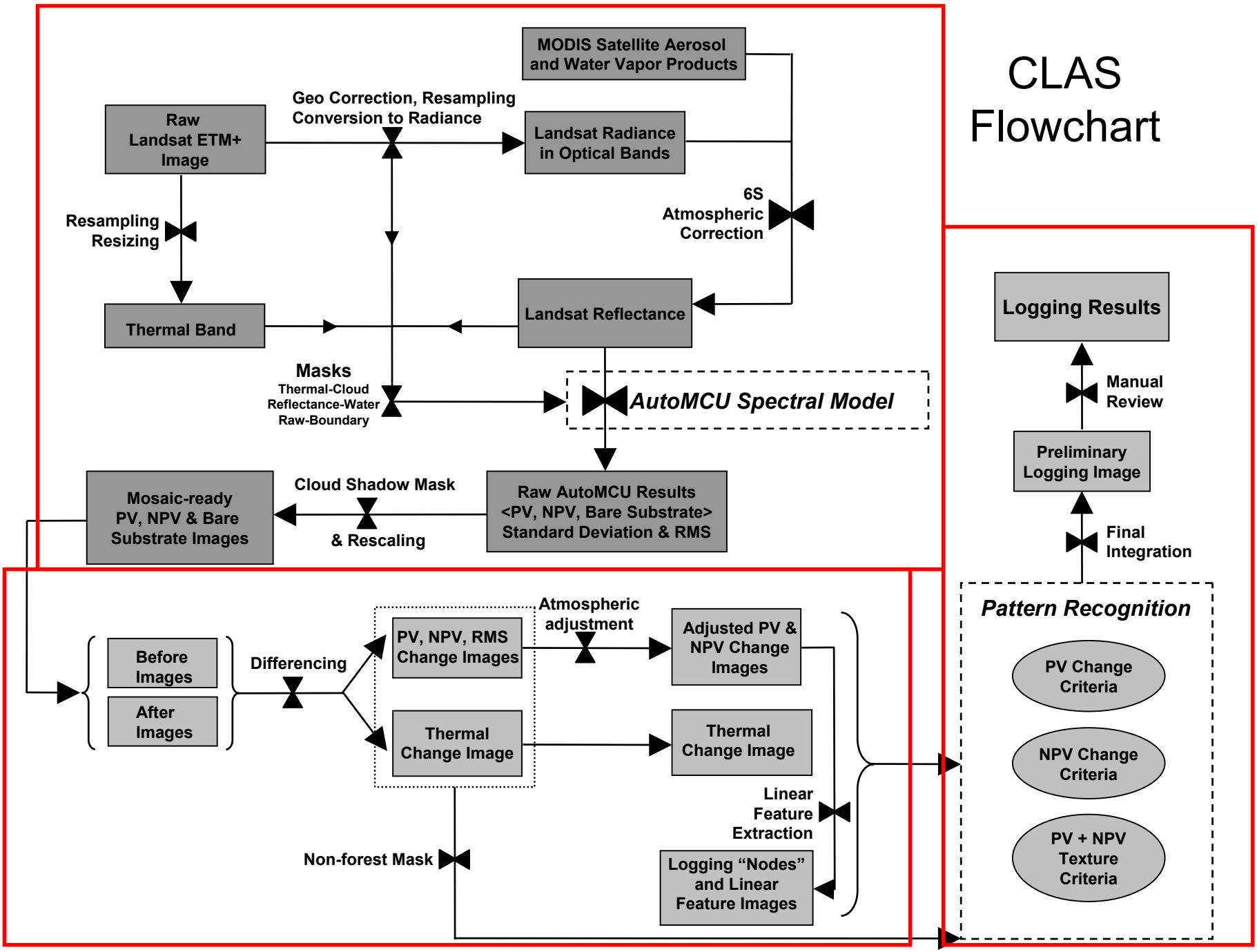
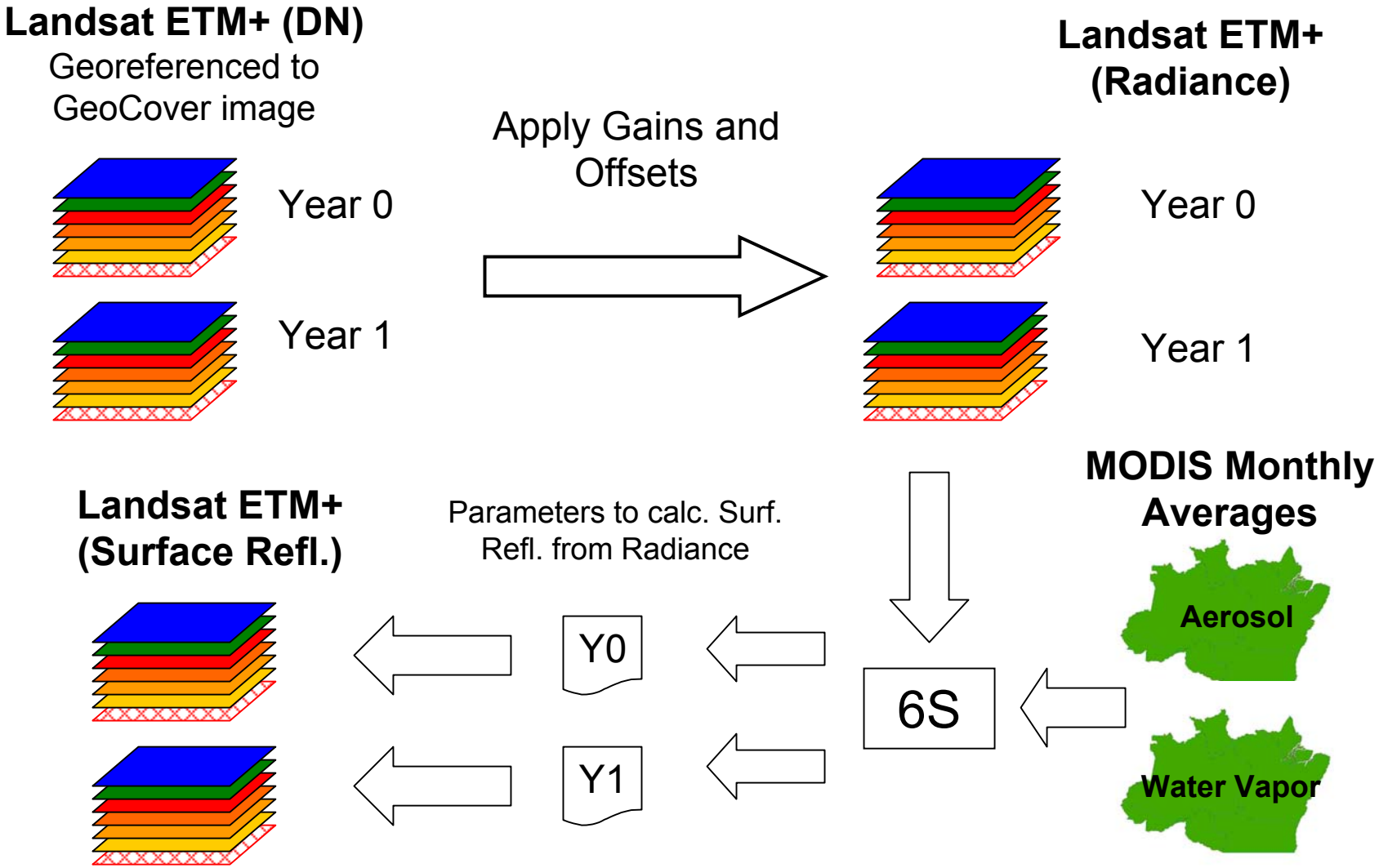
The Carnegie Landsat Analysis System (CLAS): An automated approach to large-scale canopy damage analysis

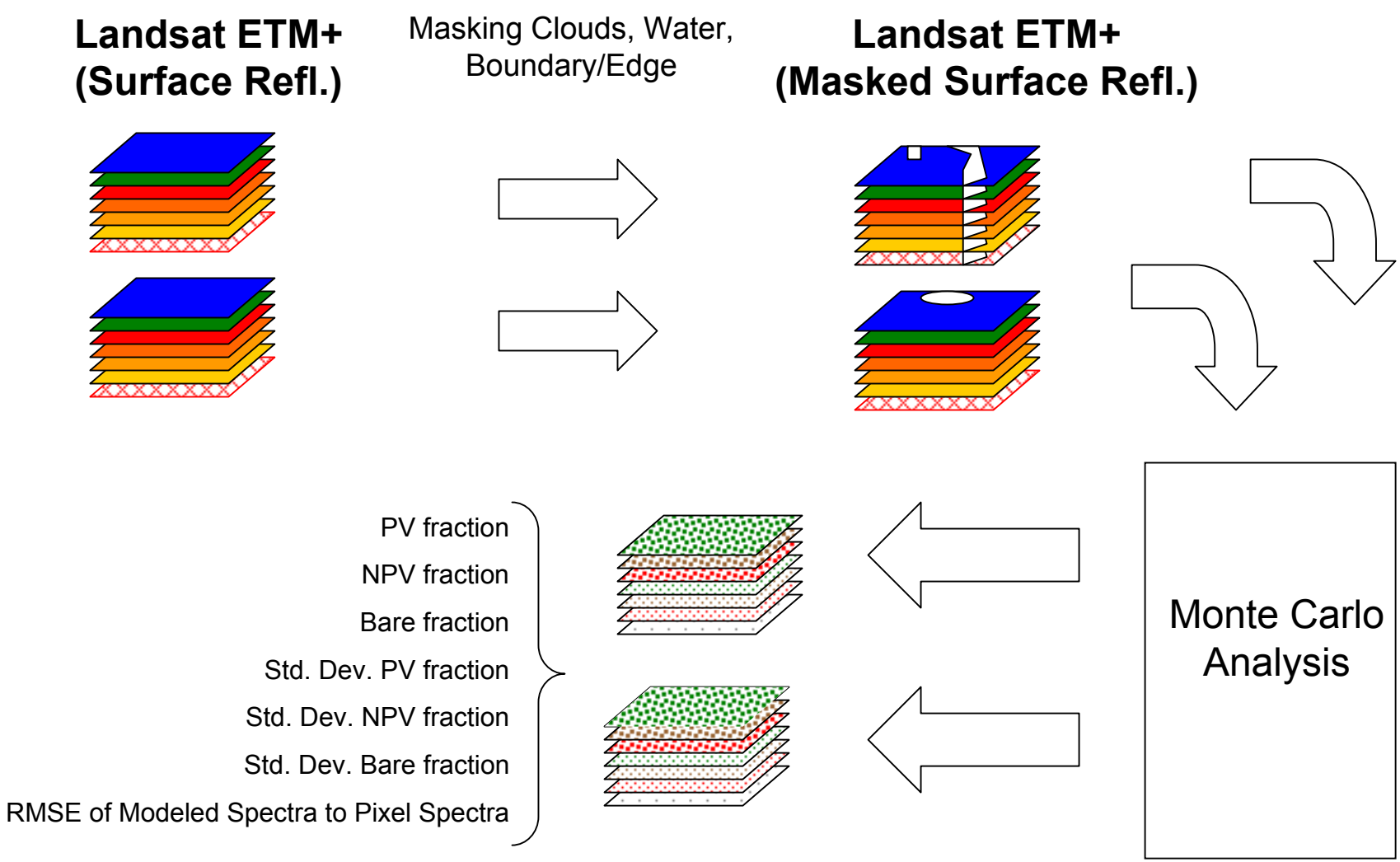
David Knapp, Greg Asner,
Eben Broadbent, Paulo J.C. Oliveira,
Michael Keller, J. Natalino Silva

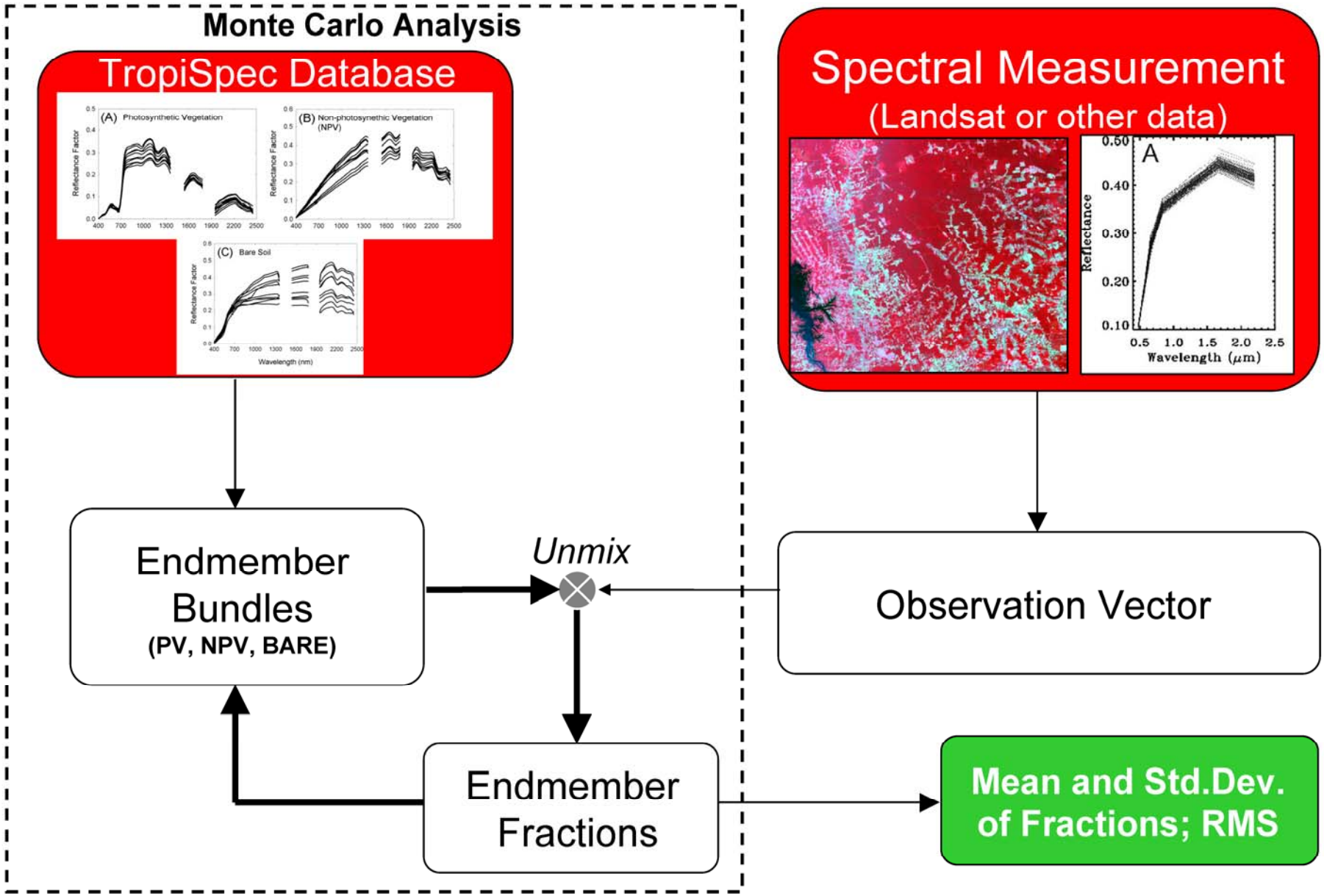

CLAS Flowchart
MODIS Satellite Aerosol and Water Vapor Products
Raw Landsat ETM+ Image
Geo Correction, Resampling Conversion to Radiance
Landsat Radiance in Optical Bands
Resampling Resizing
6S Atmospheric Correction
Thermal Band
Landsat Reflectance
Masks
Thermal-Cloud
Reflectance-Water
Raw-Boundary
AutoMCU Spectral Model
Mosaic-ready PV, NPV & Bare Substrate Images
Cloud Shadow Mask
& Rescaling
Raw AutoMCU Results <PV, NPV, Bare Substrate> Standard Deviation & RMS
Logging Results
Manual Review
Preliminary Logging Image
Final Integration
Pattern Recognition
PV Change Criteria
NPV Change Criteria
PV + NPV Texture Criteria
Before Images
After Images
Differencing
PV, NPV, RMS Change Images
Atmospheric adjustment
Adjusted PV & NPV Change Images
Thermal Change Image
Thermal Change Image
Linear Feature Extraction
Non-forest Mask
Logging "Nodes" and Linear Feature Images

