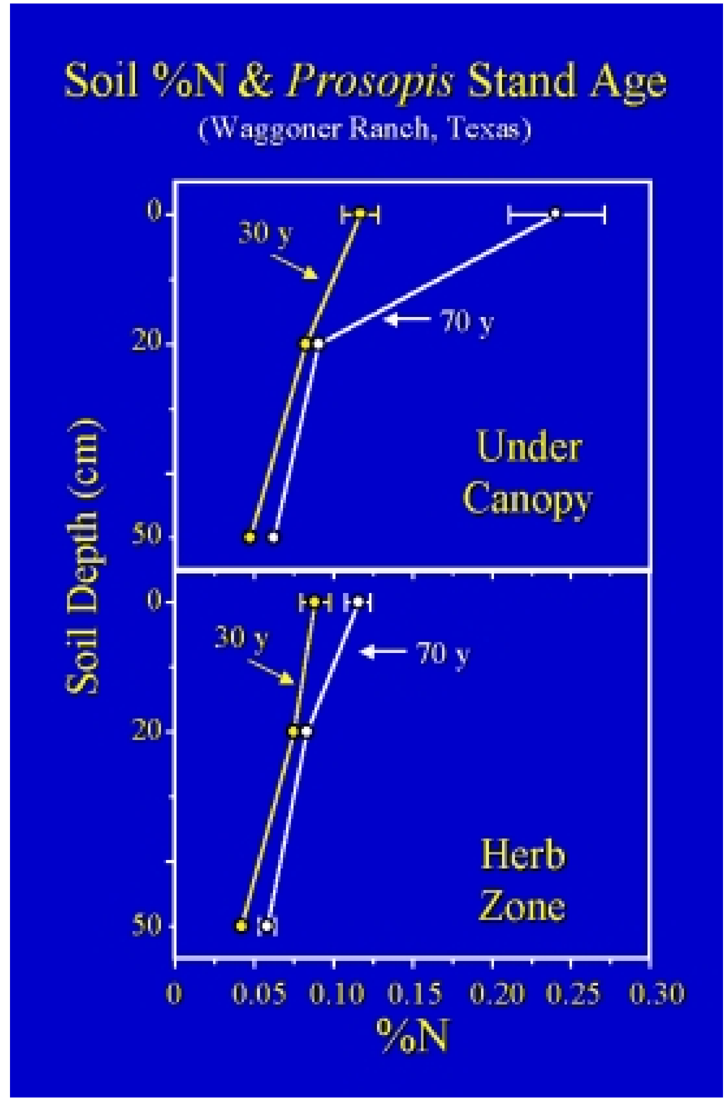
NMHC Emissions & Land Cover Change

(Guenther et al. 1999)

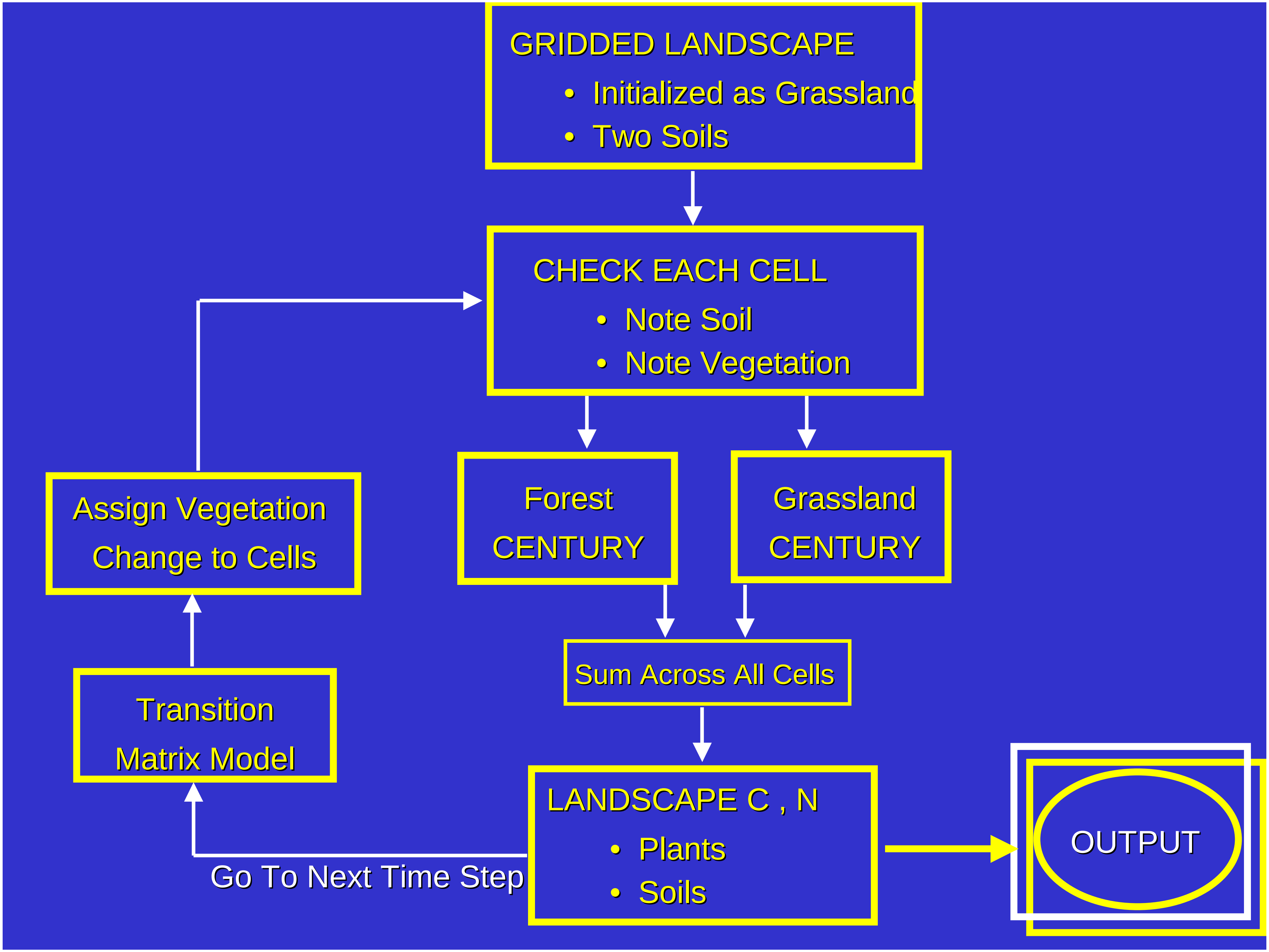


Non-methane hydrocarbons affect tropospheric chemistry (greenhouse gas half-life, ozone production, OH^- radical chemistry). Increases in woody plant abundance have increased NMHC emissions 3-fold at the La Copita site.

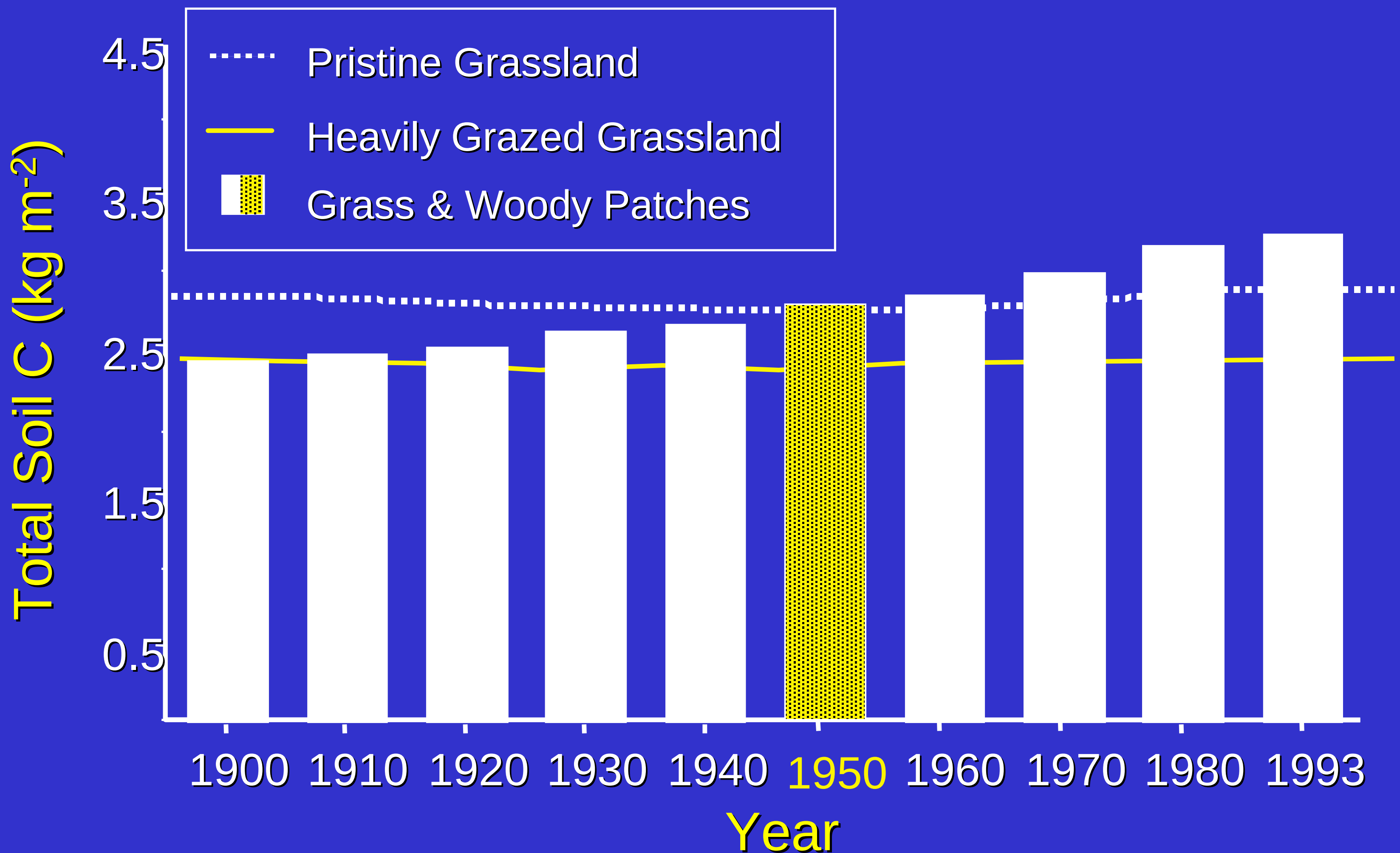




Soil carbon and nitrogen concentration and mass increase subsequent to woody plant establishment.


