How to monitor a changing planet?

or

How access to more observations is improving what we can do with remote sensing!

or

Time Series Analysis of Landsat Data for Continuous Monitoring of Land Cover Change and Condition

- Curtis Woodcock (and many others)

  Boston University, Department of Earth and Environment

Community Goals?

- Reconstruct the history of the surface of Earth
  - Provide maps of surface characteristics at any time (where maps change between dates correspond to locations of land cover change!!)
- Monitor change as it is occurring
  - "management relevant"

In interesting ways, these are part of the same process!

Why Landsat is so relevant now!

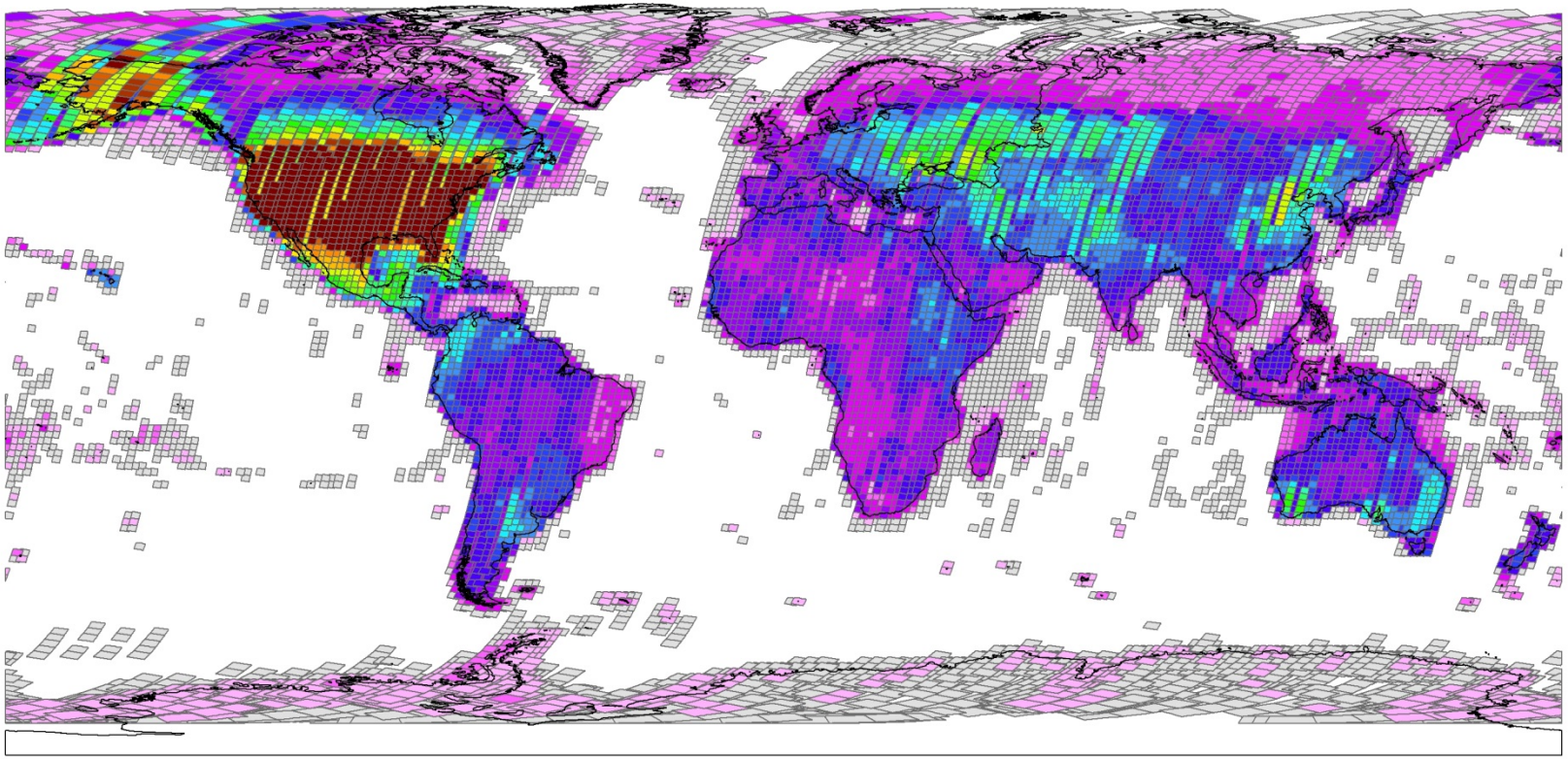
- After 40+ years, we are still learning what we can do with Landsat data – fair to say we are learning more about cool things to do with Landsat at a faster rate than anytime in the past!
- Consistent data formats – images easily stacked
- Computing capabilities
- Archive consolidation (LGAC)
- Calibration/automated atmospheric correction
- Automated Cloud and Cloud Shadow Detection
- Free Access – data policy, NASA + USGS
  - Prior to 2008, less than 10% of the images in the archive had ever been used! Now it is over 80% and only the completely cloud covered images have never been used
- Landsat 8 is the best we have ever had! Effort to build Landsat 9 has begun (currently planned for 2022). Planning for Landsat 10 is already beginning!
- The Landsat archive is the most valuable record we have of the history of the surface of Earth!