AutoMCU Module

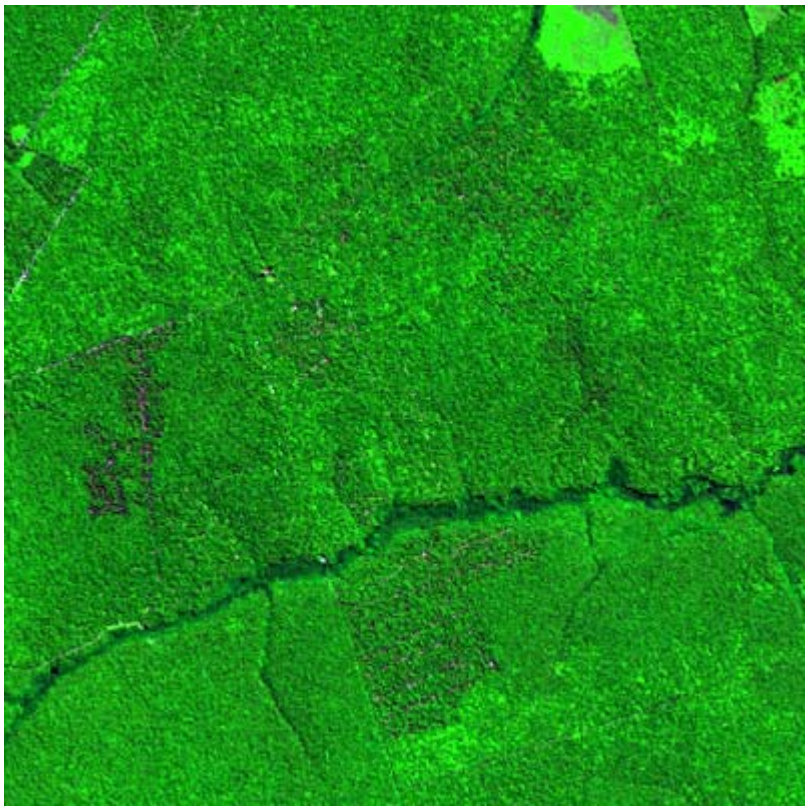


AutoMCU Module

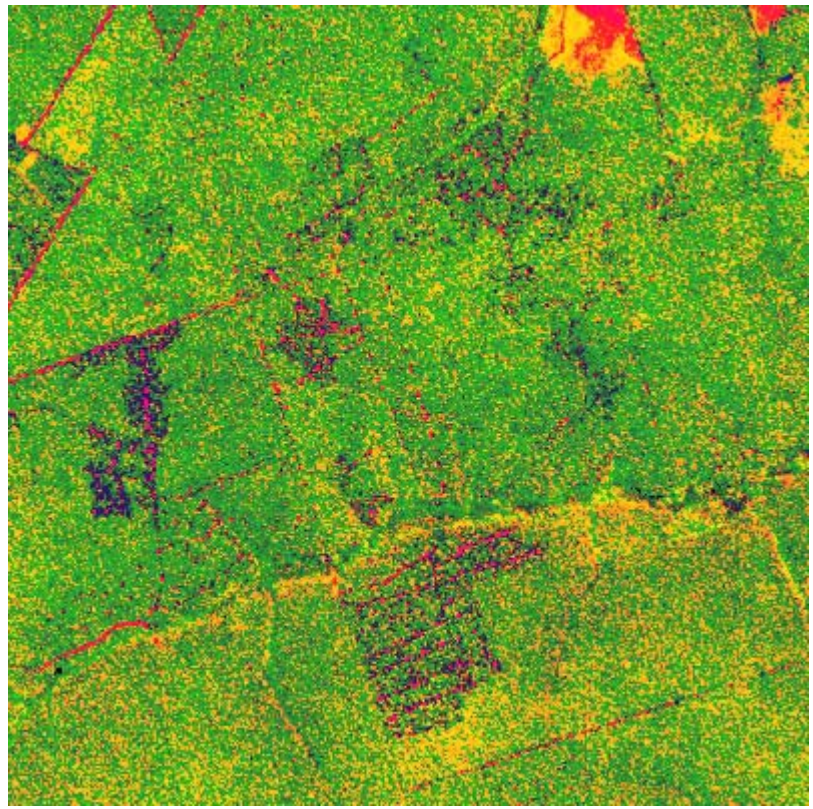



Monte Carlo Analysis
TropiSpec Database
(A) Photosynthetic Vegetation
(B) Non-photosynthetic Vegetation (NPV)
(C) Bare Soil
Reflectance Factor
Wavelength (nm)
Spectral Measurement
(Landsat or other data)
A
Reflectance
Wavelength (μm)
Endmember Bundles
(PV, NPV, BARE)
Unmix
Observation Vector
Endmember Fractions
Mean and Std.Dev. of Fractions; RMS

AutoMCU Results



Reflectance (Bands 5, 4, 3; RGB)

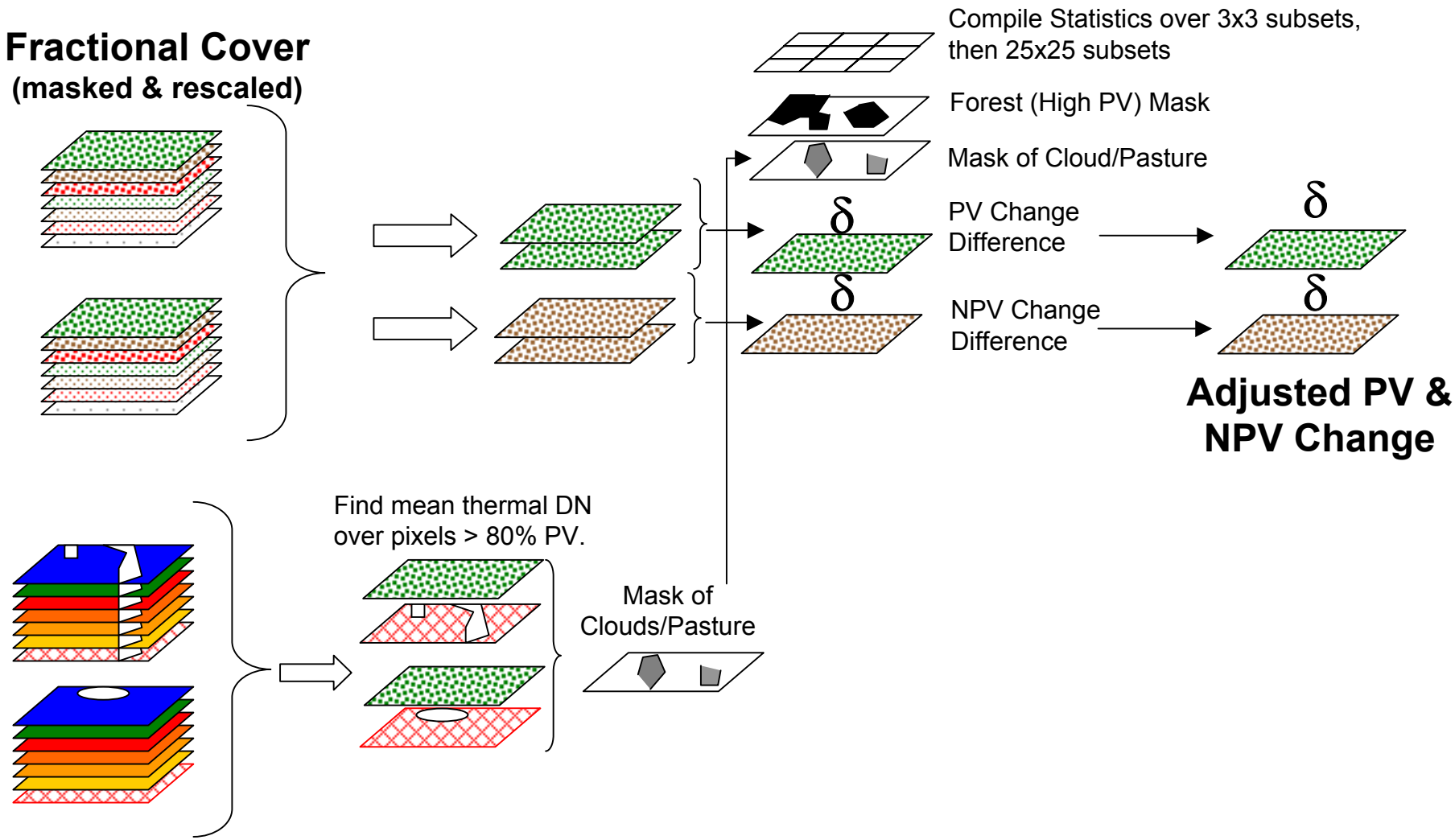


Fractional Cover (PV, NPV, Bare)

PV NPV Bare

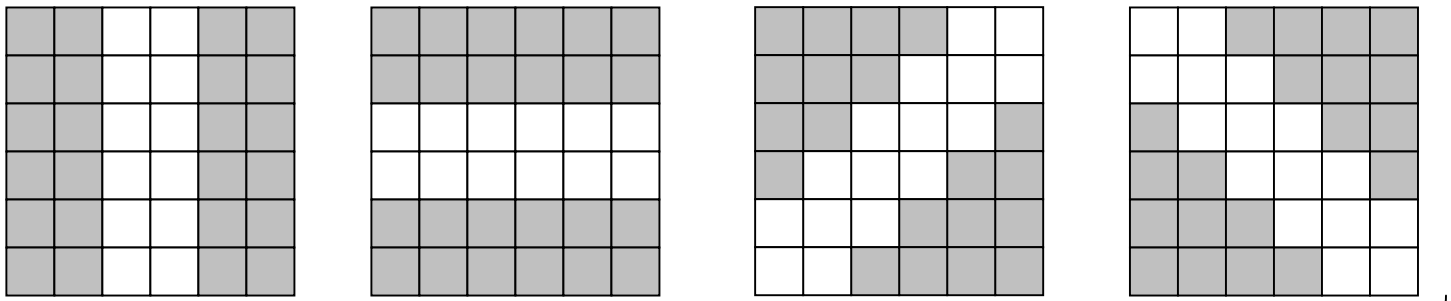
Logging Detection

PV & NPV Change

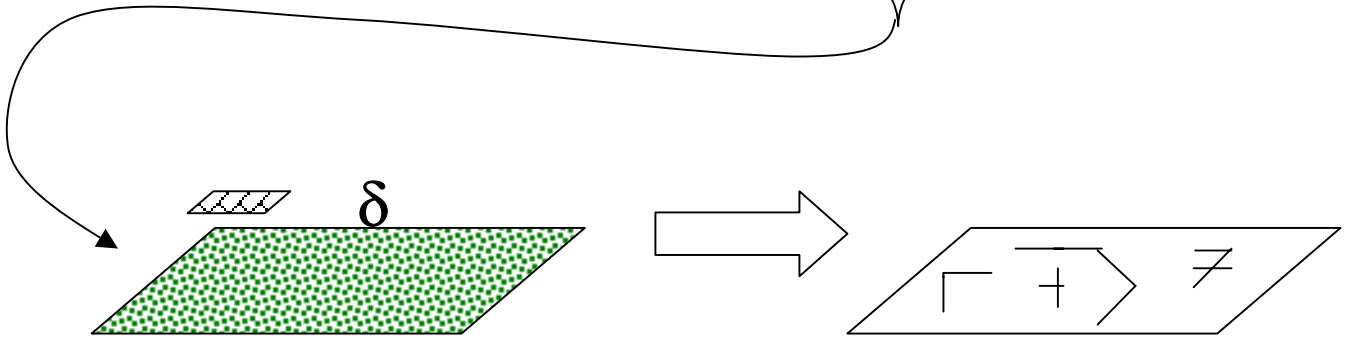


Logging Detection

Linear Feature Detection



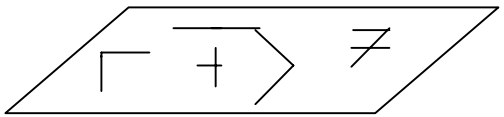
Direction Masks



Logging Detection

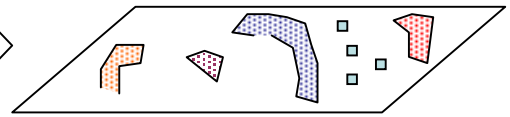
Node (Deck) Detection

Linear Features

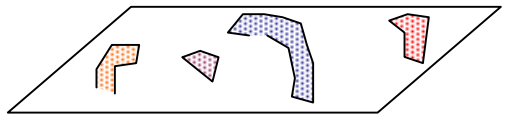


Tests for Density of Linear Features and Multi-Directionality within 15x15 kernel.