GRIDDED LANDSCAPE
• Initialized as Grassland
• Two Soils
CHECK EACH CELL
• Note Soil
• Note Vegetation
Forest CENTURY
Grassland CENTURY
Sum Across All Cells
LANDSCAPE C , N
• Plants
• Soils
OUTPUT
Go To Next Time Step
Transition Matrix Model
Assign Vegetation Change to Cells

LANDSCAPE-SCALE SOIL CARBON MASS



Estimates of C-sequestration by dryland woody plants must account for deep root systems (photo by S. Archer, La Copita site, Texas)

ASSESSMENT OF CONSEQUENCES

ULTIMATELY DEPENDS ON ACCURATE, REGIONAL MONITORING OF:

- Pattern And Extent Of Encroachment
- Net Outcome Of Encroachment vs. Clearing
- Rate Of Regeneration After Clearing

REMOTE SENSING: A CRITICAL TOOL

Quantitative Remote Sensing

- Spectral vegetation indices such as NDVI are single values attempting to describe a multivariate condition.

    * NDVI:biophysical relationships are often locationally-, temporally- and vegetation-dependent

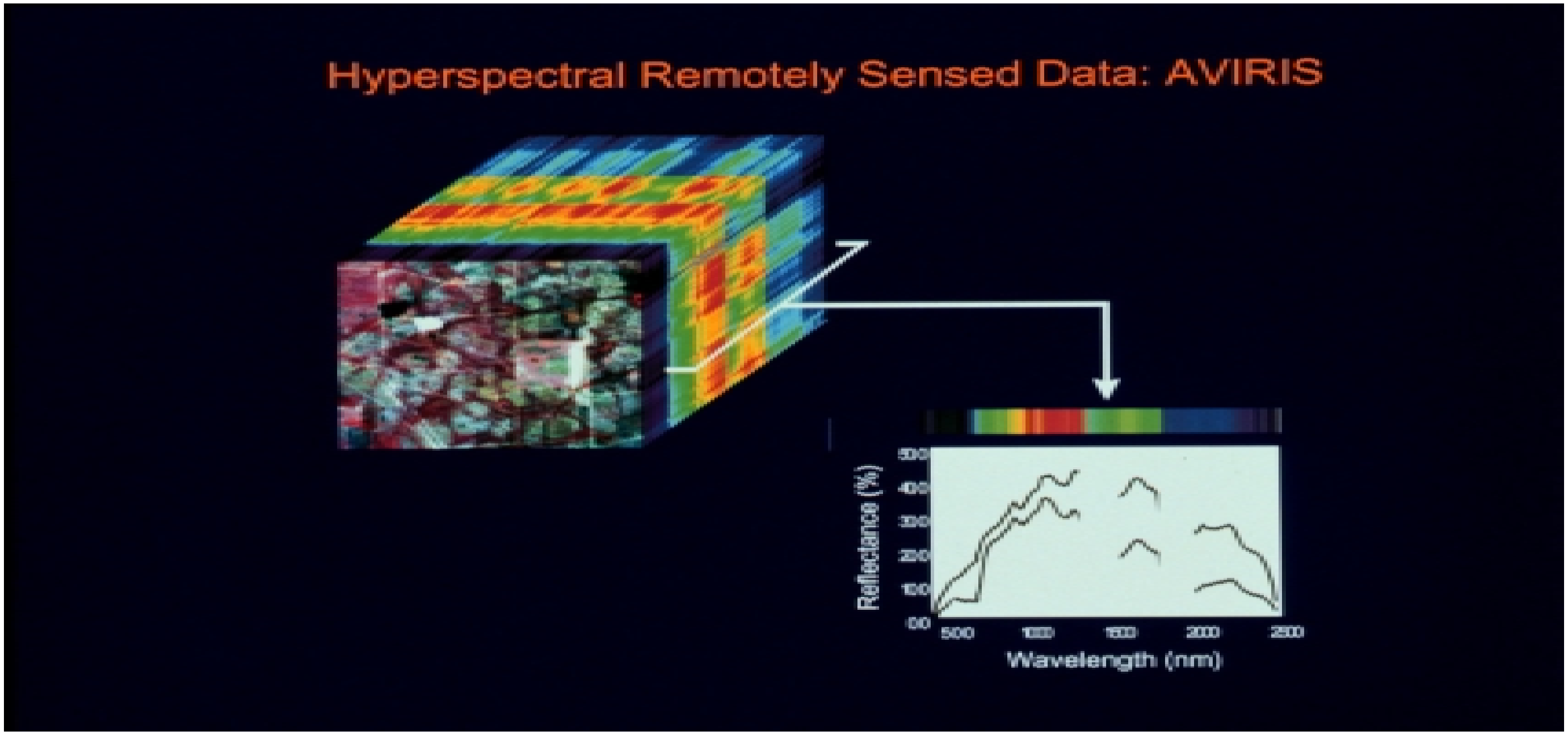
- Techniques utilizing canopy radiative transfer theory and sub-pixel analyses quantify contributions of individual landscape components (e.g. green foliage, litter) to measured reflectance.

- Quantitative remote sensing measures the key structural attributes, vertically and horizontally, in changing landscapes.

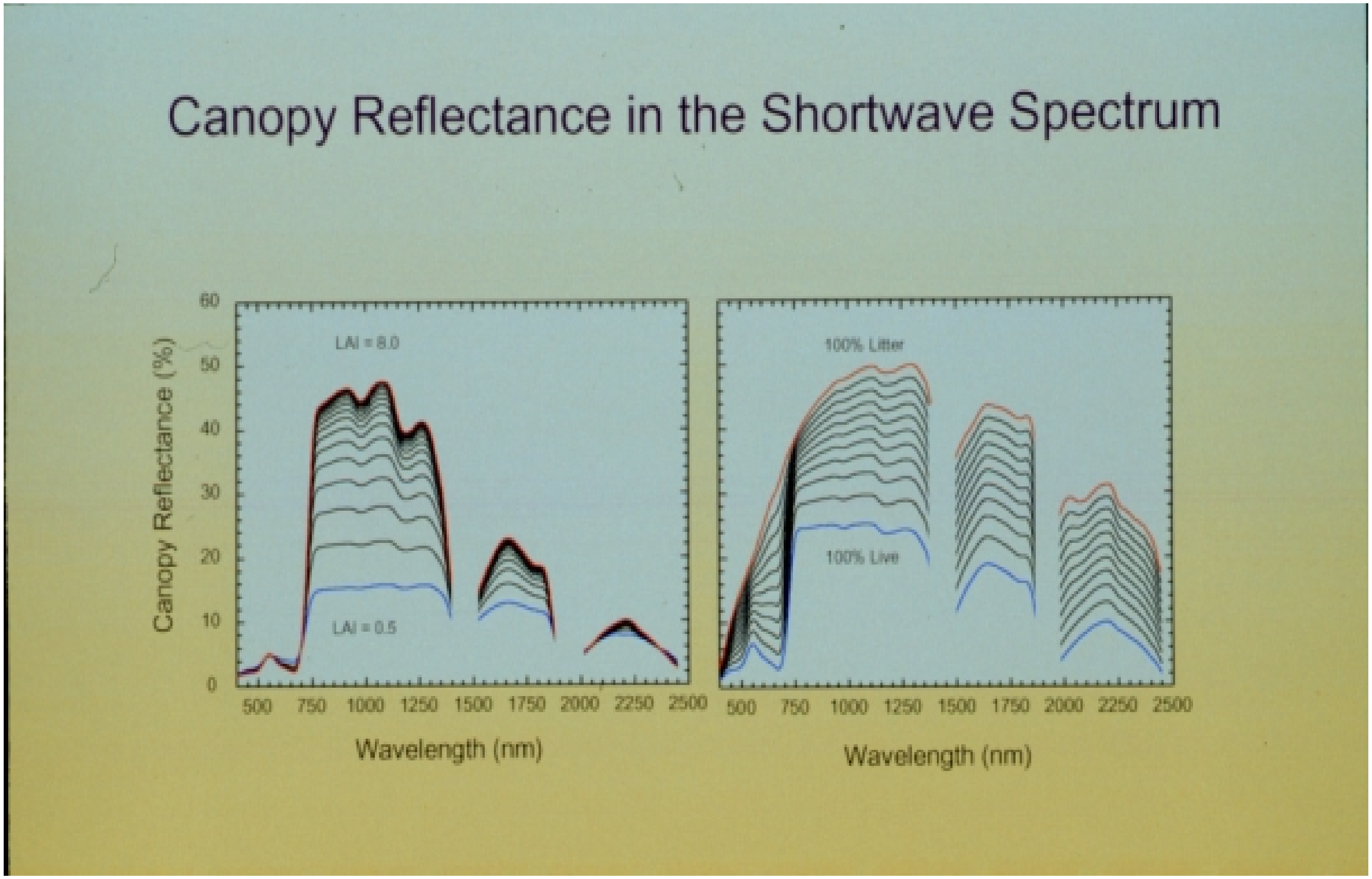
Spectral Mixture Analysis

Reflectance from a heterogeneous canopy or landscape is:

- A composite of signals from each component
- A function of the type and quantity of the reflecting components and their relative influence on the measured response.



A cube of AVIRIS data showing how endmembers of landscape components can be distinguished. The high spectral resolution (~10 nm) gives a nearly continuous reflectance signal which can be used to differentiate landscape/ vegetation components when used in conjunction with radiative transfer and mixing models.