Landsat Global Archive Consolidation

- Notes:
  - About 5.8 million images in archive (Jan 1, 2015)
  - To date 3.2 million images added by LGAC
  - LGAC will consolidate an additional ~ 2.3 million images into the UGSG archive
  - When complete, over 70% of the images in the archive will be present due to LGAC
  - Regional and temporal representation is improved

Wulder, M.A, J.C. White, T.R. Loveland, C.E. Woodcock, A.S. Belward, W.B. Cohen, G. Fosnight, J. Shaw, J.G. Masek, and D.P. Roy. (In review). The global Landsat archive: Status, consolidation, and direction.

USGS archive prior to LGAC

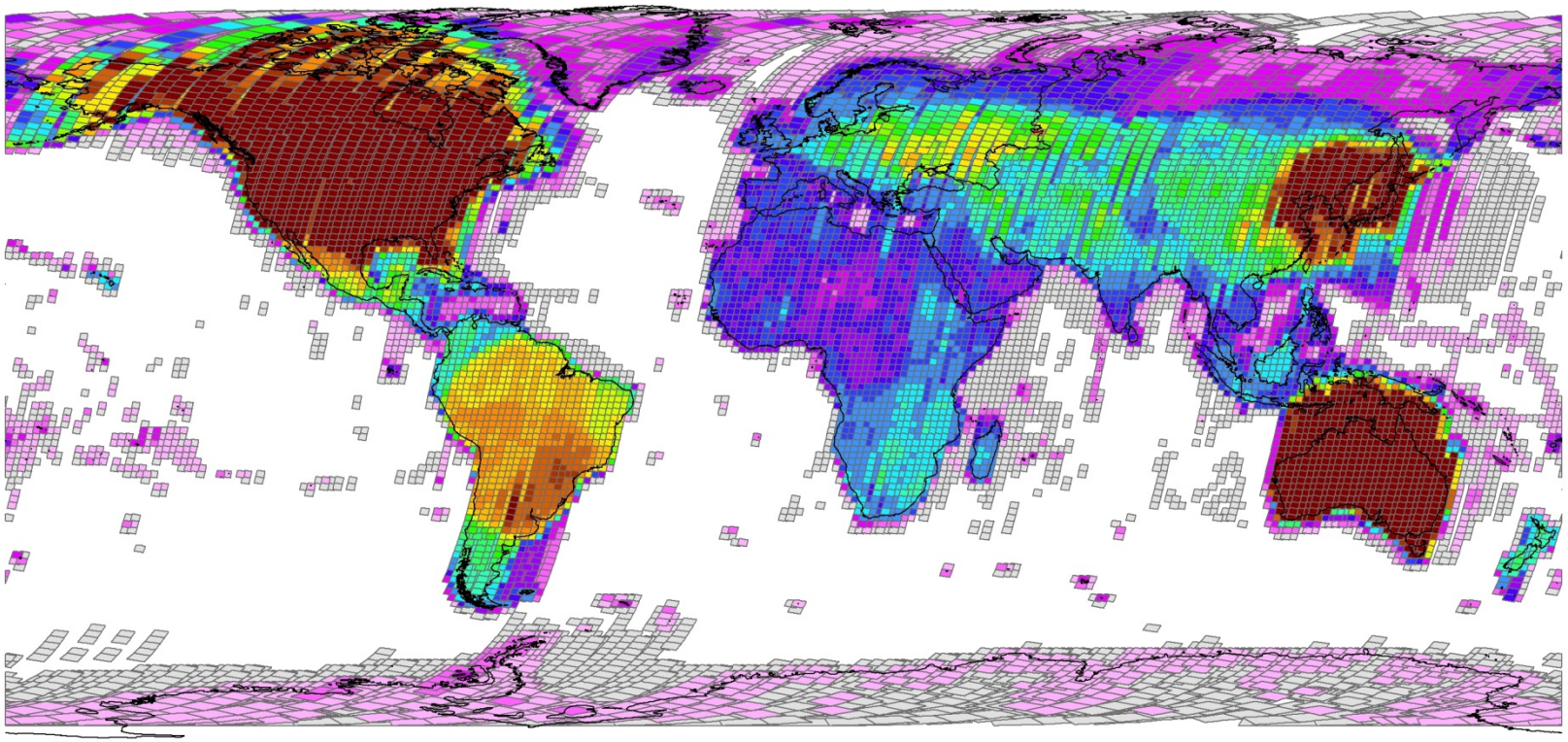


Number of images

1-50	200-250	400-450	600-650	800-850
50-100	250-300	450-500	650-700	850-900
100-150	300-350	500-550	700-750	900-950
150-200	350-400	550-600	750-800	>950