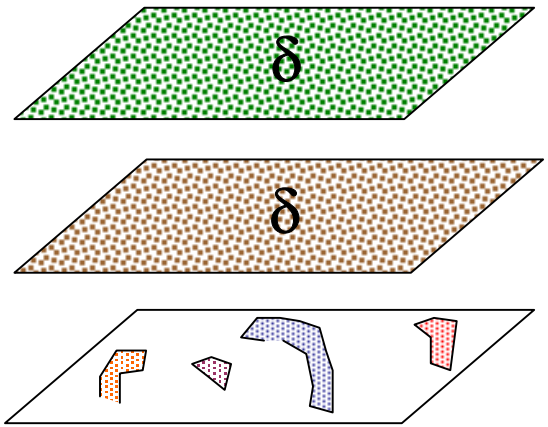
Augmented Node Image



Despeckling

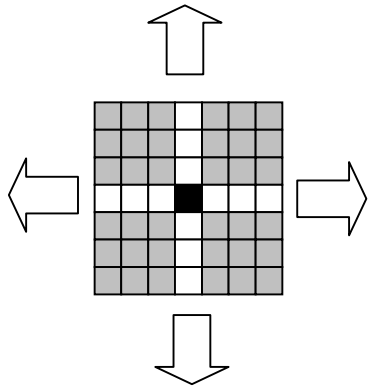


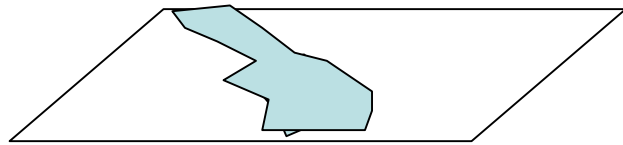
Logging Detection

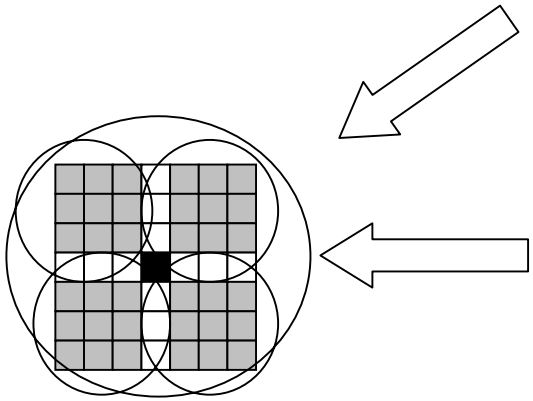


Logging Criteria

- >75% valid data pixels within 7x7 kernel.
- Non-forested area < 12%.
- 60%< Mean After PV > 93%
- Mean PV Change > 9%
- Mean NPV Change < 2%
- Mean PV Change Std. Dev. > 33%
- Mean NPV Change Std. Dev. > 46%
- > 6 pixels with PV Change > 80%
- > 6 pixels with PV Change < 85%
- Masked area < 2 pixels







Subset Criteria

- ≥ 2 subsets with PV Change (PVC) ≥ 32% Stdev.
- ≥ 2 subsets with Mean PVC ≥ 60% Stdev.
- ≥ 2 subsets with ≥ 1 pixel w/PVC ≥ 80%.
- ≥ 2 subsets with NPVC ≥ 46% Stdev.
- ≥ 2 subsets with Mean NPVC ≤-5% ≥ -65% Stdev.
- ≥ 2 subsets with ≥1 pixel w/ Mean NPV Change ≤ -85%.

Logging Detection

Manual Auditing Criteria

High Damage Criteria

- Abundance of logging decks
- Obvious linear features (roads & skid trails)
- Severe canopy damage
- Areal extent > 1 hectare
- Evidence of logging from previous year in close proximity
- Presence of access roads or rivers

Logging Detection

Manual Auditing Criteria

Low Damage Criteria

- Few to no visible logging decks
- Obvious linear features
- Presence of access roads and rivers
- Linear features are tree-like in formation (graduating from higher to lower damage linear features)
- Evidence of logging from previous years in close proximity
- Speckles of recent canopy damage in PV Change image occurring at density greater than surrounding forest
- Areal extent > 6.5 hectares

Logging Detection

Manual Audit

Add neighboring areas with related canopy damage.

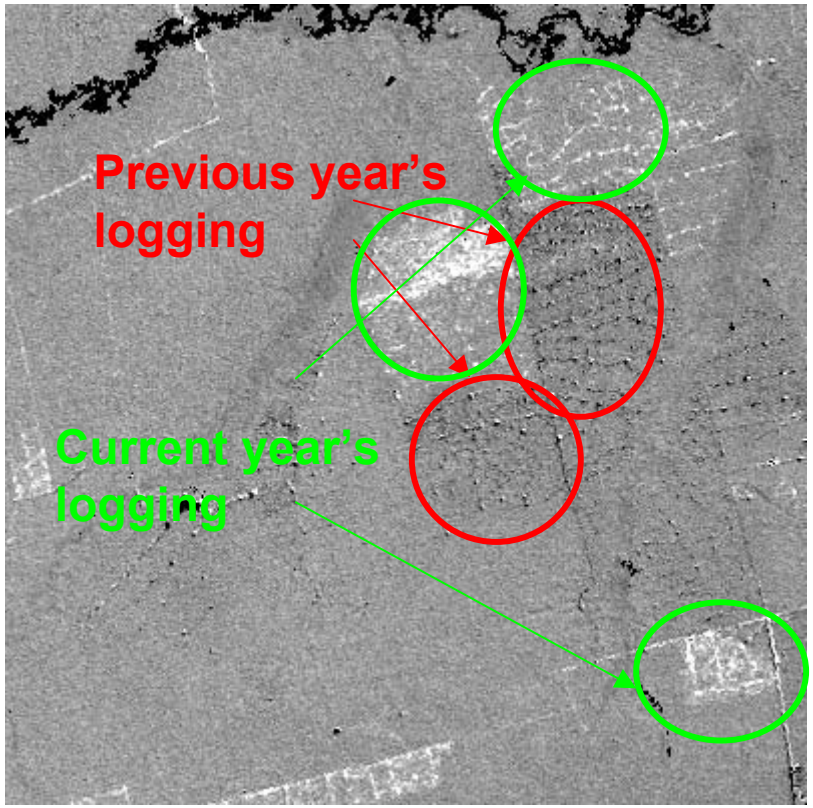
Logging Detection

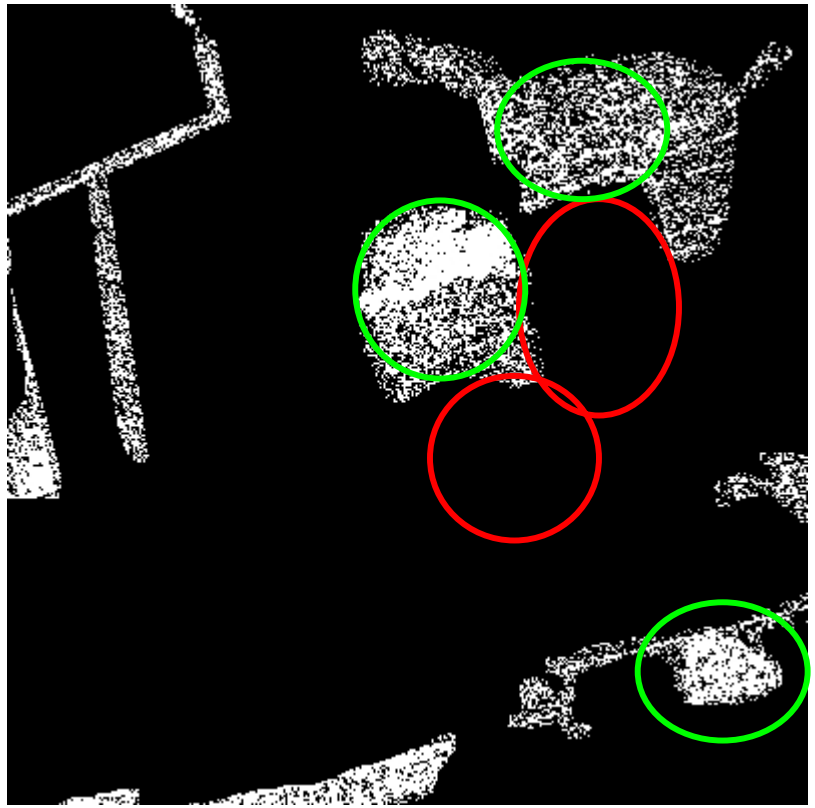
Manual Audit

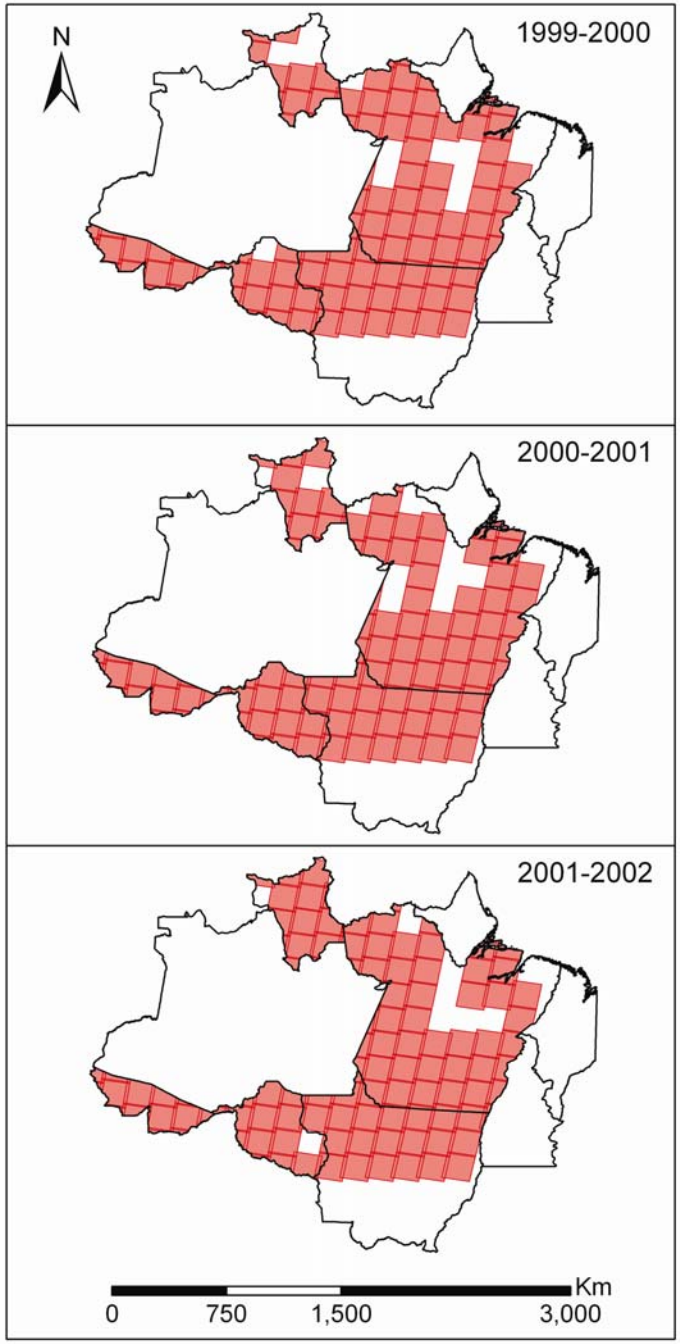
Remove areas that do not appear to be logging.

Logging Detection

PV Change Criterion







1999–2000

2000–2001

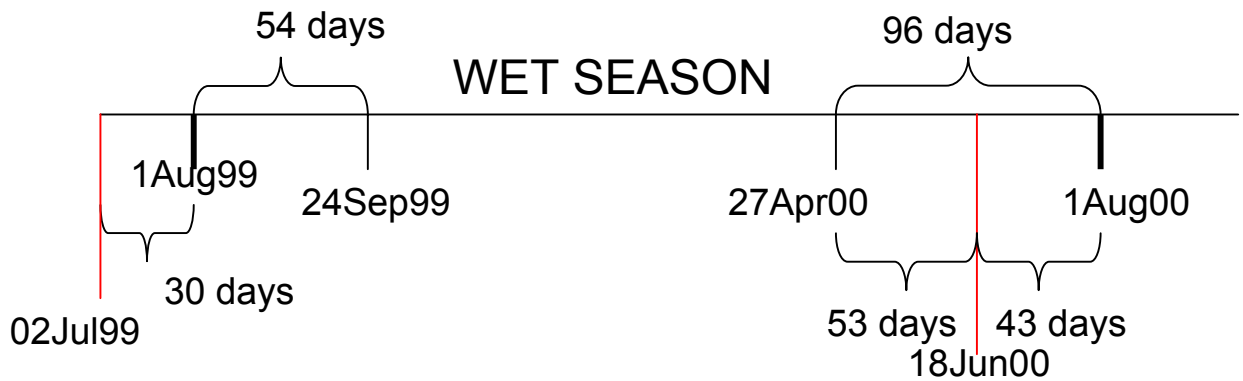
2001–2002

Logging Detection

Annualization

- Images are not usually collected exactly 1 year apart.
- Length of dry season influences deforestation and logging rates.

Dry Season End: 24-Sep-99
Dry Season Start: 27-Apr-00
Harvest Season Length: 150 days
Image Dates: 02-Jul-99 & 18-Jun-00

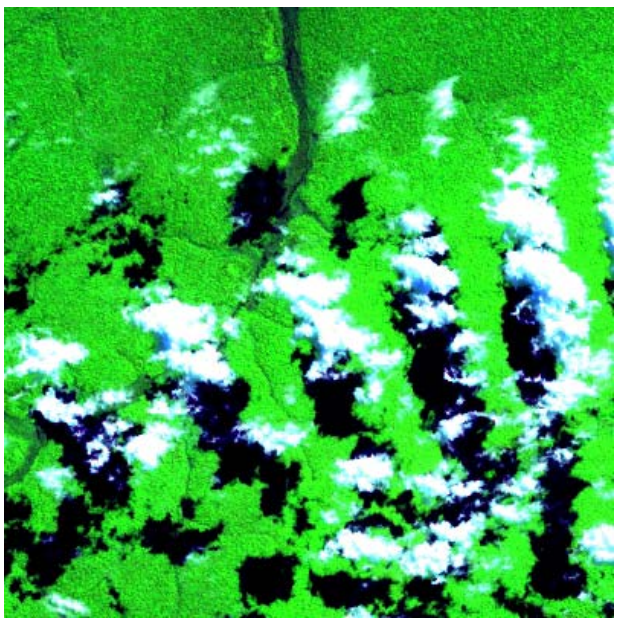


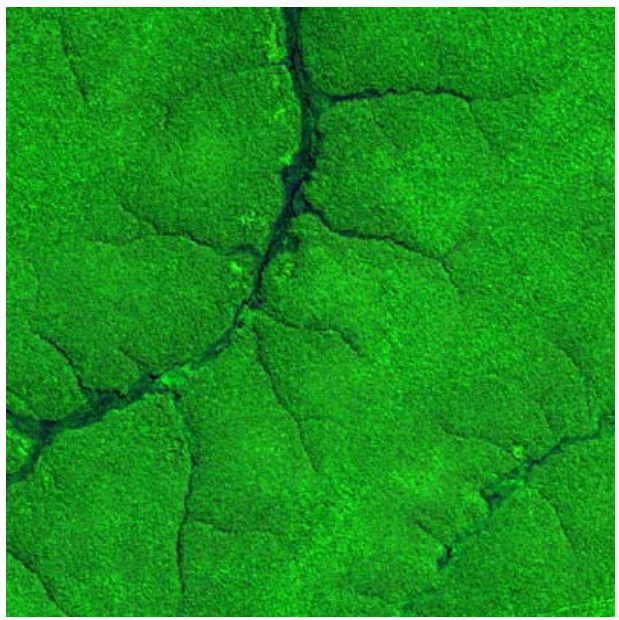
Scaling Factor = (54 / (54+30)) * (54/150) + (96 / (96-43)) * (96/150) = 1.39

Logging Detection

Unobserved Areas

- Clouds and cloud shadows that obscured potential logging activity within an image were small enough to treat as a level of uncertainty.
- Missing scenes or areas with > 50% cloud cover used logging data from the next year as an estimate for the current year.
- Areas that showed the most logging also had the fewest clouds. Thus, the amount of uncertainty due to clouds was low (< 5%).