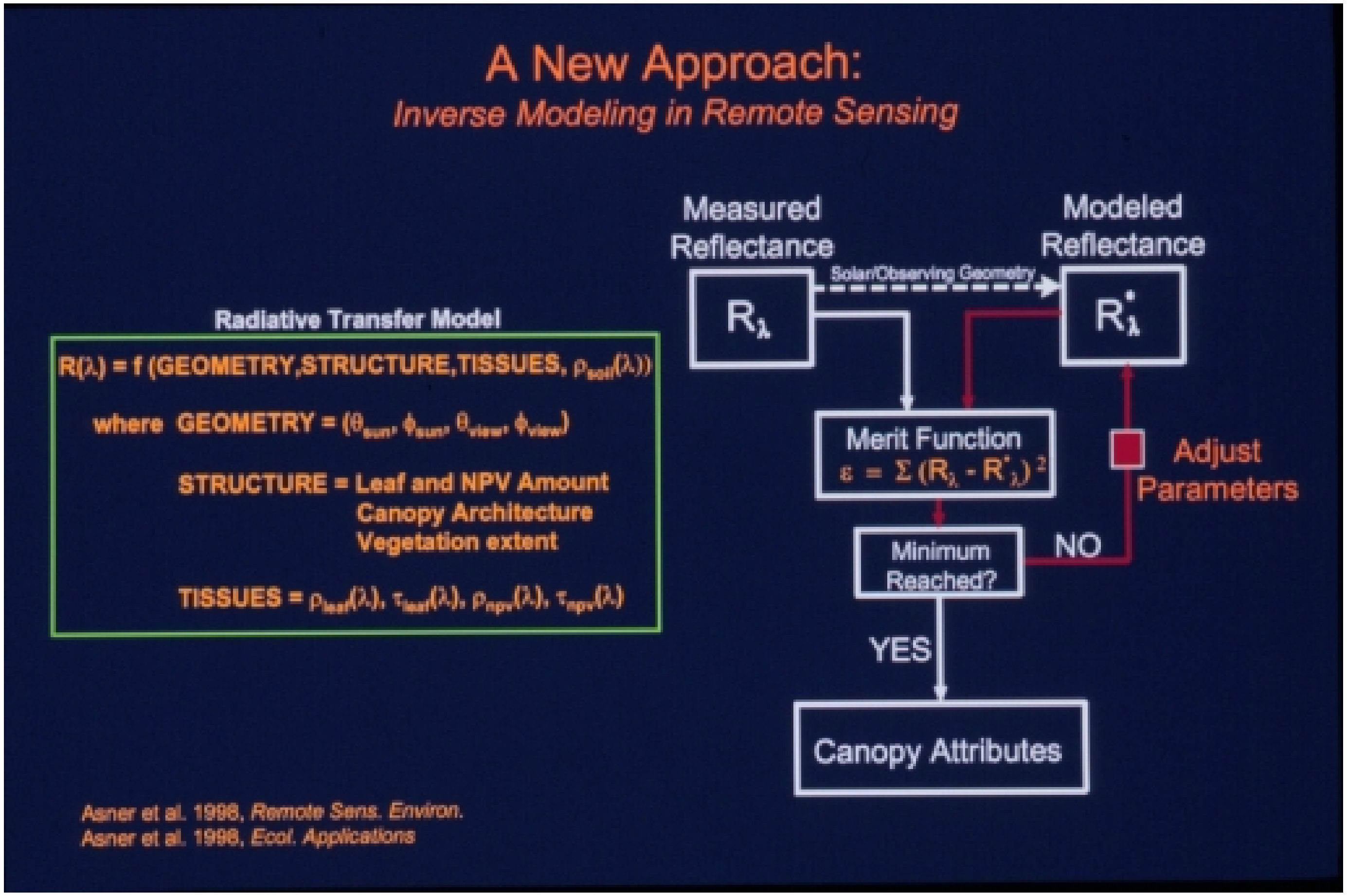
Magnitude of the hyperspectral reflectance signal is highly sensitive to leaf area and non-photosynthetic (litter, woody stems) materials in plant canopies (Asner *et al.* 1998. *Ecol. Appl.* 8:1022-1036)

Radiative Transfer Model

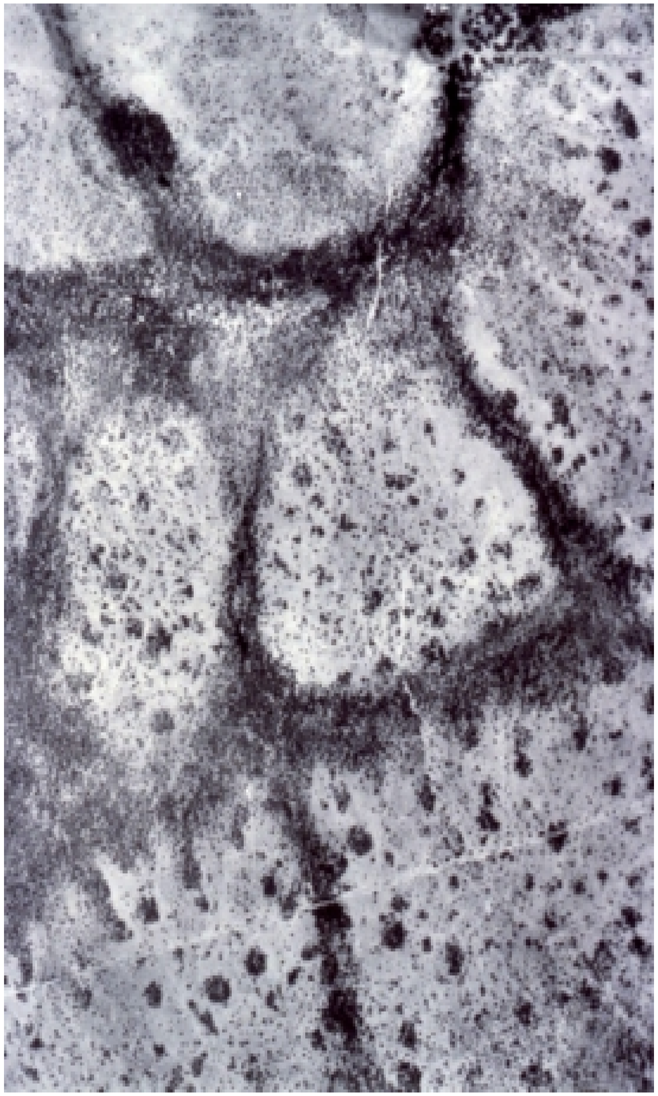
Produces top-of-canopy reflectance spectra from:

- LAI
- NPVAI*
- Leaf/stem orientation
- Leaf/stem optical properties
- Sun/view orientation
- % Vegetation cover
- Soil reflectance

*Non-Photosynthetic Vegetation



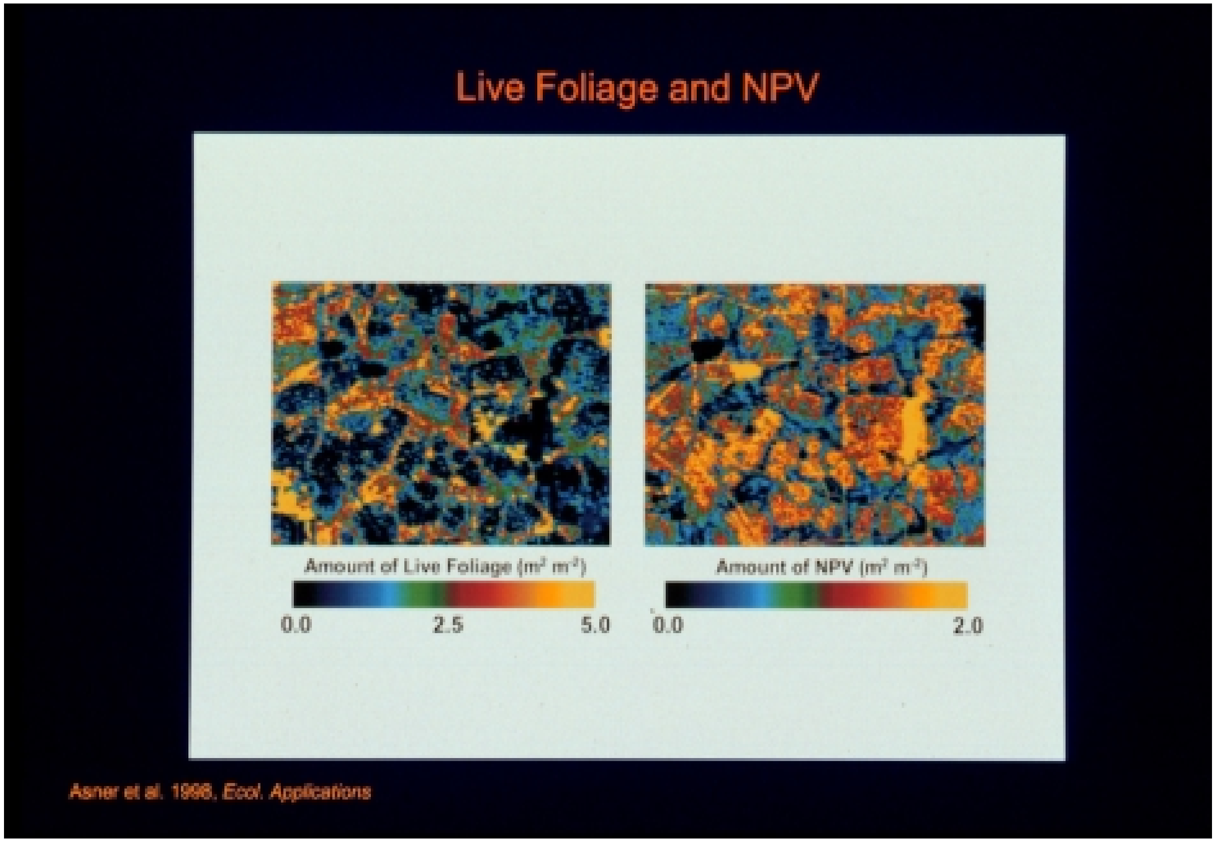
Structural attributes producing the canopy reflectance observed by a remote sensing instrument can be derived from radiative transfer models which have been appropriately constrained (Asner *et al.* 1998. *Ecol. Applications* 8:1022-1036).



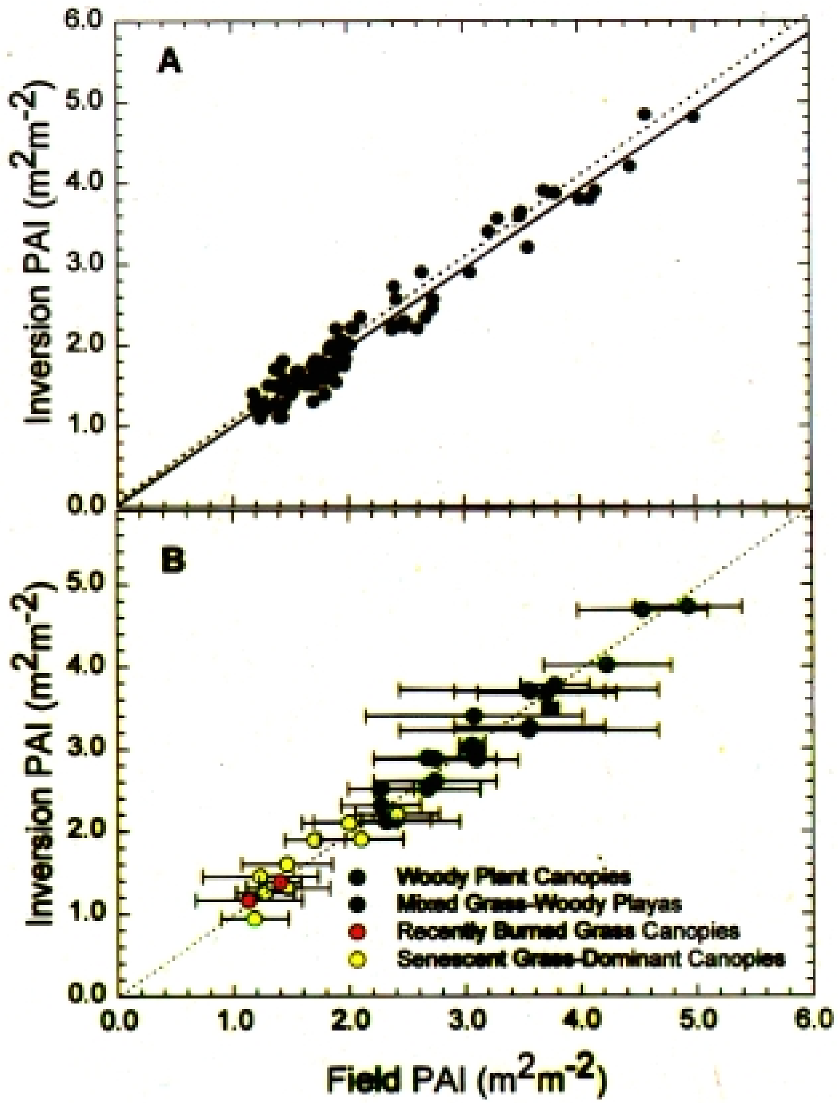
Black & white aerial photo of the La Copita site in southern Texas, showing rheticulate , polygonal vegetation patterns.