Archive holdings pre-LGAC

USGS archive up to Jan 1, 2015

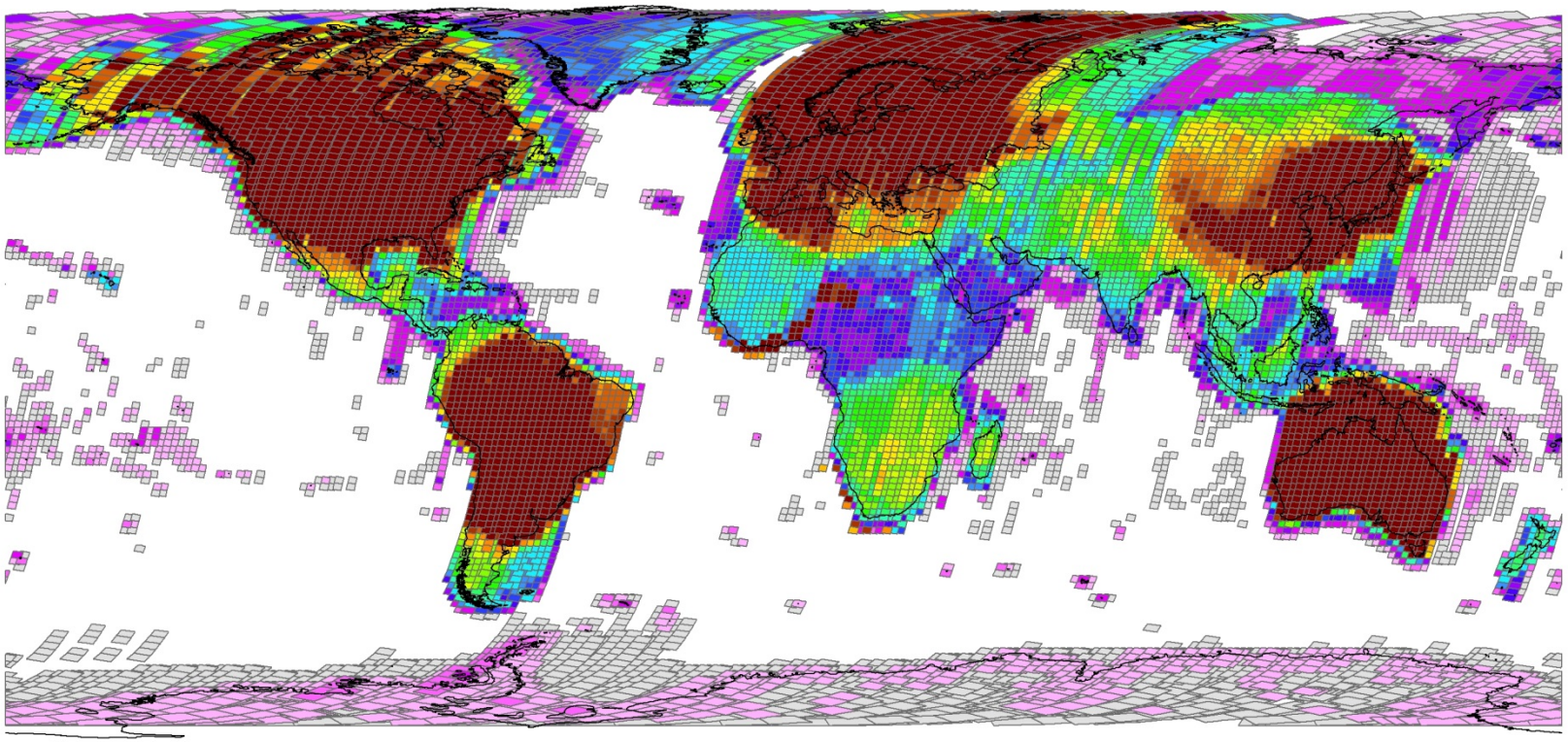


Number of images

1-50	200-250	400-450	600-650	800-850
50-100	250-300	450-500	650-700	850-900
100-150	300-350	500-550	700-750	900-950
150-200	350-400	550-600	750-800	>950

Archive holdings as of January 1, 2015

Future archive once outstanding images added



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100-150	300-350	500-550	700-750	900-950
150-200	350-400	550-600	750-800	>950