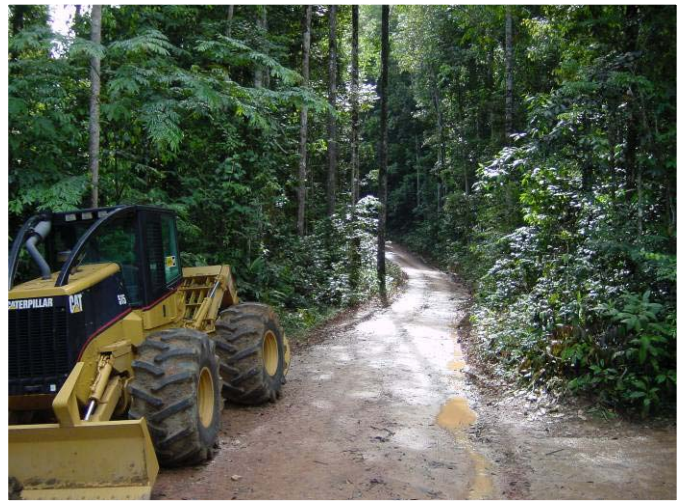


Greg Next

Why does selective logging matter in Amazônia?

- Biosphere-atmosphere exchange of carbon
- Regional climate and the hydrological system
- Biogeochemical processes
- Forest management
- Forest structure, habitat and biological diversity
- Land-use legacies and precursors to other disturbances

Why is it difficult to monitor selective logging in tropical forests?



- ***Difficult to observe***
  - Clouds
  - Capability of available sensors
- ***Challenging methods issues***
  - Low sensitivity to many types of canopy damage
  - Biophysically “under-determined”
  - Difficult to automate (big region, multi-temporal)
- ***Biophysics of selective logging***
  - Canopy structural damage
  - Dynamics of canopy regrowth
  - Ground-to-satellite signatures

Summary of Sensor Capabilities for Logging Studies

Sensor	Spatial Resolution	Number of Optical Channels Used	Geographic Cover (freq., footprint, etc)	% of Damage Classes Missed	Precision of Logging Analysis
EO-1 Hyperion	30 m	180	Low	Lowest 5% (new)	80-95%
	Low geographic coverage				
Landsat 7 ETM+	30 m	6	Medium	Lower 50% (trad.) Lower 20% (new)	70-80%
	Low spectral resolution				
EO-1 Advanced Land Imager	30 m	9	Low	Lower 50% (trad.) Lower 20% (new)	70-80%
	Low coverage, low spectral resolution				
Landsat 5 TM	30 m	6	Medium	Lower 60% (trad.) Lower 40% (new)	60-70%
	Low spectral resolution, lower signal performance				
SPOT MSS	20 m	3	Low	Lower 50%	60-70%
	Low spectral resolution, low coverage				
MISR	1000 m	4 (multi-angle)	Medium-high	Lower 80%	20-25%
	Low spatial resolution, low spectral resolution				
MODIS	1000 m	7	High	Lower 80%	20-25%
	Low spatial resolution, low spectral resolution				

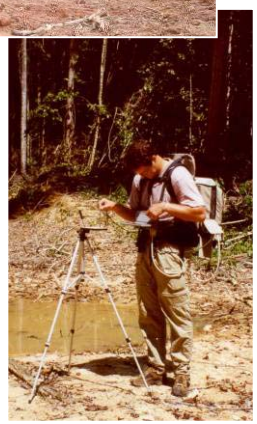
Tough choices; no clear winners; many compromises

(Presented at 2004 LBA meeting, Brasilia)

Field Studies to Improve Our Understanding of the Biophysics of Selective Logging

1999 – 2004

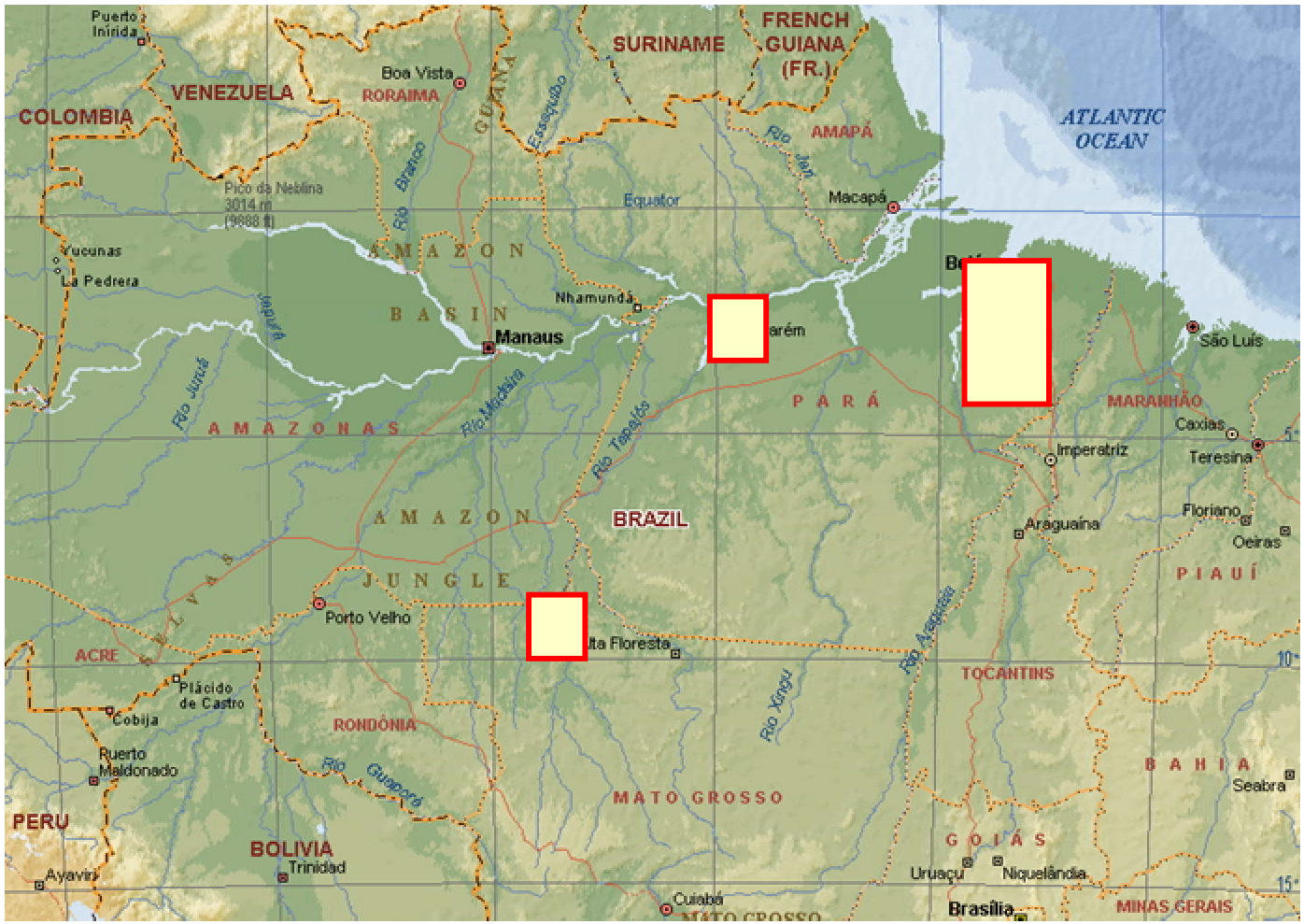
- Canopy structure
- Ground damage (roads, log decks, skids, tree falls)
- Canopy damage – gap fraction
- Environmental spectroscopy



June 2000 field crew

Canopy Disturbance and Logging Damage Projects

Tropical Forest Foundation
US Forest Service
Carnegie Institution
EMBRAPA



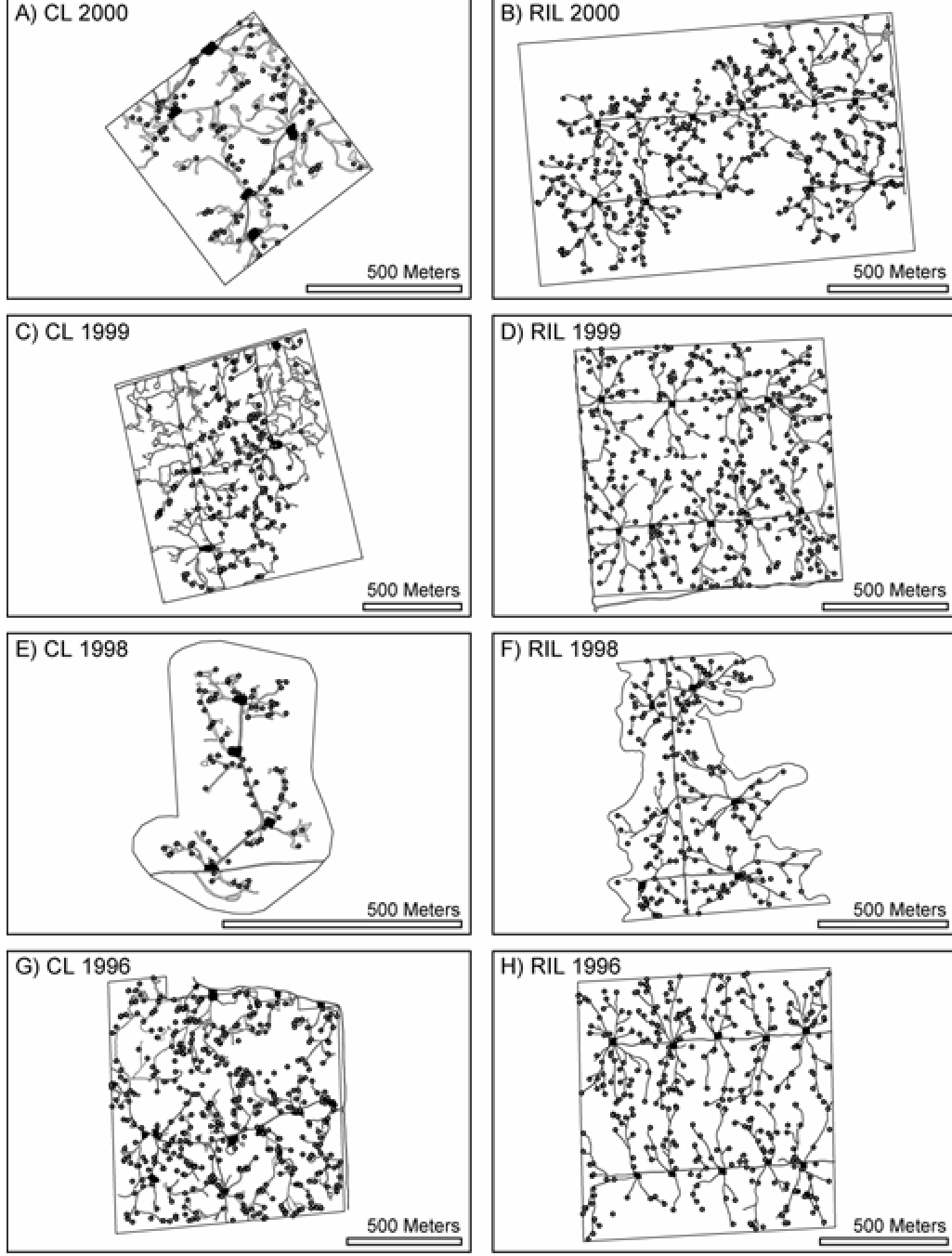
Landscape Components of Selective Logging

Canopy Disturbance and Logging Damage Projects

Detailed field surveys of ground damage caused by timber harvest.

Conventional logging (CL)
Reduced-impact logging (RIL)

Roads
Log decks (patios)
Skids
Harvested trees



Asner et al. 2004
Global Change Biology

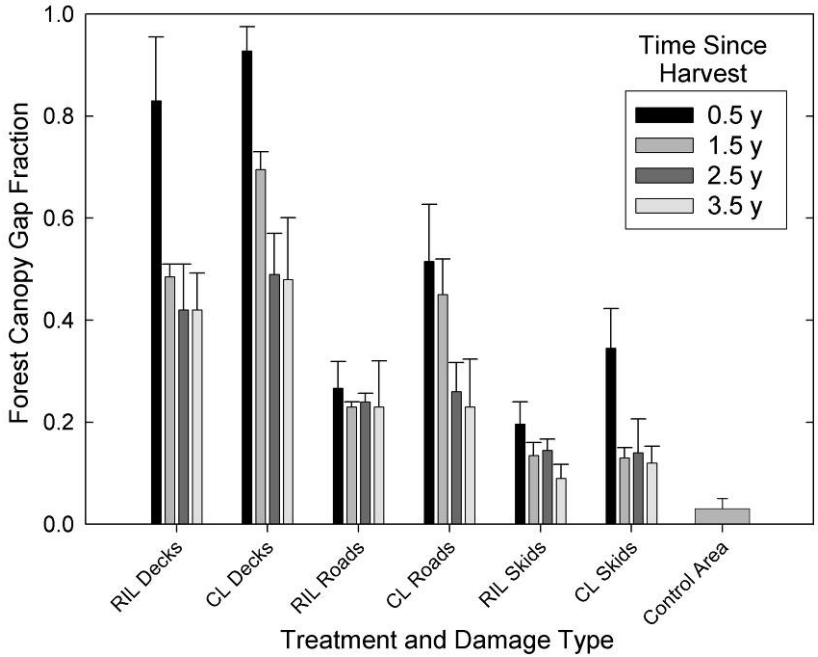
Canopy Disturbance and Logging Damage Projects

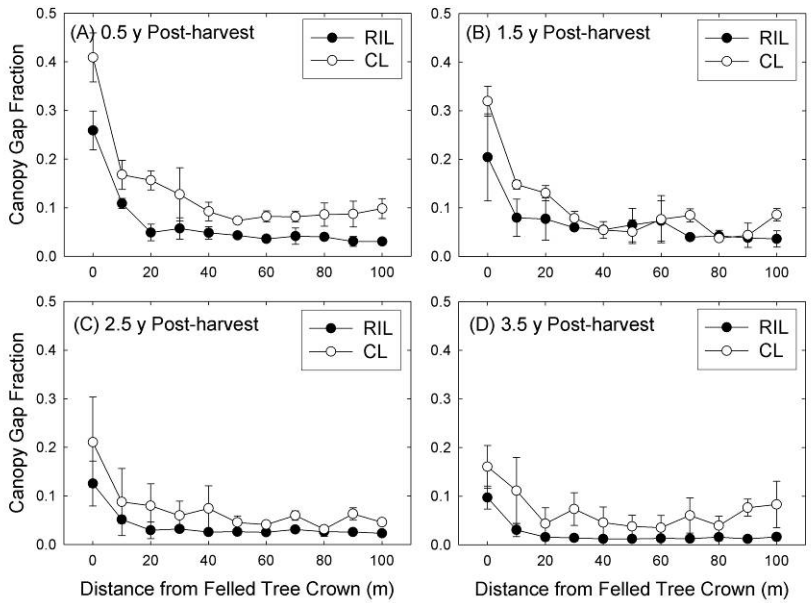
Geo-located field surveys of forest canopy gap fraction and *in situ* spectroscopy.