Black areas are woody plant canopies; grey areas are dominated by grasses. Sandy loam uplands are characterized by discrete shrub clumps dispersed in a grassy matrix; these give way (1-3% slopes) to closed-canopy woodlands in clay loam intermittent drainages

AVIRIS was successfully used to quantify structural and functional attributes of this complex landscape (next slides)



Spectral Mix. Anal. --> Live v. Dead Fractions --> RT Model Inversion --> area indices of live foliage and non-photosynthetic vegetation (NPV) at La Copita site, Texas (Asner *et al.* 1998. *Ecol. Appl.* 8:1022-1036). AVIRIS imagery is from August 1993 when grasses are dormant and shrubs are green and physiologically active.



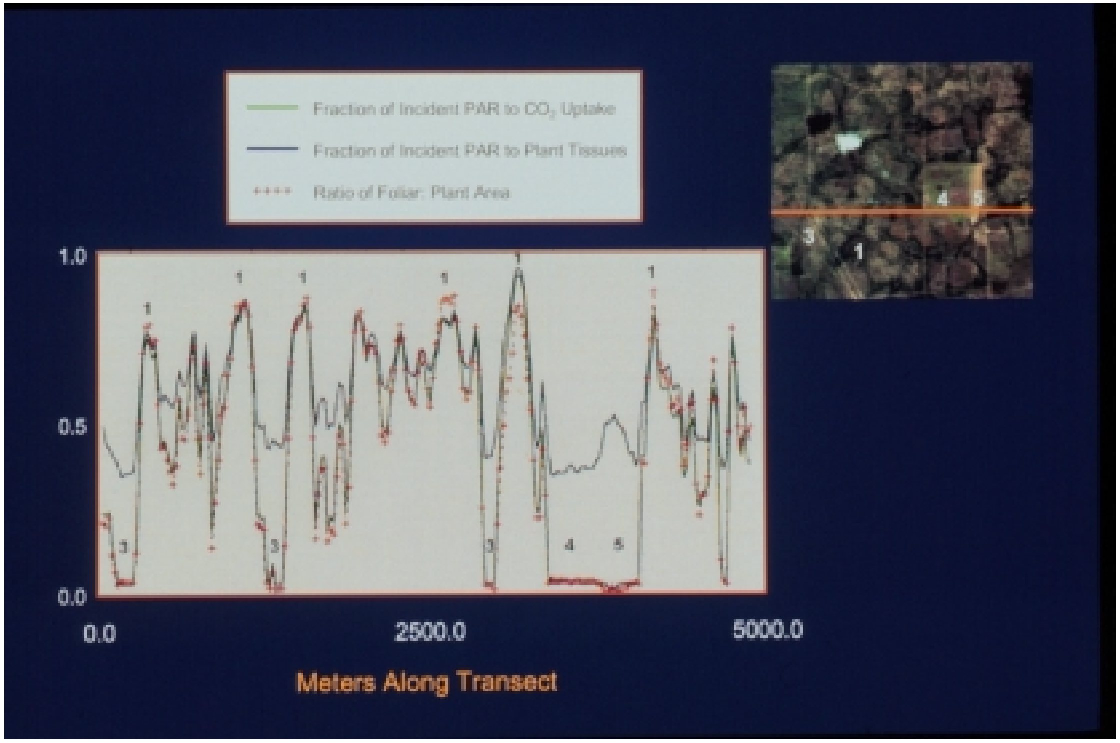
Agreement between ground (LAI-2000 instrument) and remotely sensed estimates of Plant Area Index, La Copita site, Texas

A). Area-weighted field data w/i AVIRIS pixels

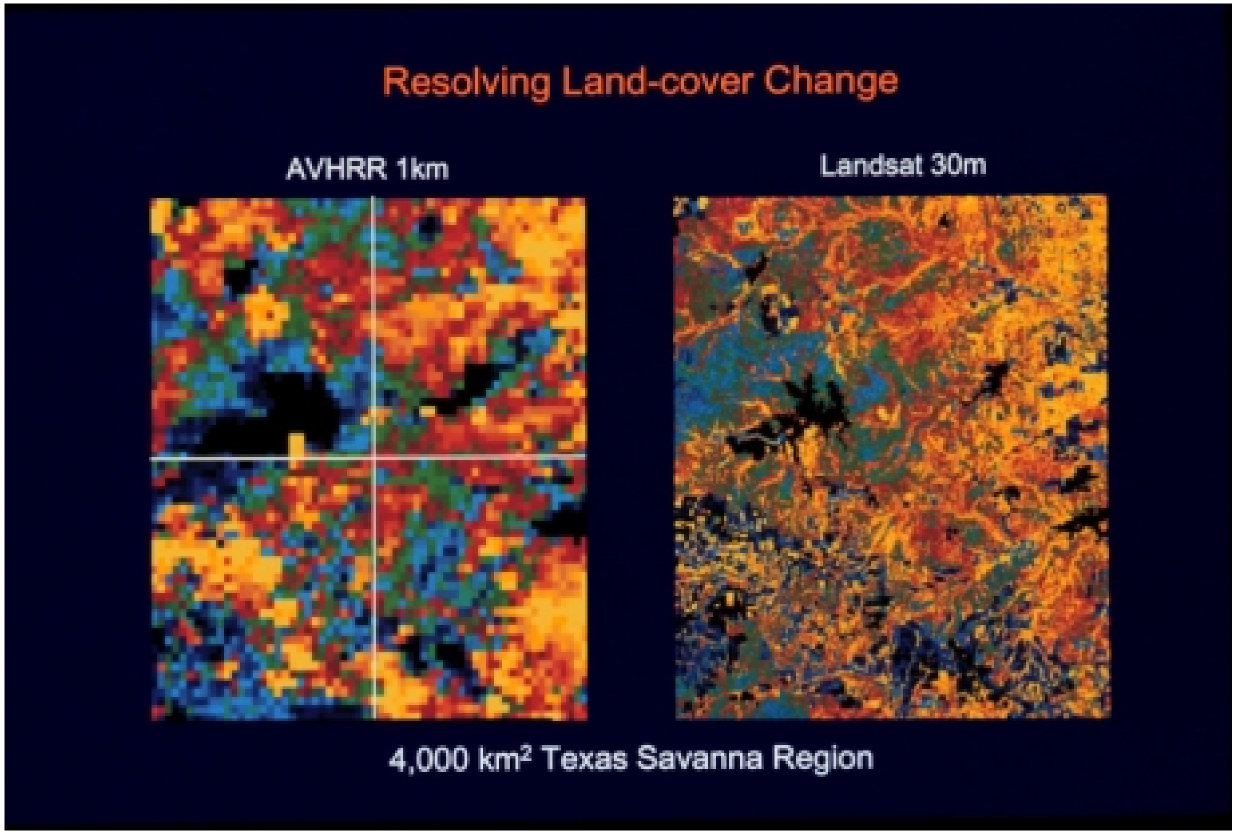
B). Not area-weighted

Asner *et al.* 1998. *Ecol. Appl.* 8:1022-1036

Asner *et al*. 1998. *Ecol. Appl.* 8:1022-1036



1 = closed-canopy woodland
2 = playas
3 = uplands
4 + 5 = pasture
6 = cropland
7 = cloud/shadow

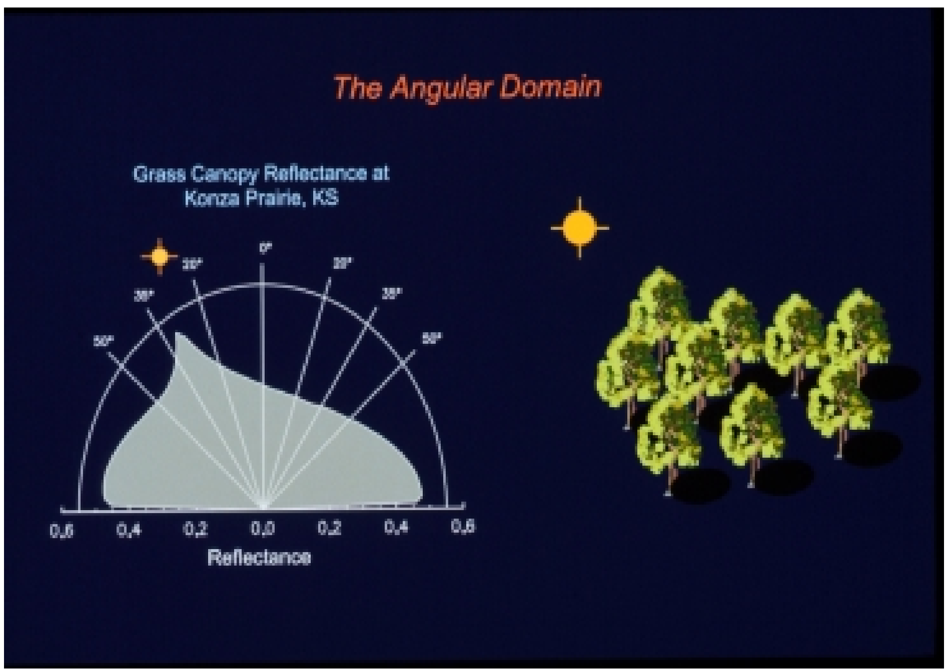


Land cover heterogeneity and change seen at 30 m resolution is lost at coarse (1 km) resolution. However, AVHRR can be used in conjunction with radiative transfer models to generate information useful for interpreting vegetation structure/function in TM scenes.