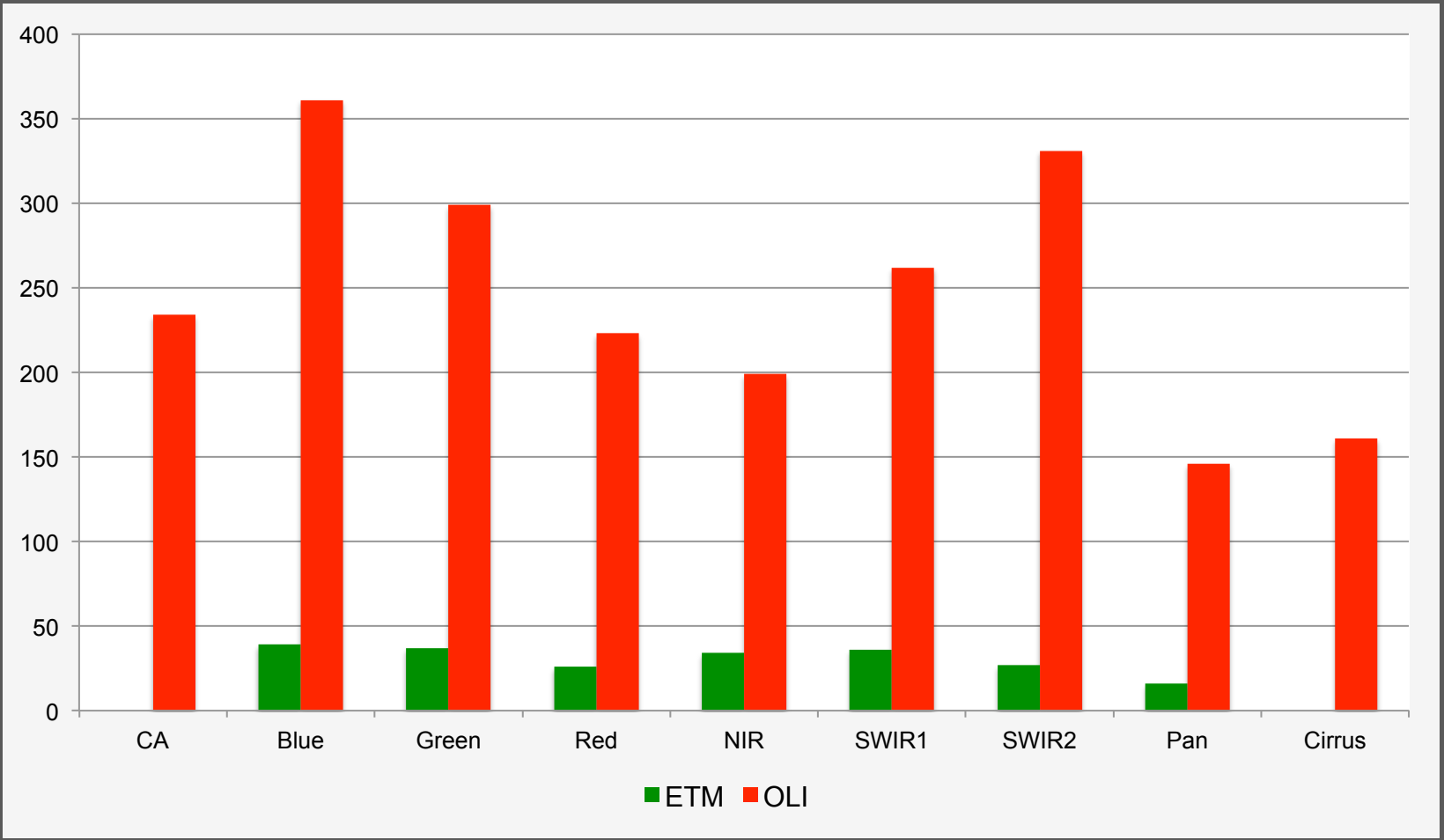
Potential future archive holdings (with LGAC)


LDCM Launch
February 11, 2013


NASA
EROS • GSFC • KSC
LDCM
LANDSAT
Data Continuity Mission
NASA • USGS


LDCM Reaches WRS-2
April 12, 2013

Landsat 8 Signal-to-Noise



USGS

Improved SNR allows the more accurate detection and characterization of subtle land and water conditions and changes.

Daily global Landsat acquisitions

- Landsat 5 and Landsat 7 era (circa 2010)
  - Landsat 5: 200 images/day
  - Landsat 7: 300 images/day
  - Total – 500 images/day added to the archive

- Landsat 7 and Landsat 8 era (circa 2015)
  - Landsat 7: 470 images/day
  - Landsat 8: 725 images/day
  - Total – 1,195 images/day added to the archive

USGS

Brief History of Remote Sensing of Change

- Make maps and compare them
- Compare images
- Compare images with what you expect to see
  - Use all available observations (assume individual observations are noisy)
  - Clear clouds, shadows and snow (2-step process) and atmospherically correct
  - Fit a model for each pixel (starting at the beginning)
  - Compare new observations with model predictions based on the history of past observations for each pixel

One trend is increasing use of the entire Landsat archive – often in the form of a time series

- New kinds of information from Landsat
  - Detection of more subtle disturbance
  - More reliable disturbance detection
  - Trends in ecosystem health and growth
  - Forest phenology – both average and interannual
  - Peak greenness – as indications of trends in ecosystem health and climate response
  - Improved ability to map forest composition

ELSEVIER

Remote Sensing of Environment 82 (2002) 285–302

Remote Sensing of Environment

www.elsevier.com/locate/rse

The spectral/temporal manifestation of forest succession in optical imagery The potential of multitemporal imagery