Conventional logging (CL)
Reduced-impact logging (RIL)

Roads
Log decks (patios)
Skids
Harvested trees

37 logging areas in total
42,300 meters of data collections





Asner et al. 2004
Global Change Biology

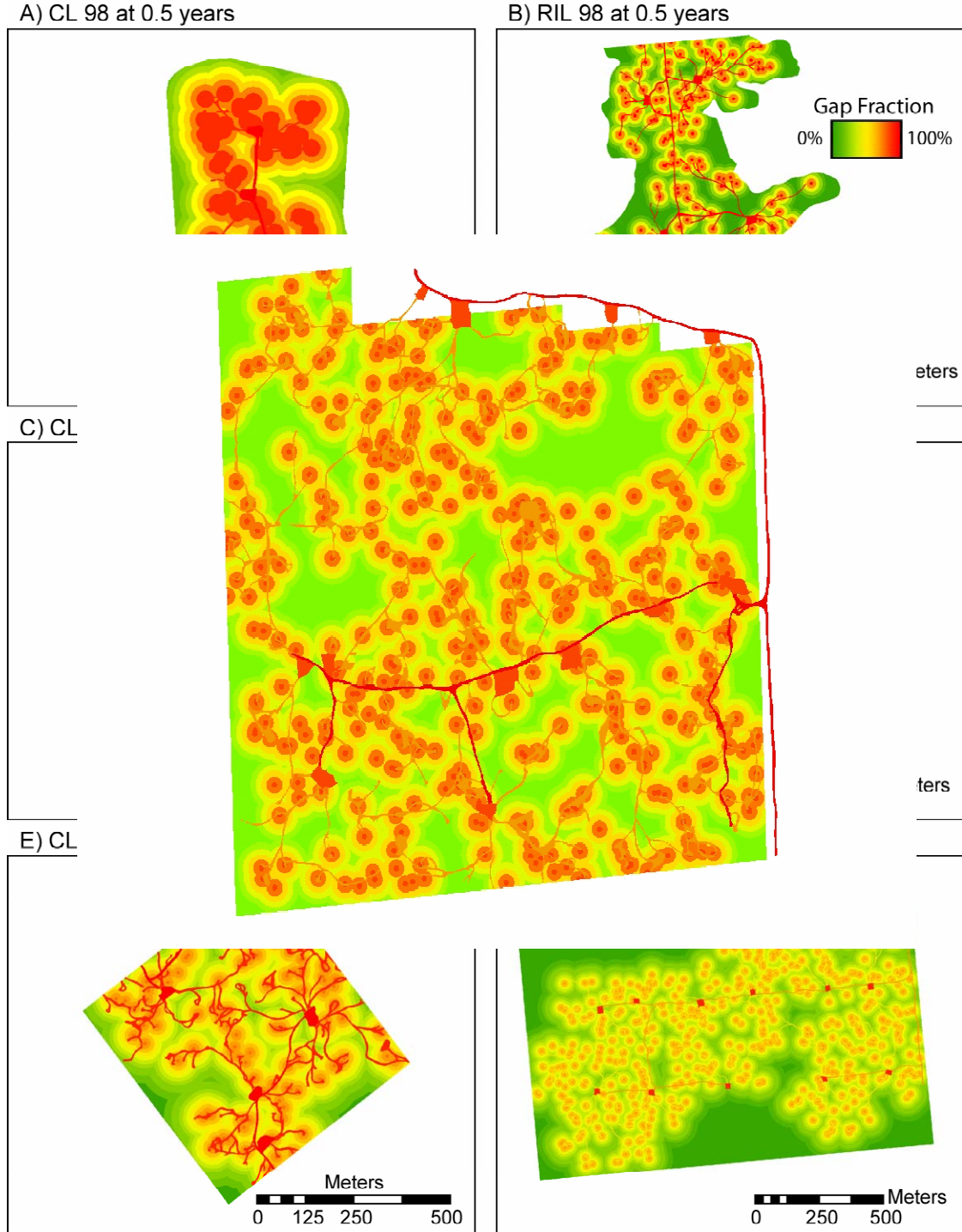
Canopy Disturbance and Logging Damage Projects

To gain a clear idea of what is going on in terms of canopy gap opening and closure following timber harvest

Detailed field surveys of ground damage caused by timber harvest.

Conventional logging (CL)
Reduced-impact logging (RIL)

Roads
Log decks (patios)
Skids
Harvested trees



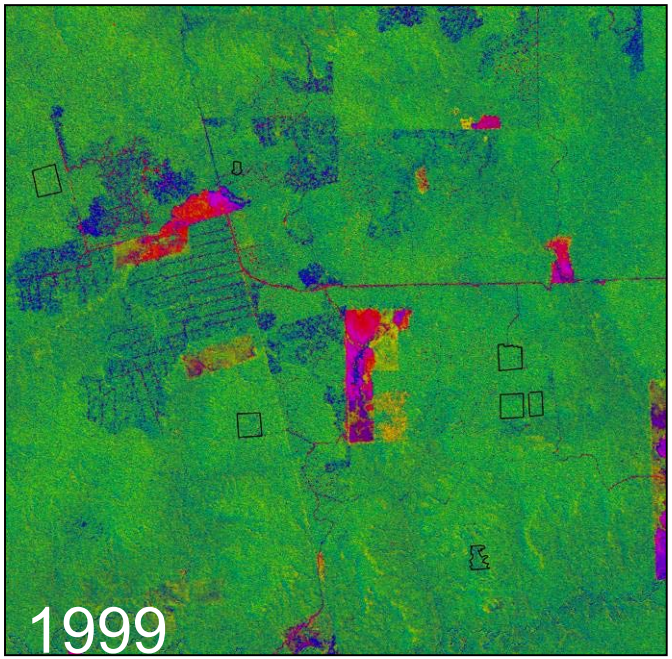
Asner et al. 2004
Global Change Biology

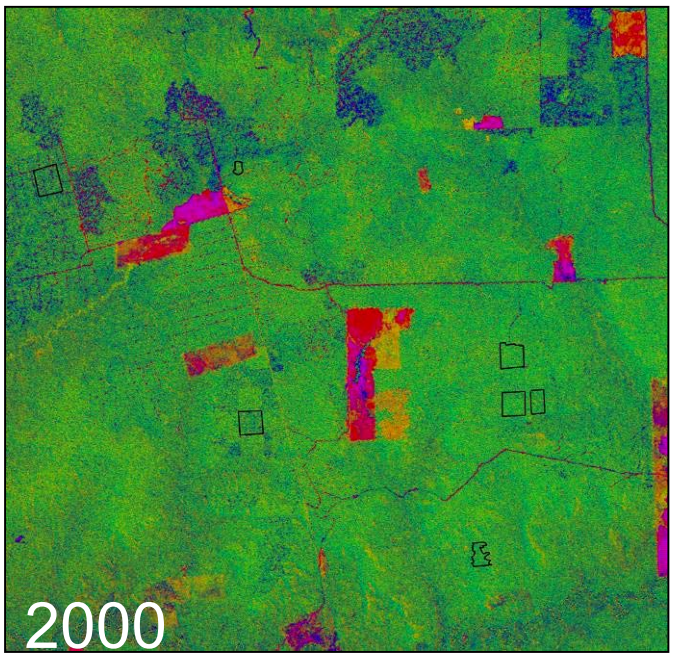
Correlation Matrix (r) of Logging Variables

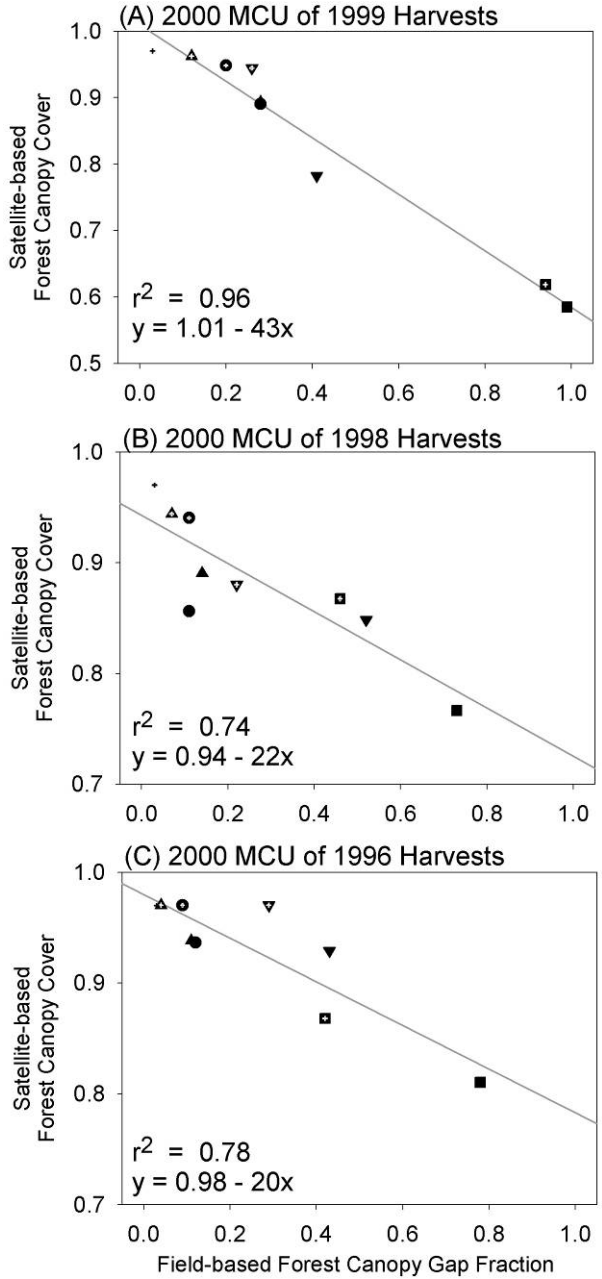
	Harvest Area (ha)	*Trees* Felled	*Trees/ ha*	*Roads*	*Patios*	*Skids*	*Total* Damage
Harvest Area (ha)	---						
Trees Felled	**0.96**	---					
Trees/ha	0.45	0.25	---				
Roads	0.53	0.31	0.53	---			
Patios	**0.42**	**0.33**	**0.46**	**0.31**	---		
Skids	**0.91**	**0.94**	**0.95**	0.49	0.52	---	
Total Damage	0.55	0.50	0.15	0.63	0.66	**0.98**	---
Damage/Tree	0.31	0.39	0.41	0.16	0.24	**0.92**	0.83

Asner et al. 2004
Global Change Biology

Photosynthetic Vegetation Fractional Cover (PV) and Canopy GAP

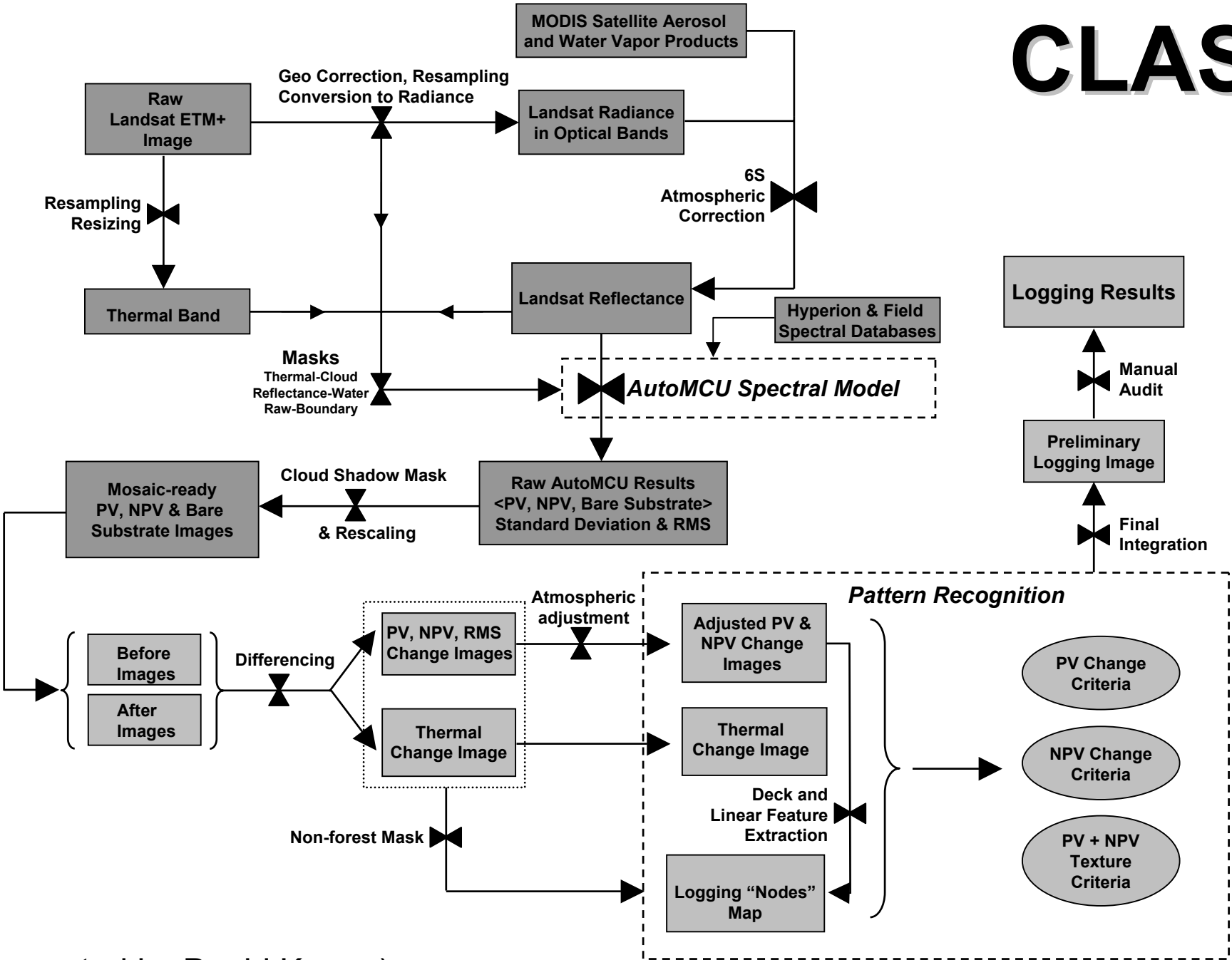






Asner et al. 2004
Ecological Applications

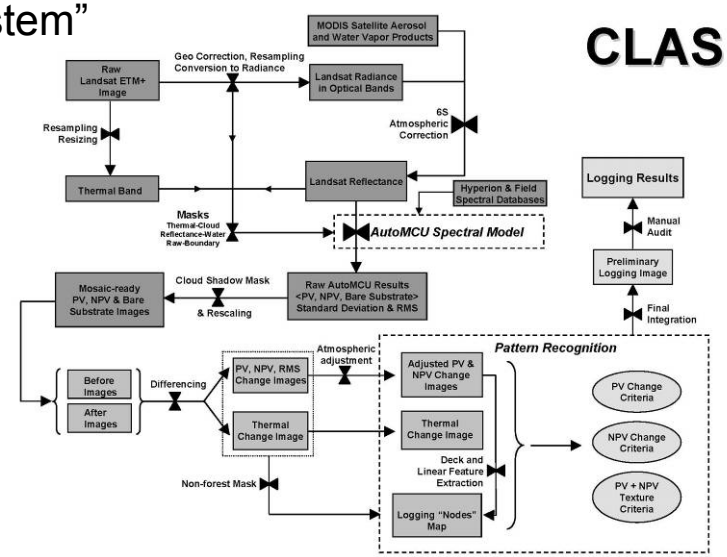
CLAS



(Presented by David Knapp)