Satellite Data Fusion and Radiative Transfer Inverse Modelling
(Asner *et al.* 1998. *JGR* 103:28,839-28,853)

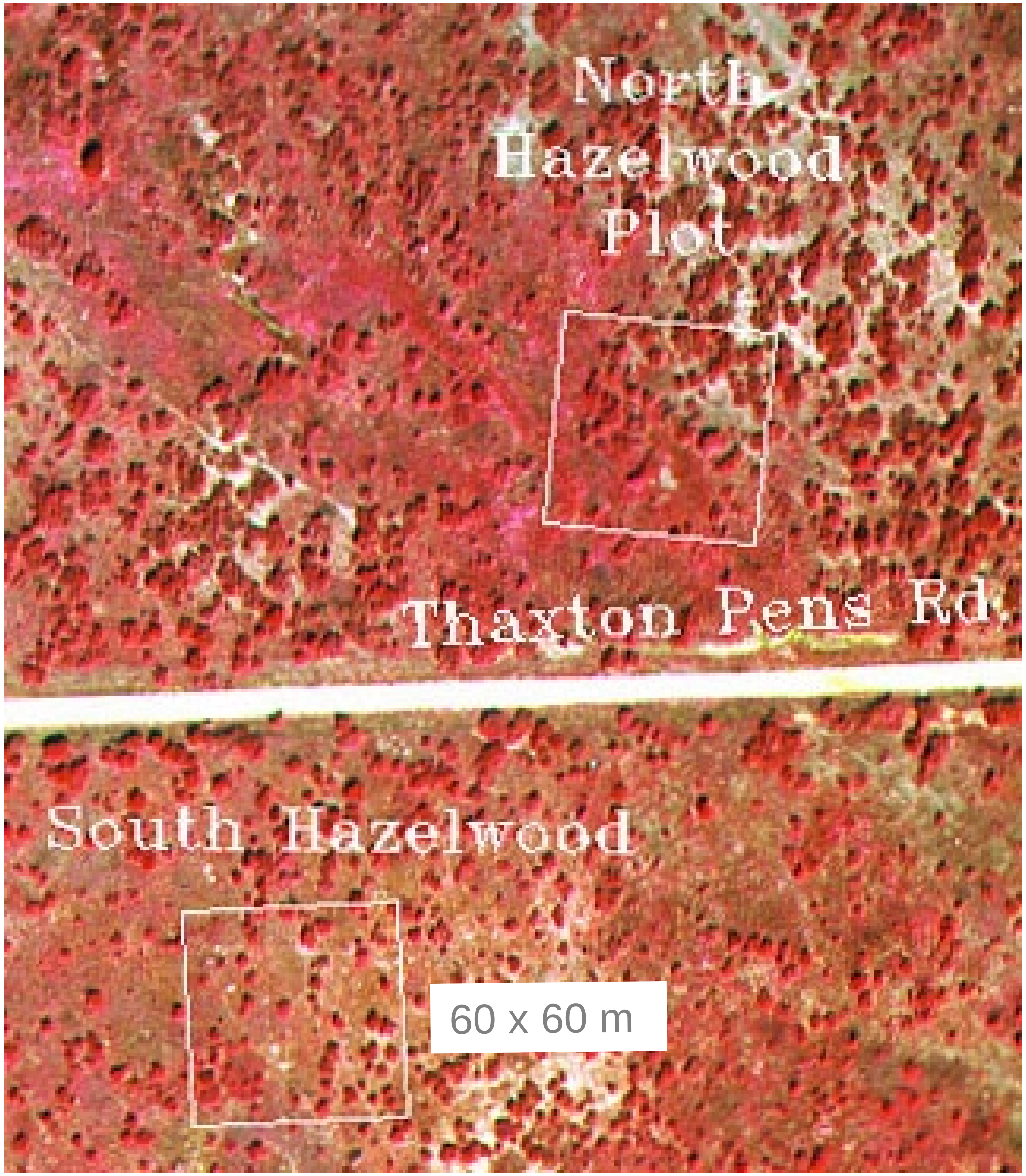
- Spectral mixture analysis of LANDSAT image (Sep 92) used to quantify tree, grass and soil fractions, tree density and tree crown dimensions.

- AVHRR multi-angle reflectance analyzed with RT model to estimate LAI



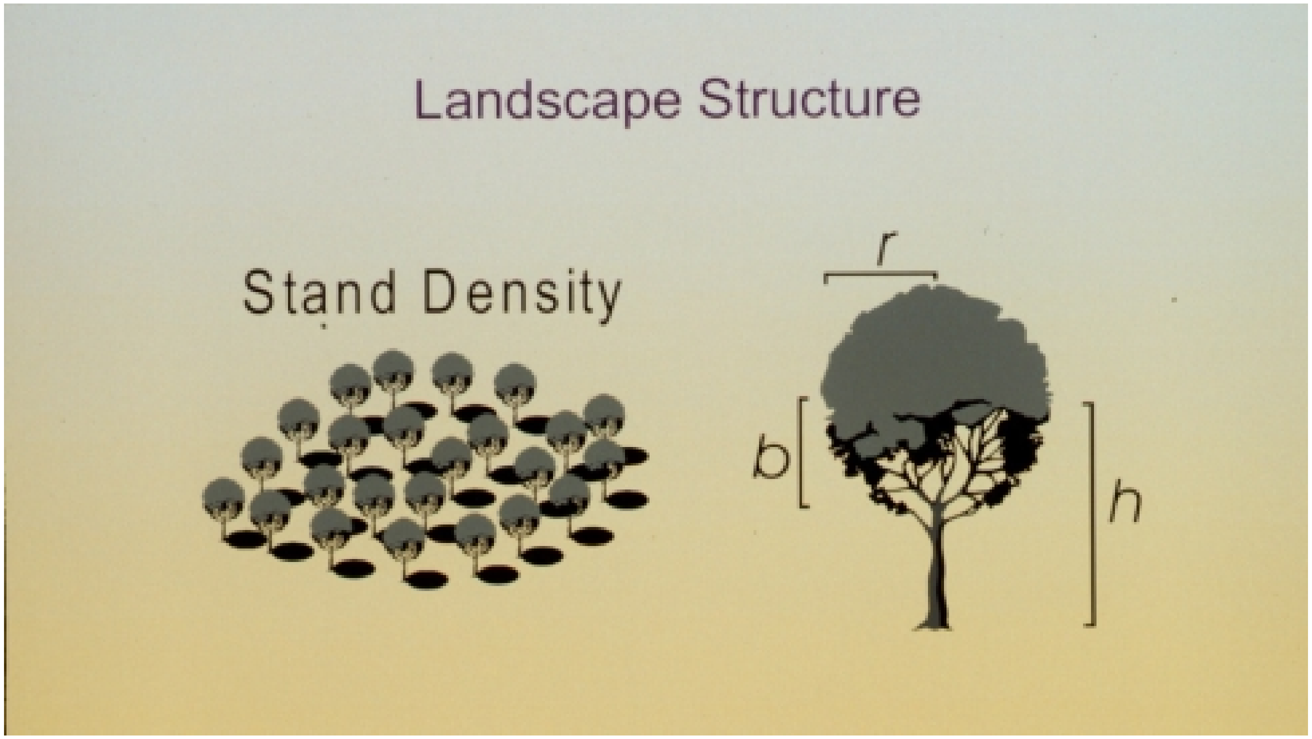
- 13 AVHRR images were acquired over a 10 day period in July 1992 for our north Texas site.

- The slight differences in view angles from these images produced a series of unique reflectance values that were interpreted by inverting a radiative transfer model



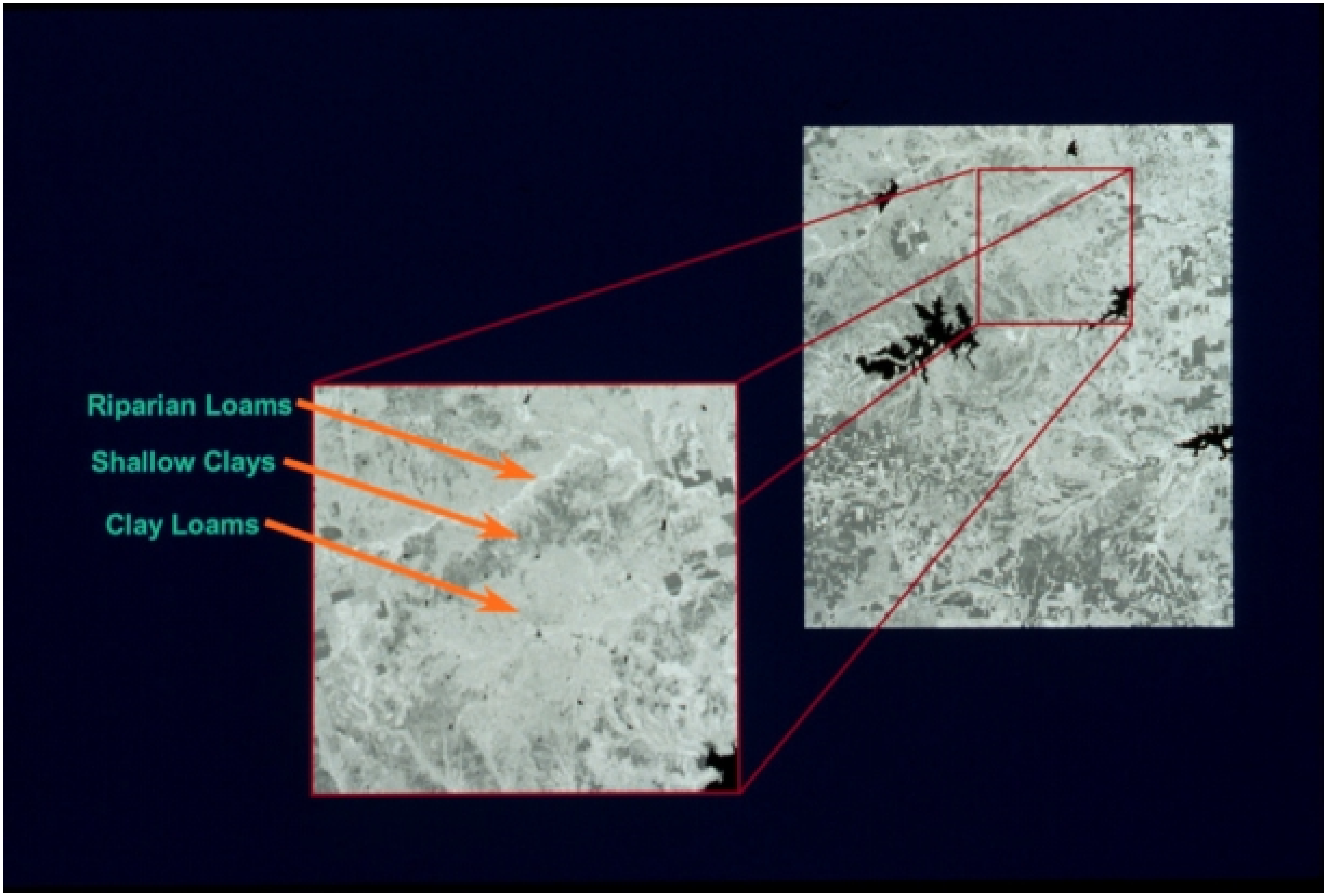
Ground Truth Plots Waggoner Ranch (n=23)

- LAI/PAI
- Leaf, Litter, Bark Optics
- Stem/Canopy Density
- Canopy Area
- Biomass (Allometry)
- Soil $\delta^{13}C$, $\delta^{15}N$, BD [C], [N]

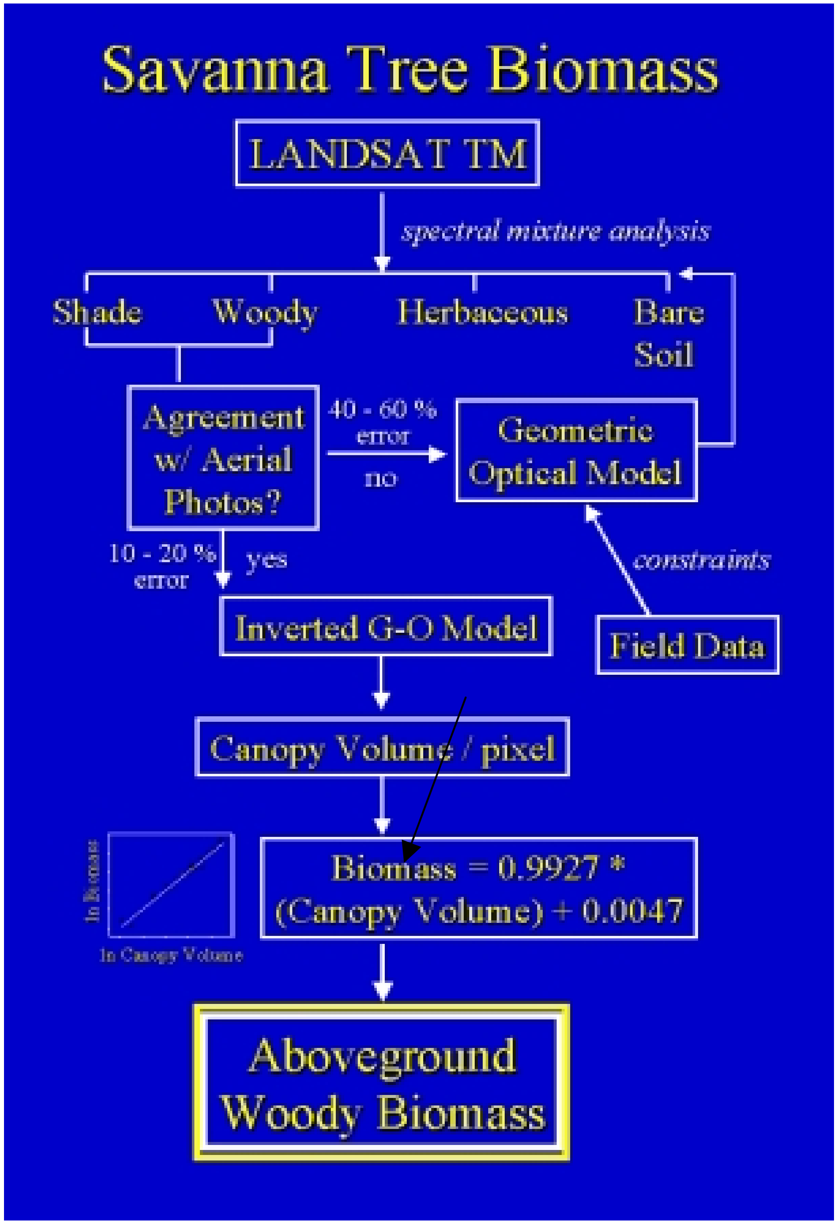


Shading between overstory/understory canopies was derived from tree crown dimensions and their ratios. These relationships were used to Parameterize a geometric-optical model and produce shadow-corrected LANDSAT cover fractions for AVHRR (Asner *et al.* 1998. *JGR* 103:28,839-28,853).

Prosopis aboveground biomass in ground truth plots, Waggoner Ranch, Texas spans 3 orders of magnitude and is a function of soil depth and brush management history.

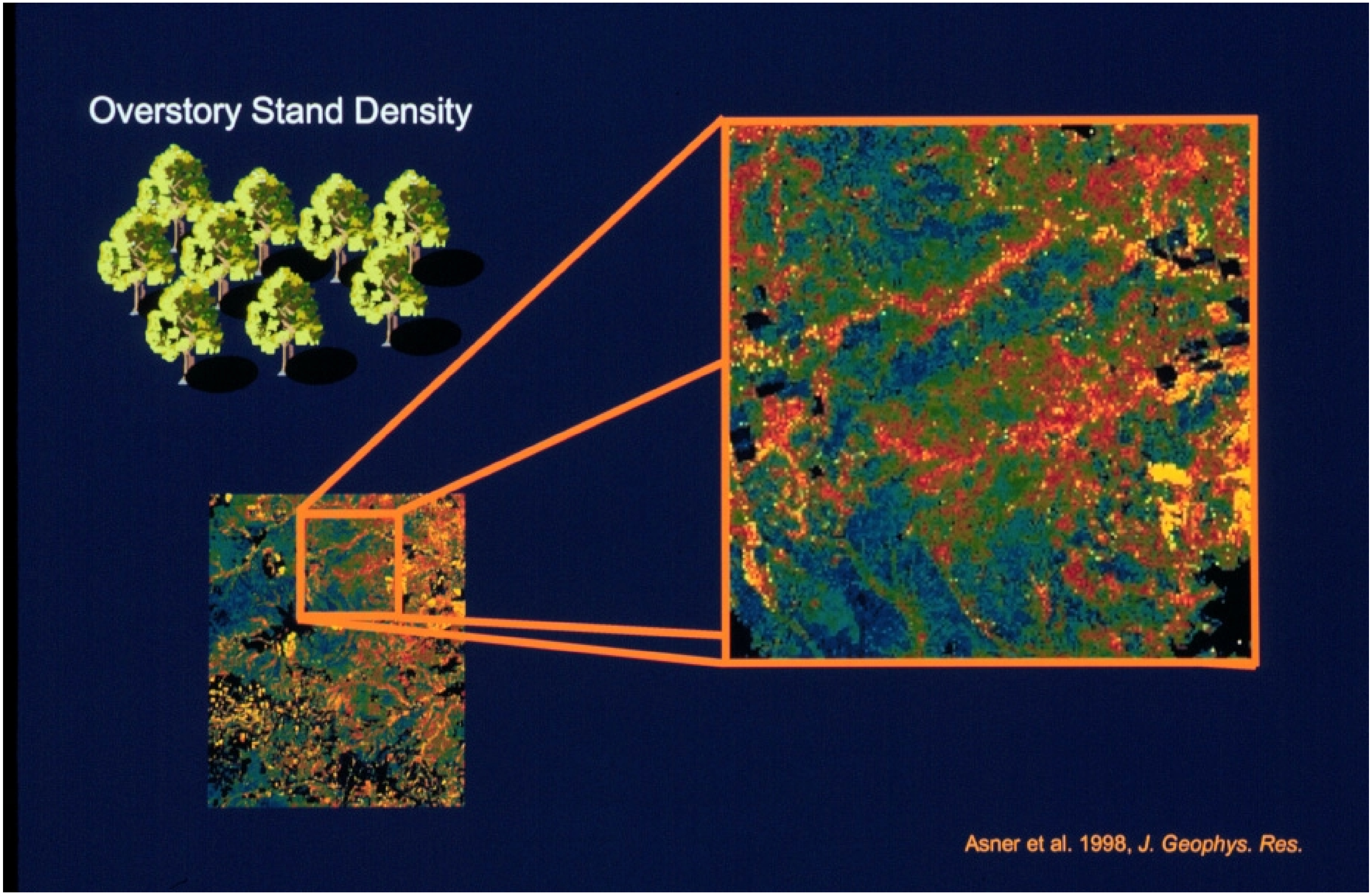


NDVI image, northern Texas savanna region,
Including 200,000 ha Waggoner Ranch

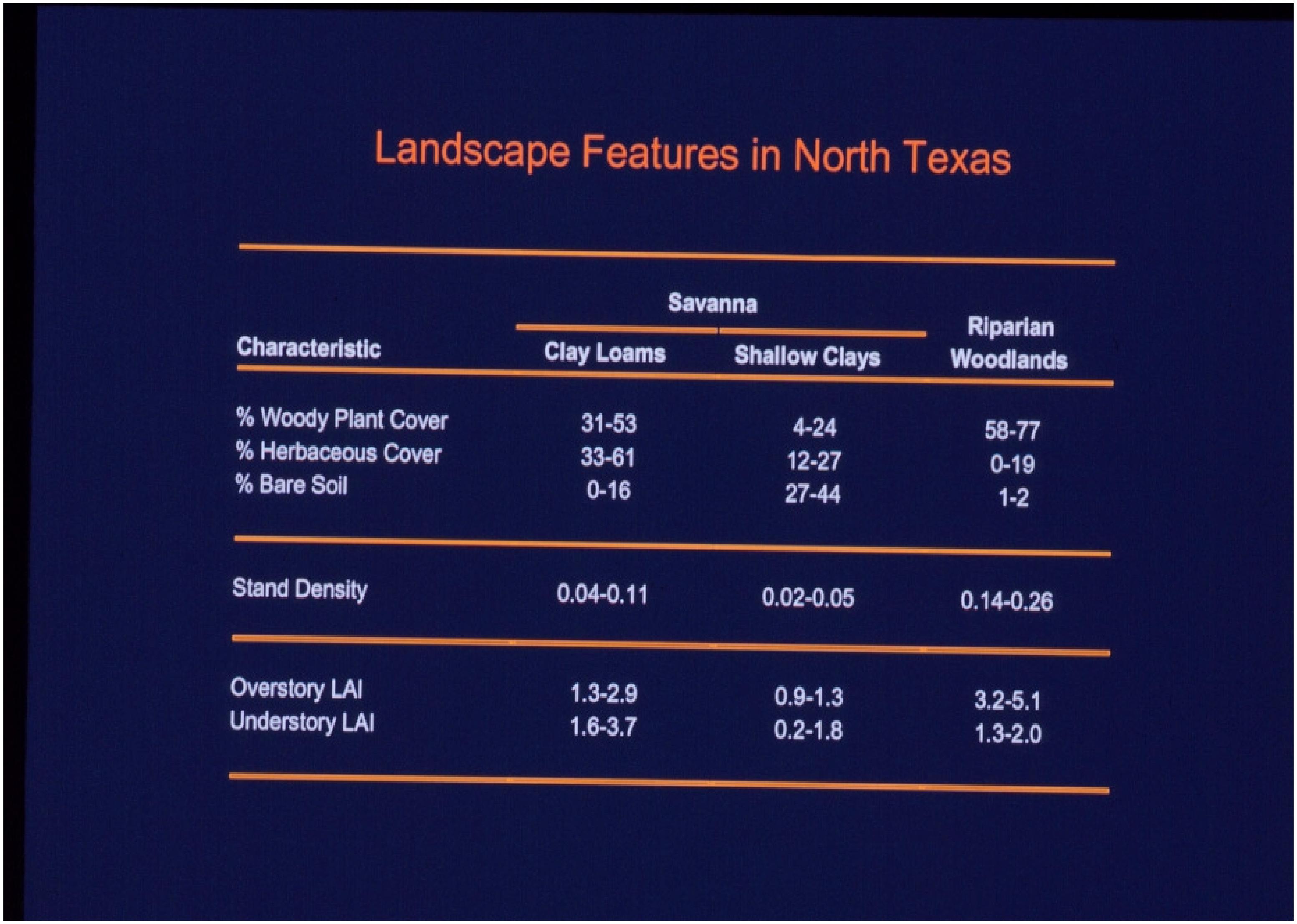


Protocol for estimating savanna tree biomass at Waggoner Ranch, Texas

(Asner *et al.* 1998. JGR 103:28,839-28,853)