Some Properties of CLAS

- Core module based on changes in sub-pixel forest canopy cover
  - not based on absolute values
- Pattern recognition based on local-kernel (landscape scale) changes in the sub-pixel results
  - not based on phenology or regional atmospheric variation
- Manual audit – essential in any “automated system”
- Directly linked to forest gap fraction
  - Allows for logging intensity analyses
  - Allows for carbon loss (gross flux) analyses



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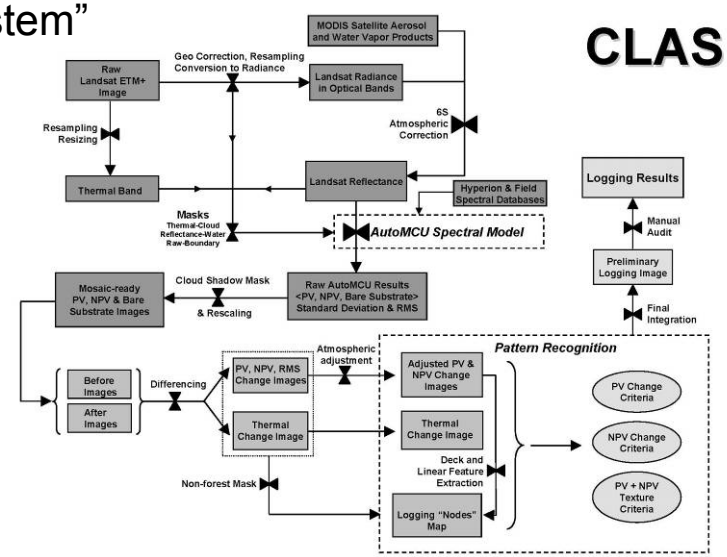

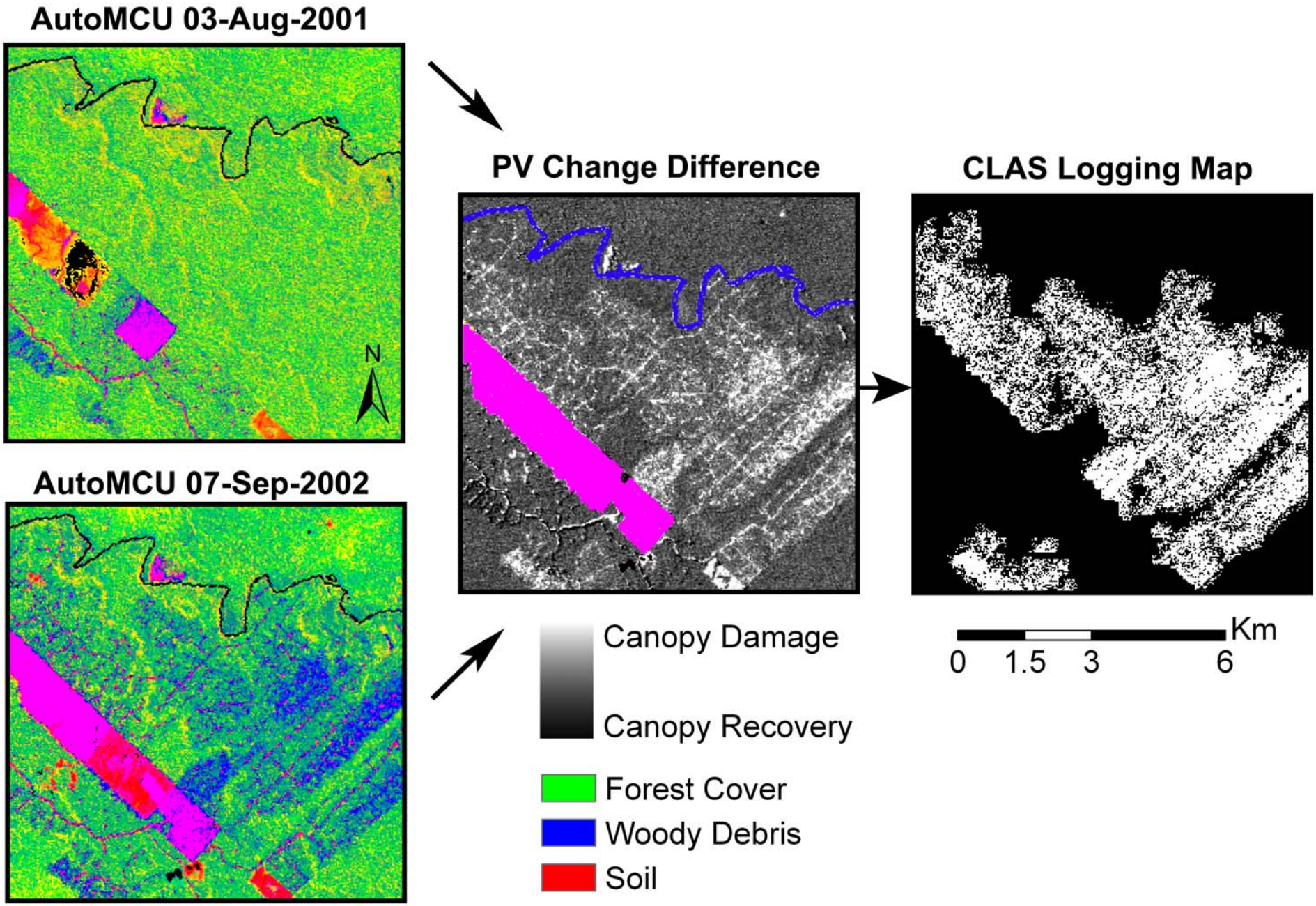

Asner et al. 2005
Science

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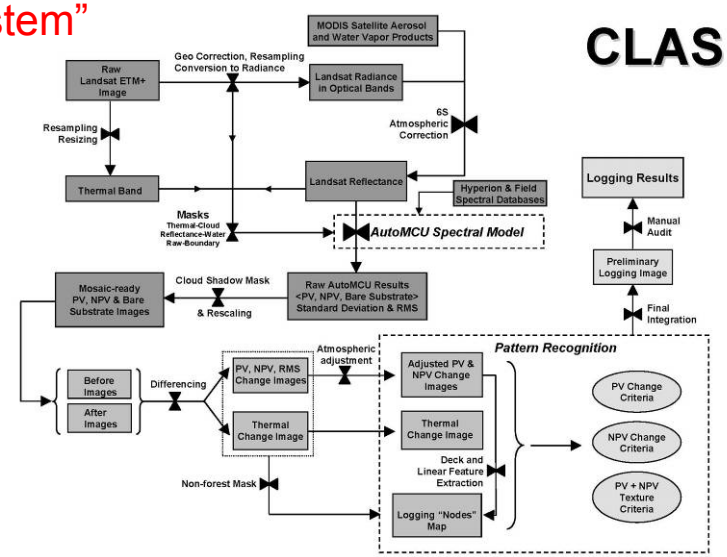

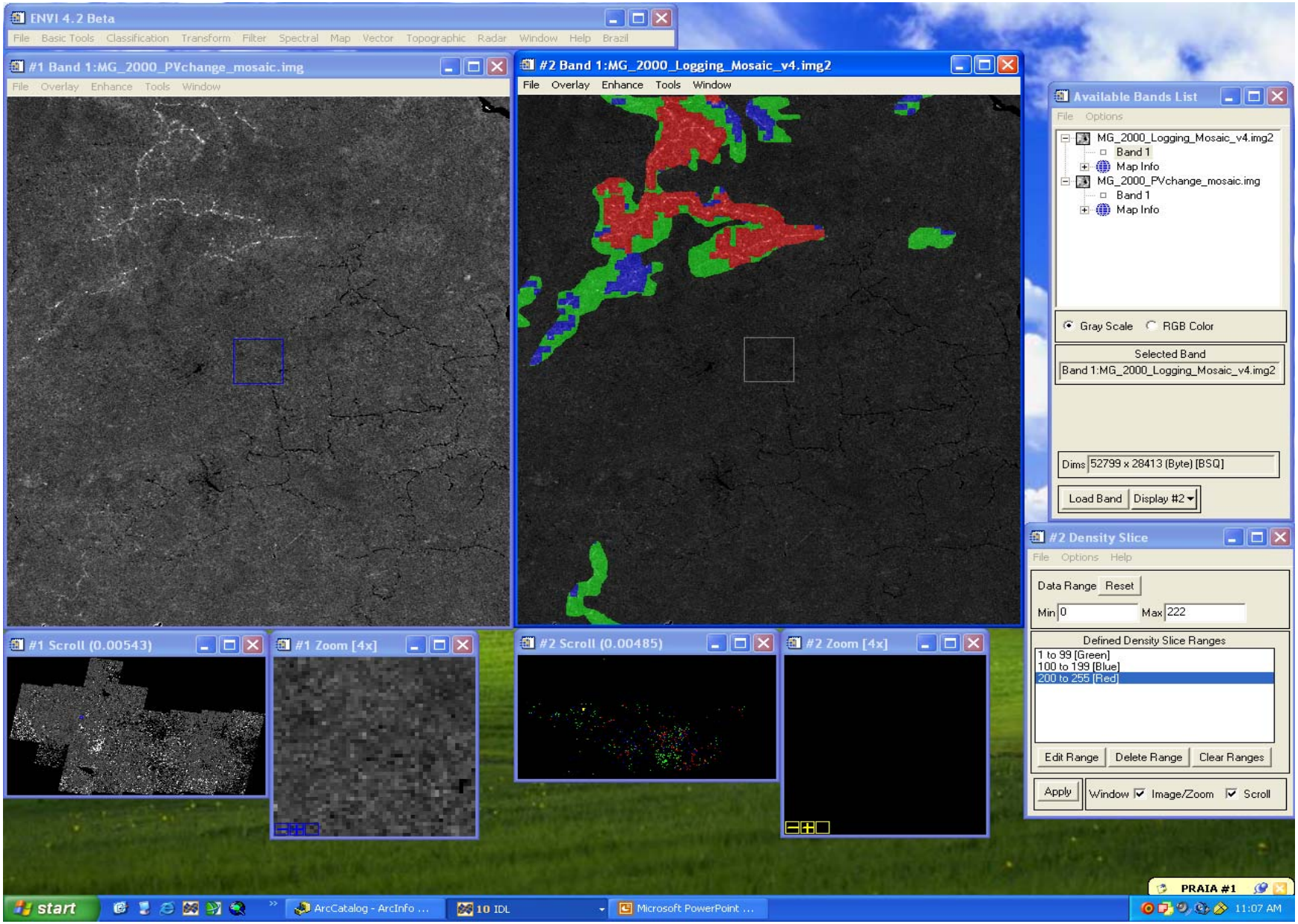
ENVI 4.2 Beta
File Basic Tools Classification Transform Filter Spectral Map Vector Topographic Radar Window Help Brazil
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File Overlay Enhance Tools Window
#2 Band 1:MG_2000_Logging_Mosaic_v4.img2
File Overlay Enhance Tools Window
Available Bands List
File Options
MG_2000_Logging_Mosaic_v4.img2
Band 1
Map Info
MG_2000_PVchange_mosaic.img
Band 1
Map Info
Gray Scale
RGB Color
Selected Band
Band 1:MG_2000_Logging_Mosaic_v4.img2
Dims 52799 x 28413 (Byte) [BSQ]
Load Band
Display #2
#2 Density Slice
File Options Help
Data Range
Reset
Min 0
Max 222
Defined Density Slice Ranges
1 to 99 [Green]
100 to 199 [Blue]
200 to 255 [Red]
Edit Range
Delete Range
Clear Ranges
Apply
Window
Image/Zoom
Scroll
#1 Scroll (0.00543)
#1 Zoom [4x]
#2 Scroll (0.00485)
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start
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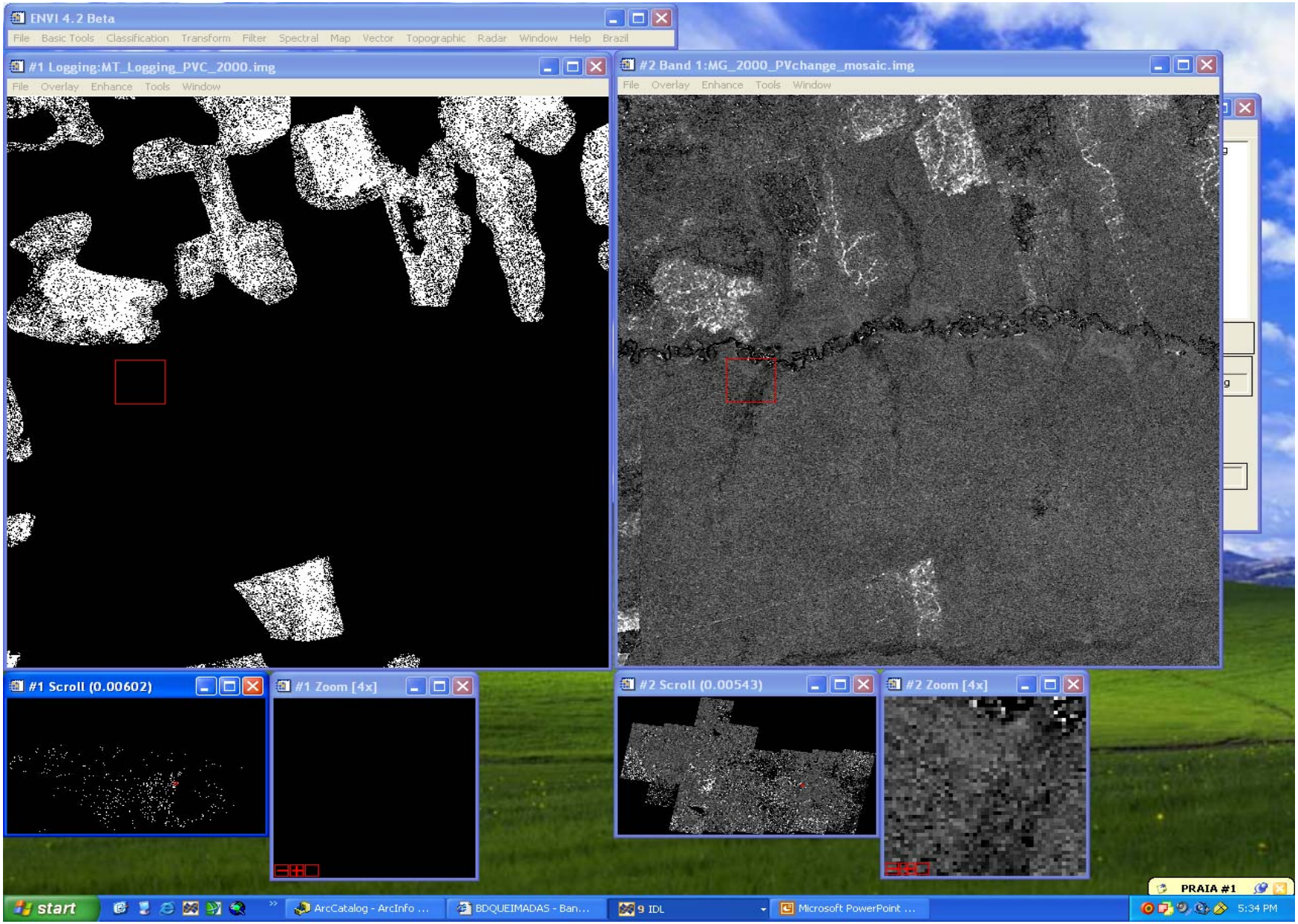
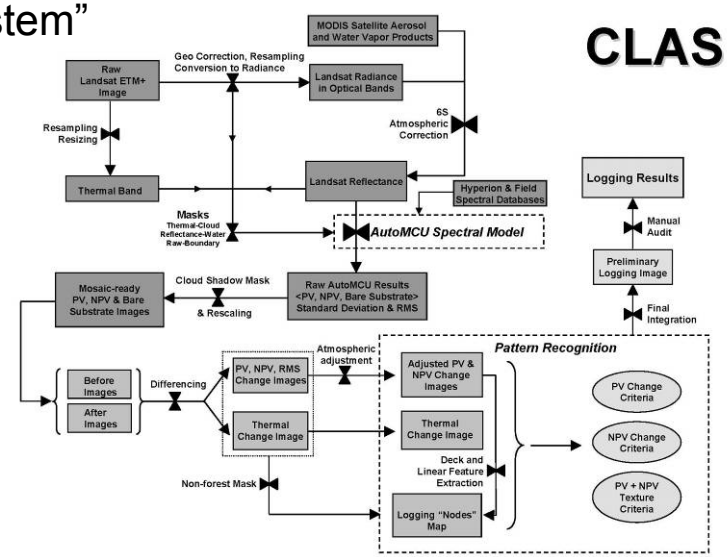
PRAIA #1
11:07 AM


ENVI 4.2 Beta
File Basic Tools Classification Transform Filter Spectral Map Vector Topographic Radar Window Help Brazil
#1 Logging:MT_Logging_PVC_2000.img
File Overlay Enhance Tools Window
#2 Band 1:MG_2000_PVchange_mosaic.img
File Overlay Enhance Tools Window
#1 Scroll (0.00602)
#1 Zoom [4x]
#2 Scroll (0.00543)
#2 Zoom [4x]
start
ArcCatalog - ArcInfo ...
BDQUEIMADAS - Ban...
9 IDL
Microsoft PowerPoint ...
PRAIA #1
5:34 PM

Some Properties of CLAS

- Core module based on changes in sub-pixel forest canopy cover
  - not based on absolute values
- Pattern recognition based on local-kernel (landscape scale) changes in the sub-pixel results
  - not based on phenology or regional atmospheric variation
- Manual audit – essential in any “automated system”
- Directly linked to forest gap fraction
  - Allows for logging intensity analyses
  - Allows for carbon loss (gross flux) analyses



Why the forest gap fraction approach?

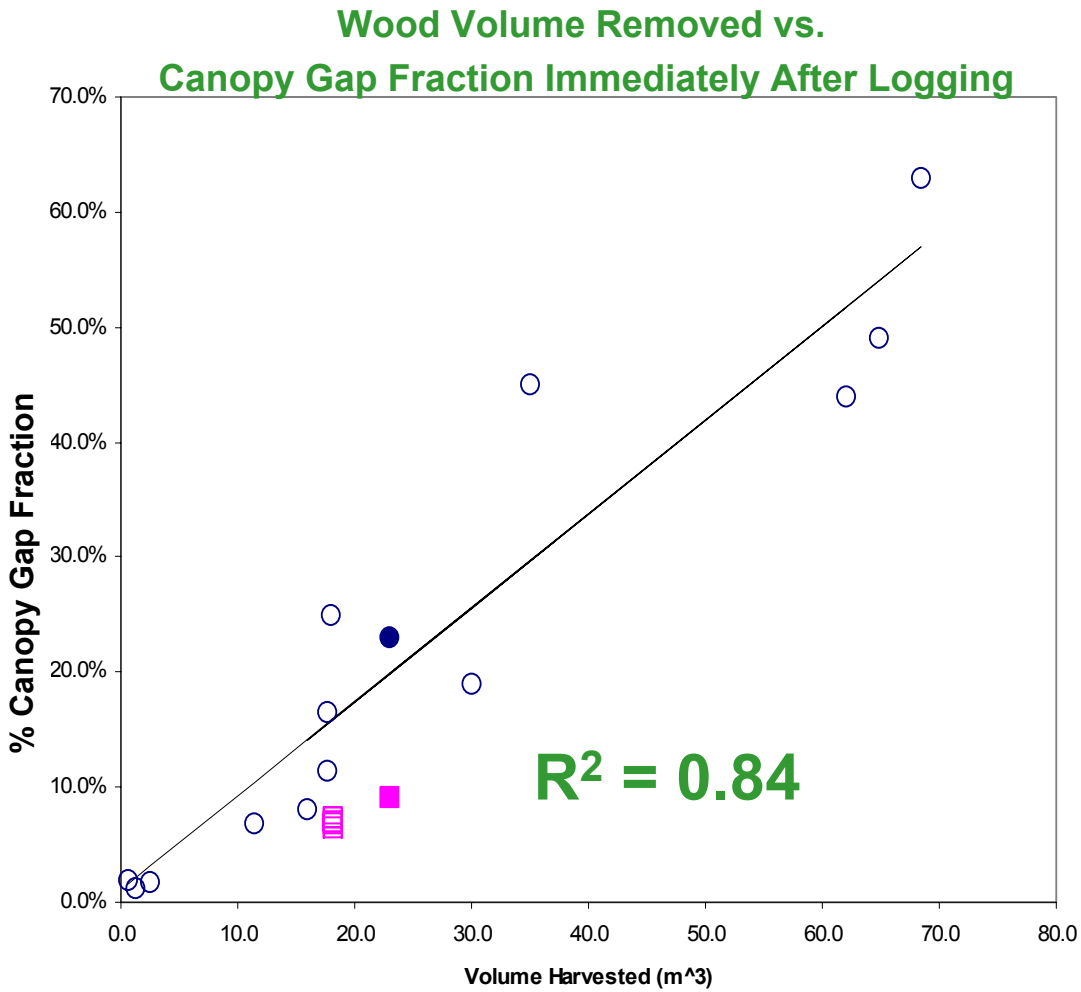
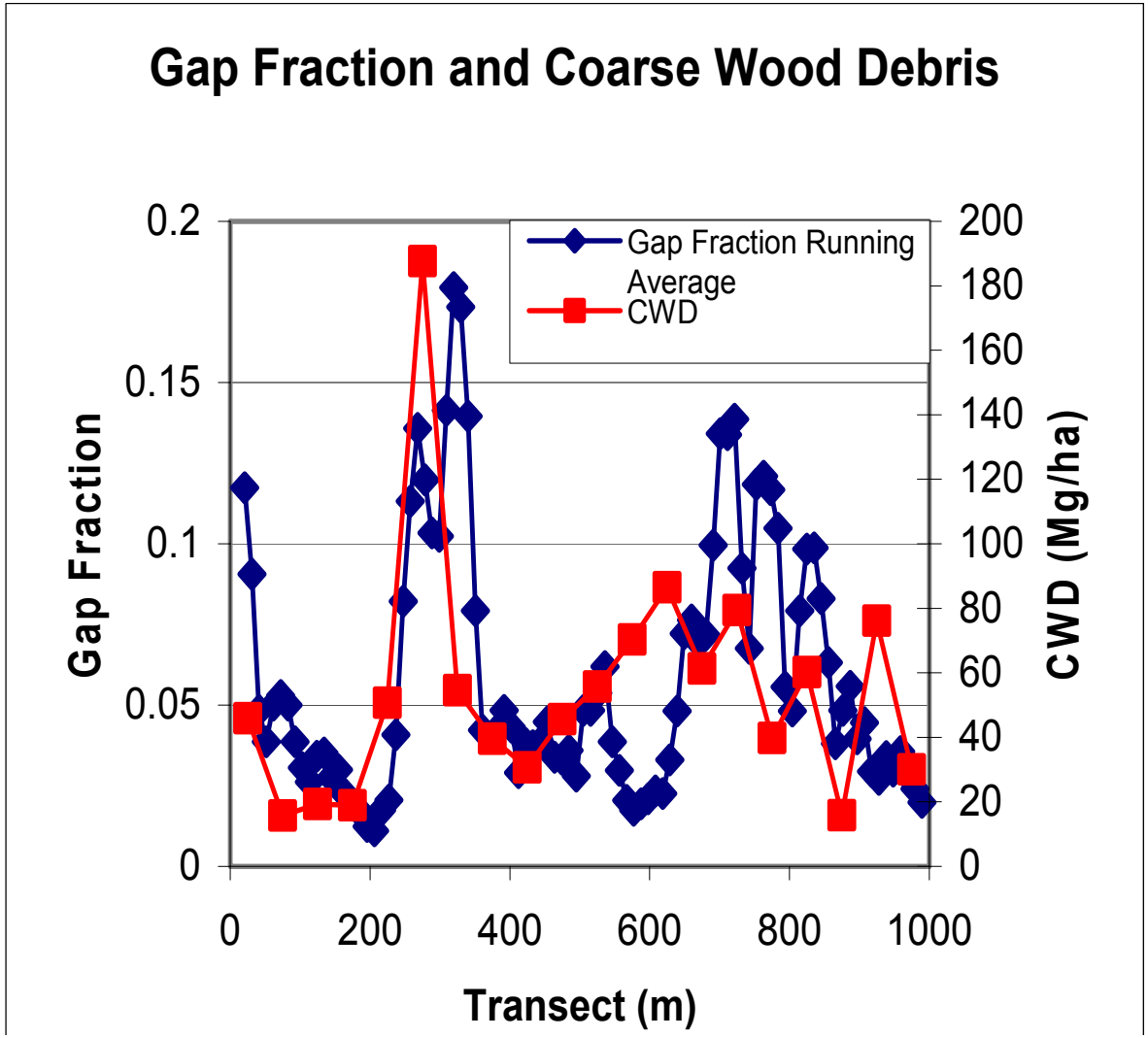


Fig. 5. Canopy damage vs. total volume harvested in 24 logging blocks shown for conventional logging (circles) and RIL (squares). Data shown were derived from this study (filled symbols) and 10 previously published studies (open symbols) (Van Der Hout, 2000; Whitman et al., 1997; Webb, 1997; Johns et al., 1996; Verissimo et al., 1995; White, 1994; Cannon et al., 1994; Verissimo et al., 1992; Uhl et al., 1991; Hendrison, 1989). The best fit least-squares linear regression for canopy loss (y; proportion of total area) vs. harvest geometric volume (x; m^3) was $y = 0.0077x + 0.0058$ ($r^2 = 0.84$). For RIL, the regression equation is $y = 0.0048x - 0.013$ ($r^2 = 0.81$).

Pereira et al. 2002
Forest Ecology and Management

Why the forest gap fraction approach?



Keller and Palace 2000

Logging Area Results
1999-2002

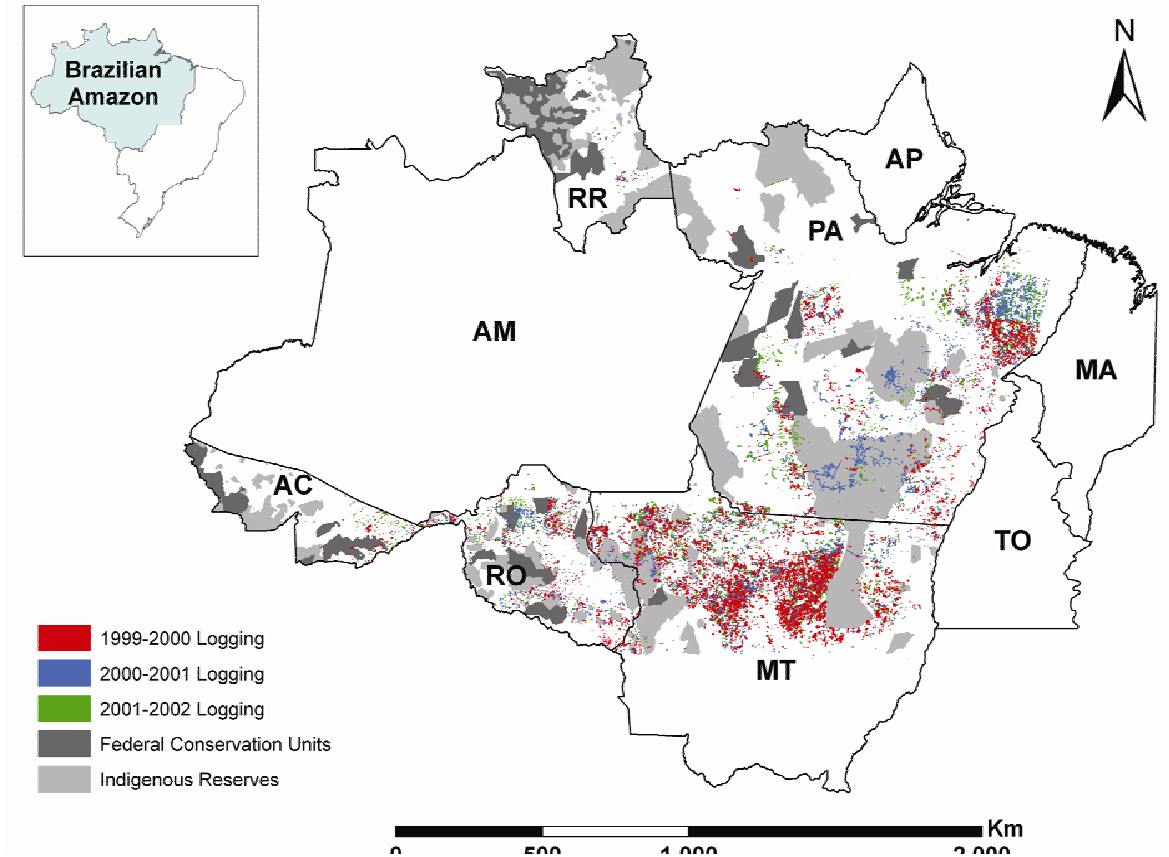


Table 1. Selective-logging rates from 1999–2002 in five major timber-producing states of the Brazilian Amazon, with comparison to the deforestation rates reported by the INPE (*18*).