Prosopis overstory stand density, Waggoner Ranch, Texas

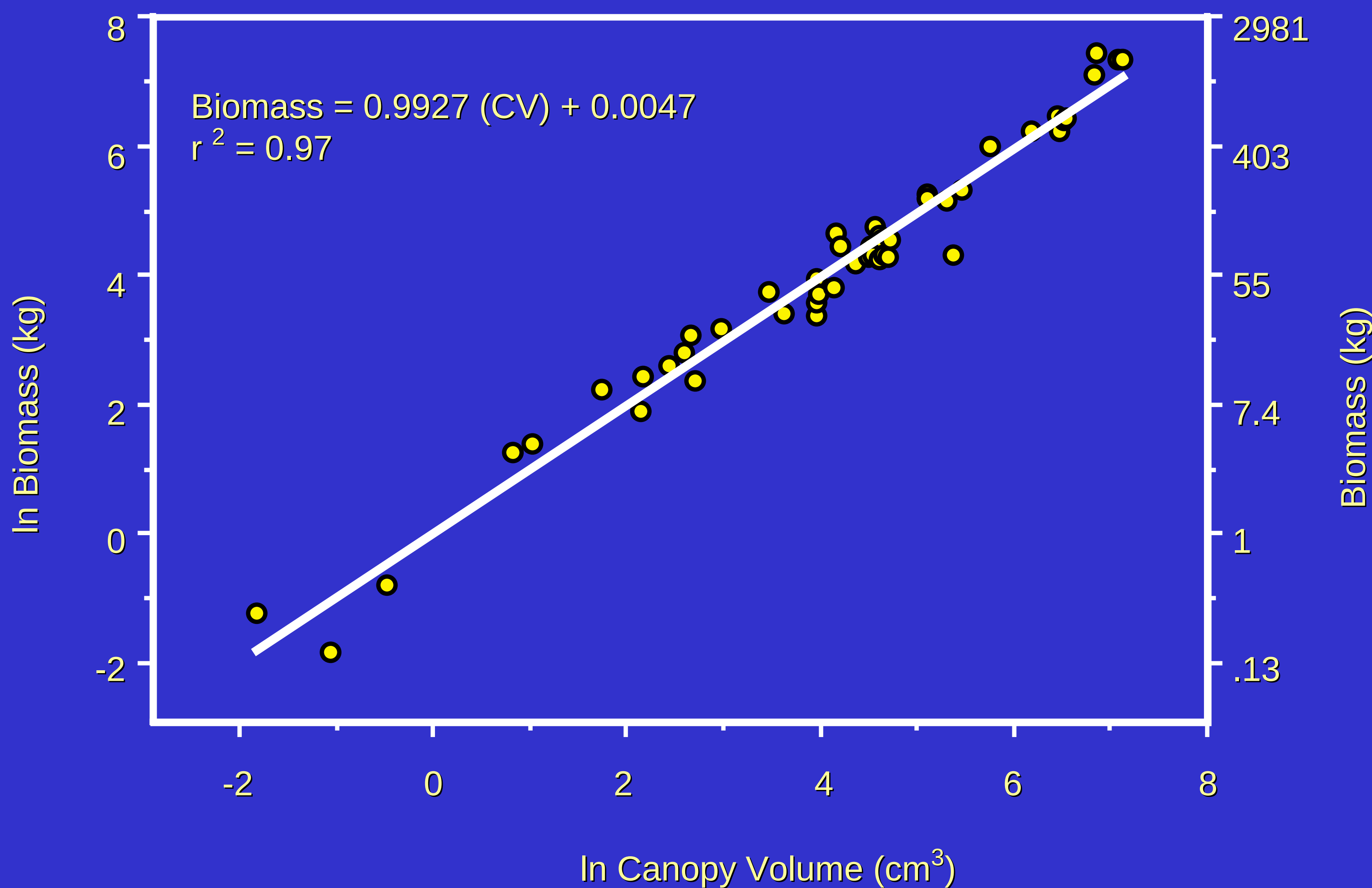


Landscape Features in North Texas

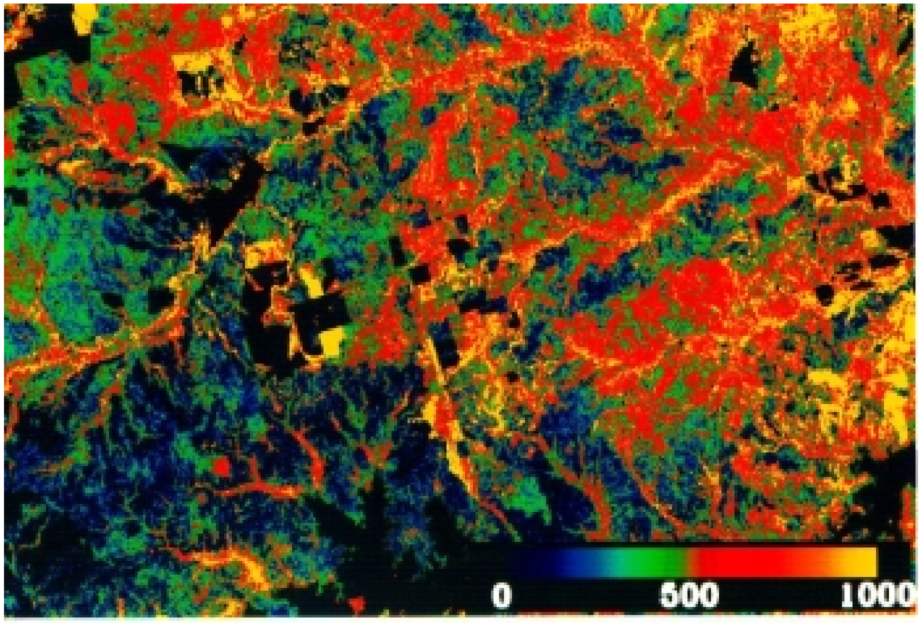
Characteristic	Savanna: Clay Loams	Savanna: Shallow Clays	Riparian Woodlands
% Woody Plant Cover	31-53	4-24	58-77
% Herbaceous Cover	33-61	12-27	0-19
% Bare Soil	0-16	27-44	1-2
Stand Density	0.04-0.11	0.02-0.05	0.14-0.26
Overstory LAI	1.3-2.9	0.9-1.3	3.2-5.1
Understory LAI	1.6-3.7	0.2-1.8	1.3-2.0

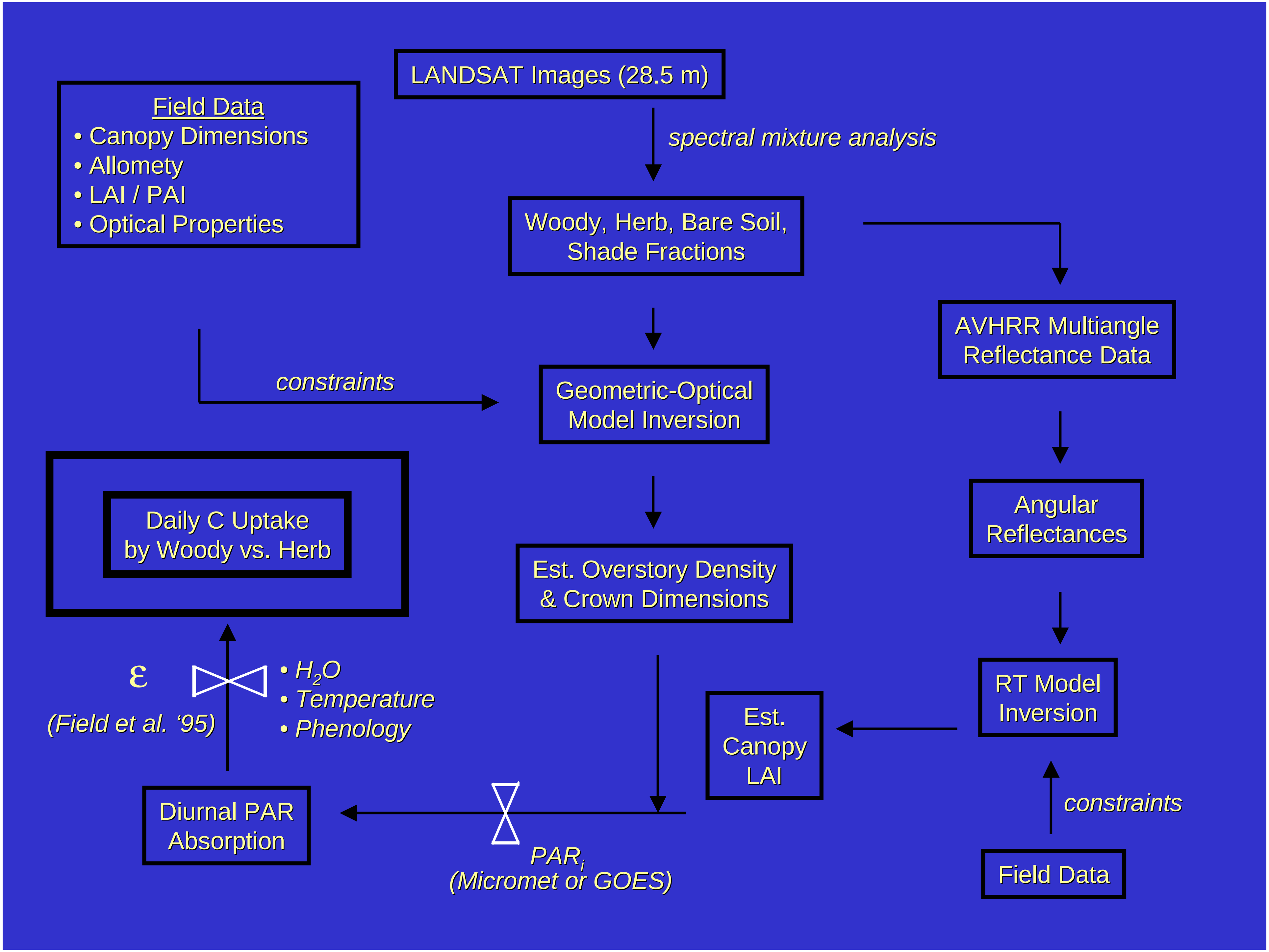
Canopy and landscape attributes acquired through spectral mixture analysis and inverse modeling (Asner *et al.* 1998. *JGR* 103:28,839-28,853).