State	1999–2000 rates (km^2 $year^{-1}$)		2000–2001 rates (km^2 $year^{-1}$)		2001–2002 rates (km^2 $year^{-1}$)	
	Logged	Deforested	Logged	Deforested	Logged	Deforested
Acre	64	547	53	419	111	727
Mato Grosso*	13,015	6,176	7,878	7,504	7,207	6,880
Pará	5,939	6,671	5,343	5,237	3,791	8,697
Rondônia	773	2,465	923	2,673	946	3,605
Roraima	32	253	55	345	20	54
Total	19,823	16,112	14,252	16,178	12,075	19,963

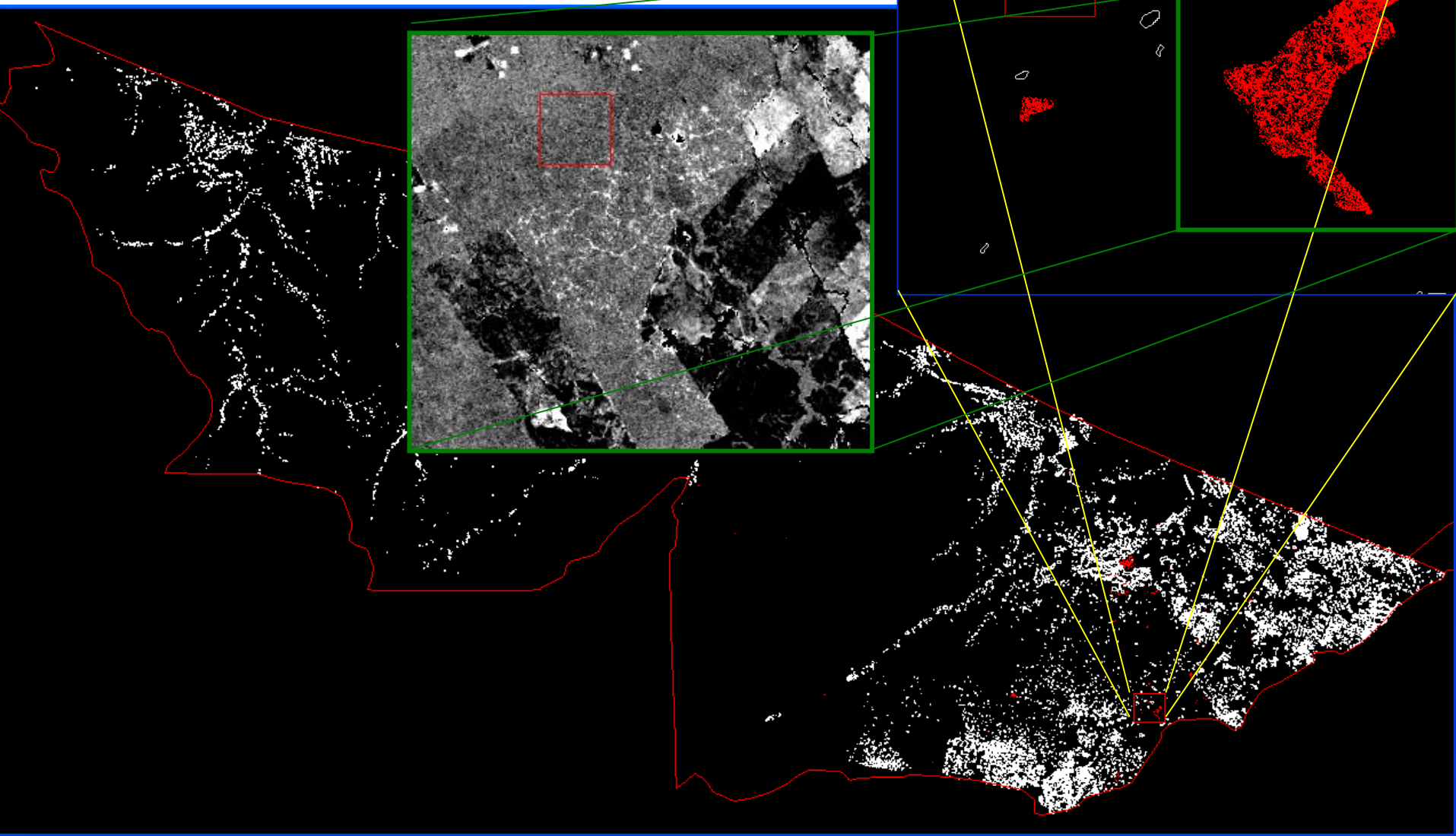
*Only the northern 58% of Mato Grosso containing forested lands was included in the analysis.

Asner et al. 2005
Science

logging polygons per state yr-1

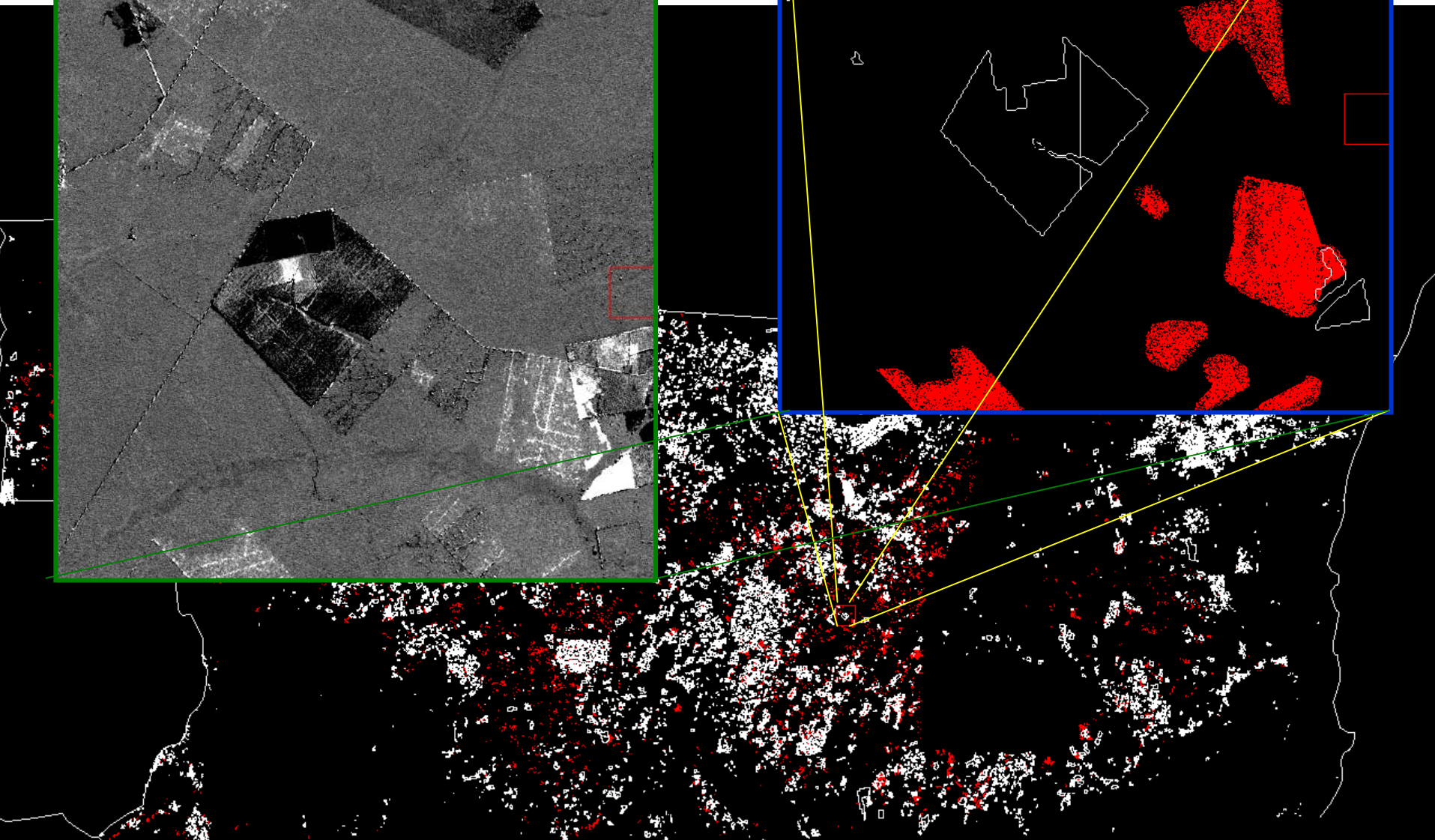
State	99-00'	00-01'	01-02'	99-02'
AC	272	229	387	888
RO	1100	1332	1064	3496
MT	4840	4683	4196	13719
PA	3089	4211	3225	10525
RR	33	110	69	212
Amazon	9334	10565	8941	28840

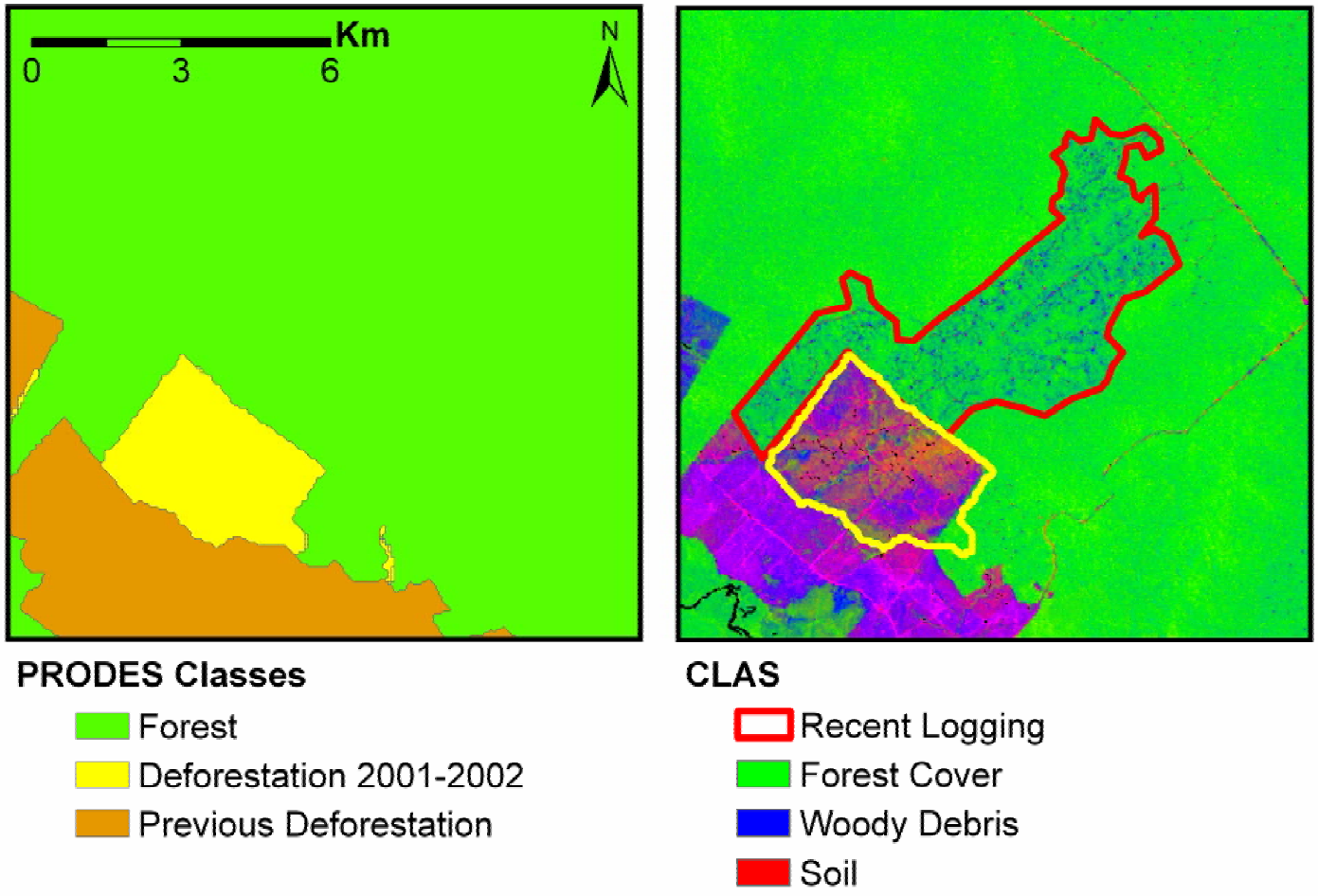
Acre deforestation and logging in year 1999-00



Mato Grosso

deforestation and logging in year 1999-00





Spatial overlap with deforestation in a given year = 6% ± 5%

Spatial overlap with deforestation up to 3 years after logging = 19% ± 11%

Asner et al. 2005
Science

Primary sources of uncertainty in *CLAS* analyses of selective logging extent in Amazonia

Source	Percentage of Total Logged Area	Method
Atmosphere	± 0.7%	Determine the percentage difference in automatically detected logged area between the atmospherically corrected image and an image with randomly selected atmospheric characteristics.
Unobserved Area	+ 5%	Percentage of cloud- and shadow- covered area compared to total logged area
Annualization	±2-9%	Standard error of the difference between dry season length for matched pairs of consecutive years from 1979-1996.
Auditor	± 12.8%	Standard error of diff between auditor estimates, on a per km^2 of logging basis
TOTAL ESTIMATED ERROR	**11-14%**	Square root of sum of squares of all other errors

Asner et al. 2005
Science

Table S3. Minimum-maximum logging estimates for Brazilian states in the Amazon based on uncertainties in CLAS logging methodology.

State	1999-2000 rates (km^2 yr^{-1})		2000-01 rates (km^2 yr^{-1})		2001-02 rates (km^2 yr^{-1})	
	Logged		Logged		Logged	
	Minimum*	Maximum†	Minimum*	Maximum†	Minimum*	Maximum†
Acre	54	78	45	66	94	133
Mato Grosso‡	10,983	15,703	6,744	9,481	6,195	8,453
Pará	4,905	7,419	4,421	6,536	3,138	4,844
Rondônia	657	931	785	1,076	804	1,113
Roraima	27	38	46	66	17	26
Total	**16,626**	**24,169**	**12,041**	**17,225**	**10,248**	**14,569**

* Composed of atmospheric, temporal interpolation, annualization, and auditor uncertainties (see text for definitions).
† Includes all uncertainties plus cloud interpolated area.
‡ Includes Northern Mato Grosso only.

Asner et al. 2005
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