Relationship between *Prosopis* biomass and plot-level canopy volume from ground truth plots, Waggoner Ranch, Texas. Remotely sensed estimates of stand density/canopy volume can be converted to biomass using this relationship.

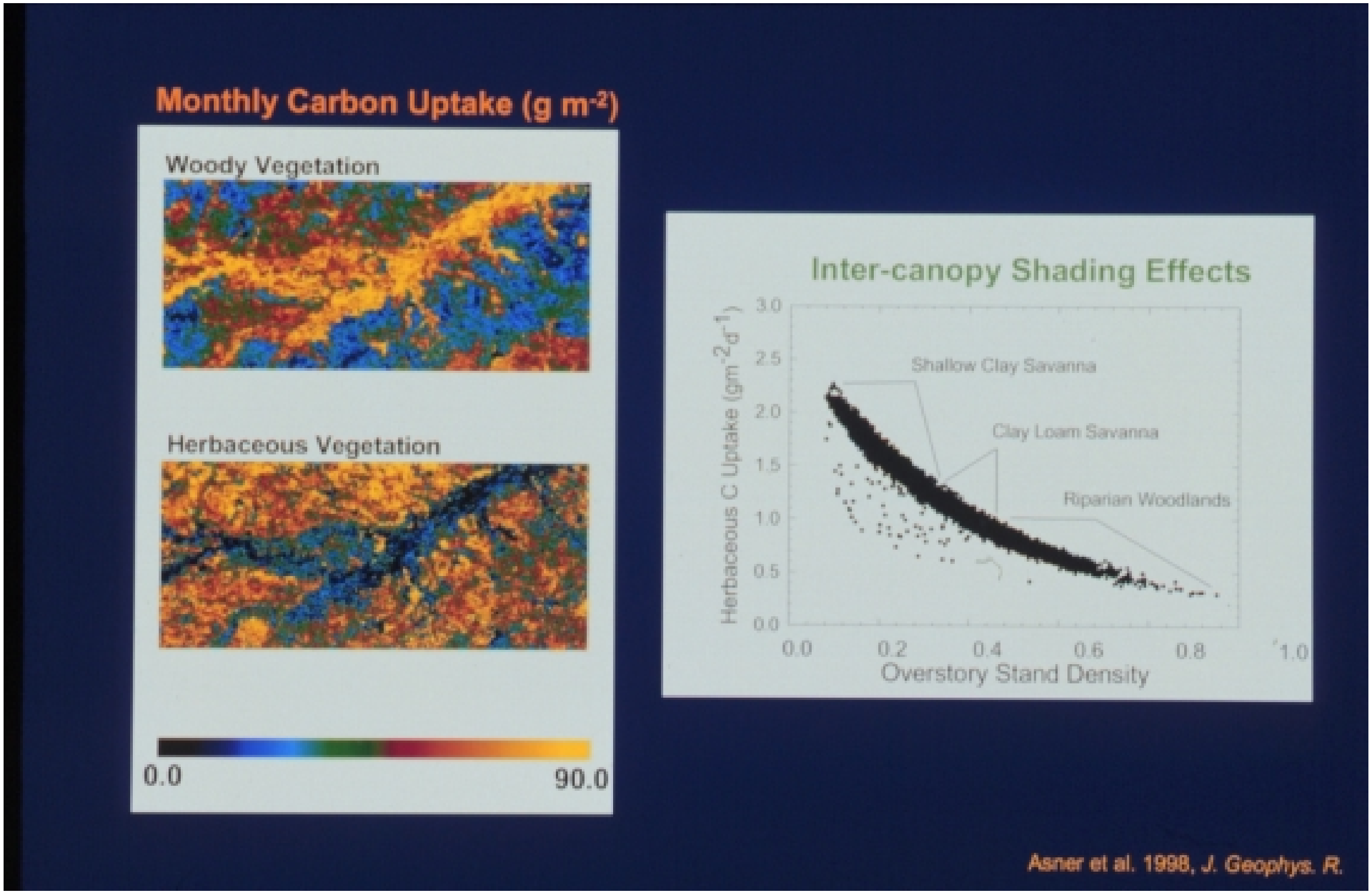


Biomass Estimates for North Texas Site





LANDSAT Images (28.5 m)
spectral mixture analysis
Field Data
• Canopy Dimensions
• Allomety
• LAI / PAI
• Optical Properties
Woody, Herb, Bare Soil, Shade Fractions
AVHRR Multiangle Reflectance Data
constraints
Geometric-Optical Model Inversion
Angular Reflectances
Daily C Uptake by Woody vs. Herb
Est. Overstory Density & Crown Dimensions
RT Model Inversion
ε
(Field et al. '95)
• H_2O
• Temperature
• Phenology
Est. Canopy LAI
constraints
Diurnal PAR Absorption
PAR_i
(Micromet or GOES)
Field Data



Regional Heterogeneity of C Uptake:

Riparian Woodlands > Clay Loam Savannas > Shallow Clay Savannas

Tree-Grass Interactions at Regional Scale:

The functional form of this curve mimics those developed from field studies of savanna's world-wide.

LINKING MODELING - REMOTE SENSING

- Integrated biophysical-biogeochemical model completed April 1999
- CSCM: Colorado-Stanford-Carnegie Multi-element Model
- Driven by remote estimates of structure (veg cover, LAI, litter) & function (fPAR) obtained via radiative transfer inverse models
- Inter-canopy/inter-vegetation effects regulated via nutrients, light, temp and hydrology
- Multiple element limitation of NPP and NEP (developed at Stanford with JC Neff, W Riley, PA Matson, and CB Field)

LINKING MODELING - REMOTE SENSING (cont)

- First tests scheduled for Wessman and Matson LCLUC projects
  (Asner New Investigator Project)
  - Evaluate highly constrained CSCM against CENTURY (non-remote sensing constrained)

- Collaborators/Contributors:
  - PA Matson, CB Field, JC Neff, W Riley,
  - R Jackson
  - W Parton

Heading Toward Project Completion

- Push research agendas at contrasting sites
  - Vegetation Structure
  - Climate

Jornada LTER Site

- Part of the Jornada del Muerto Basin in southern New Mexico at the northern end of the Chihuahuan desert

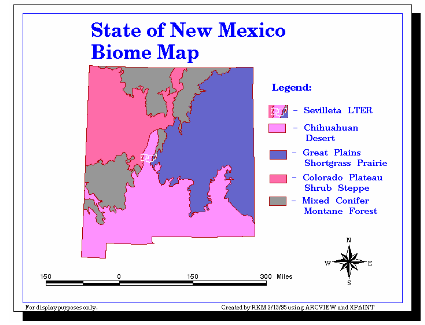
- Natural and human-induced desertification have changed ecosystem processes

- MAP 230 mm delivered in local, intense summer storms

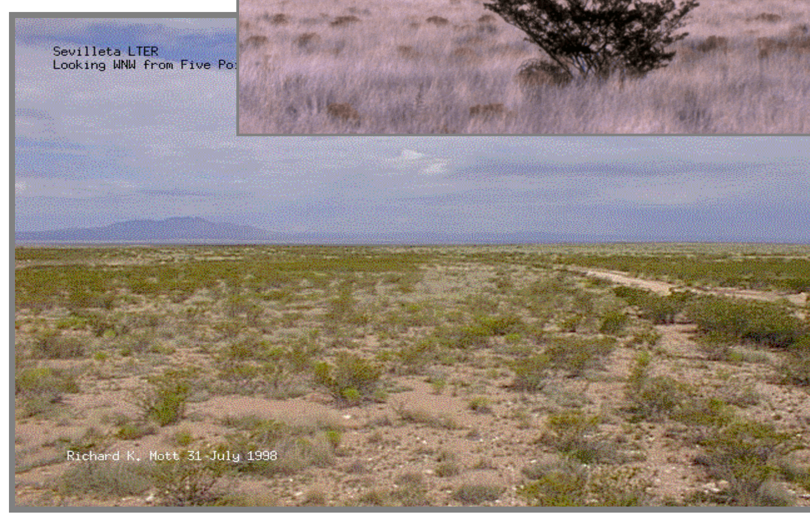
- Max monthly temp 13 - 36 °C

Sevilleta LTER Site

- A biome transition zone: Great Plains Grassland, Chihuahuan Desert, Great Basin Shrub-Steppe, Interior Chaparral, P-J Woodland, and Montane Forest



- Operated as a cattle ranch until late 1972



- MAP= 280 mm
  Range = <100 - >500 mm

- Mean monthly temp 2.5 - 27 °C

Heading Toward Project Completion

- Poised to utilize MODIS and MISR Data at Terra Launch
- Utilize improved capabilities offered by Landsat 7 and the EO-1 satellites
  - Multi-angle/multi-spectral radiative transfer algorithms ready for surface reflectance products

Heading Toward Project Completion (cont.)

- Landsat 7, EO-1 *ALI*, and EO-1 *Hyperion* will be used to separate herbaceous - woody vegetation types on seasonal basis

  - Expect better accuracy (from 40-60 to ca. 20% error) in shade & woody cover; ∴ improved estimates of woody biomass (from 10-20% to < 5% error after geometric-optical model correction).

- Vegetation types will then be represented in radiative transfer model to unmix LAI, litter, and fPAR estimates acquired daily-weekly from MODIS+MISR

Student Participation

- Texas A&M University
  - Mark Simmons - Tree/Grass & Tree/Tree Interactions
  - Andy Hubbard - Soil Respiration & Root Turnover

- University of Colorado
  - Nancy Golubiewski - Land Use in SW Rangelands
  - Seth Zunker - Nitrogen Fixation
  - Kevin Cody - Aerial Photography/GIS

Research Associates

R. Flint Hughes: CIRES Visiting Fellow/
Biosphere-Atmosphere Research Training
(BART) Postdoctoral Research Associate
(University of Colorado)
Chad McMurtry (Texas A&M)

New Collaborators

X. Ben Wu: Landscape ecologist (Texas A&M)

Related Projects

- USDA Ecosystems: soil respiration, biomass, root turnover
- NIGEC: non-methane hydrocarbon emissions
- NCEAS Tree-Grass Model Comparison Project

  - SAVANNA - CENTURY - MUSE - GRASP

- NASA-EOS Interdisciplinary Science
- NASA-NIP: landscape to regional biogeochemical modeling (CSCM model)
  - Robin Martin (Ph.D. student) - N trace gases (Sept '99)
  - Sharon Hall (Post-Doc) - lysimetry, trace gases (Oct '99)
- NSF-Ecology: Overstory-Understory Interactions (Sept '99)