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[b]*Department of Geography, Boston University, 675 Commonwealth Avenue, Boston, MA 02215, USA*
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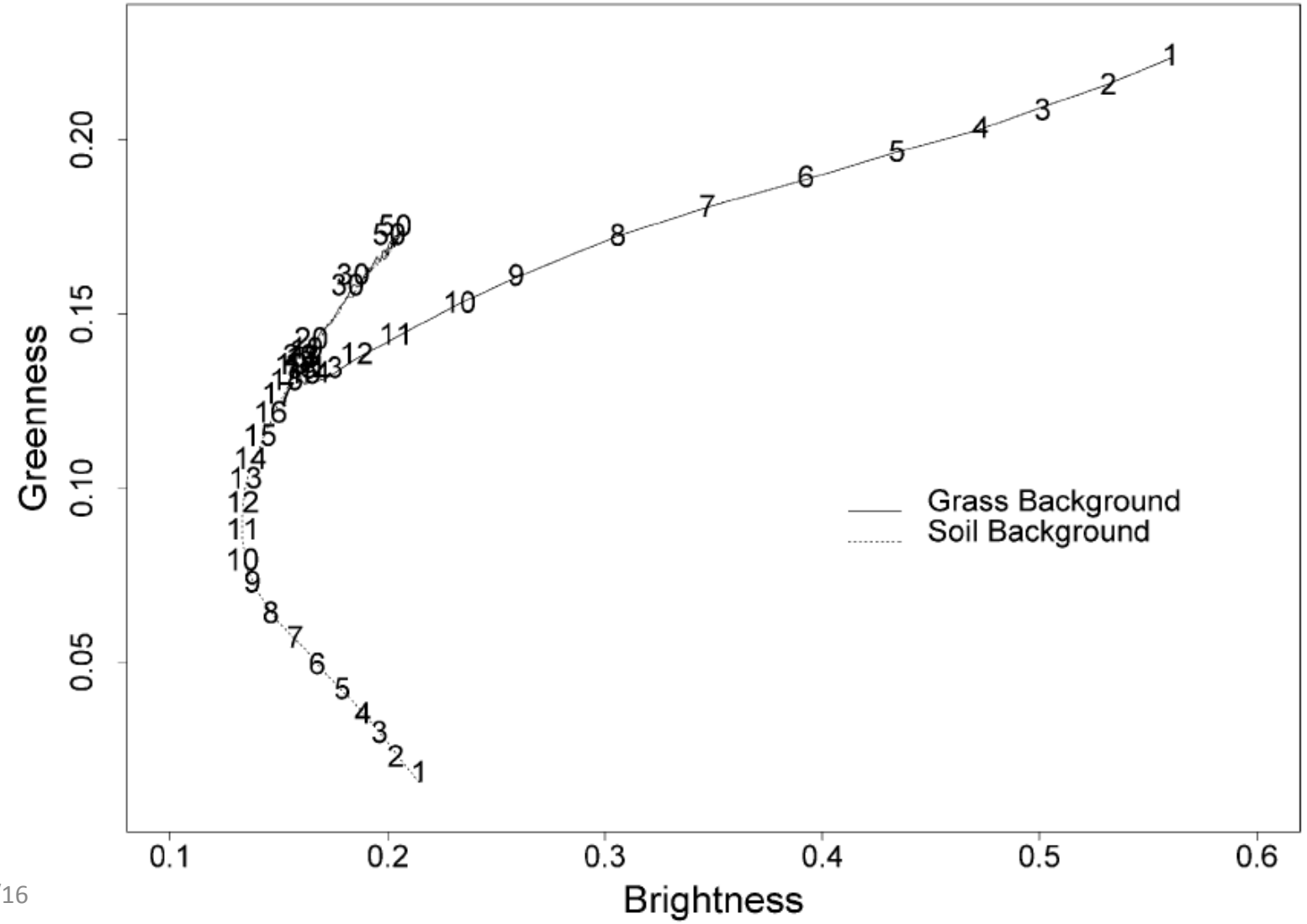
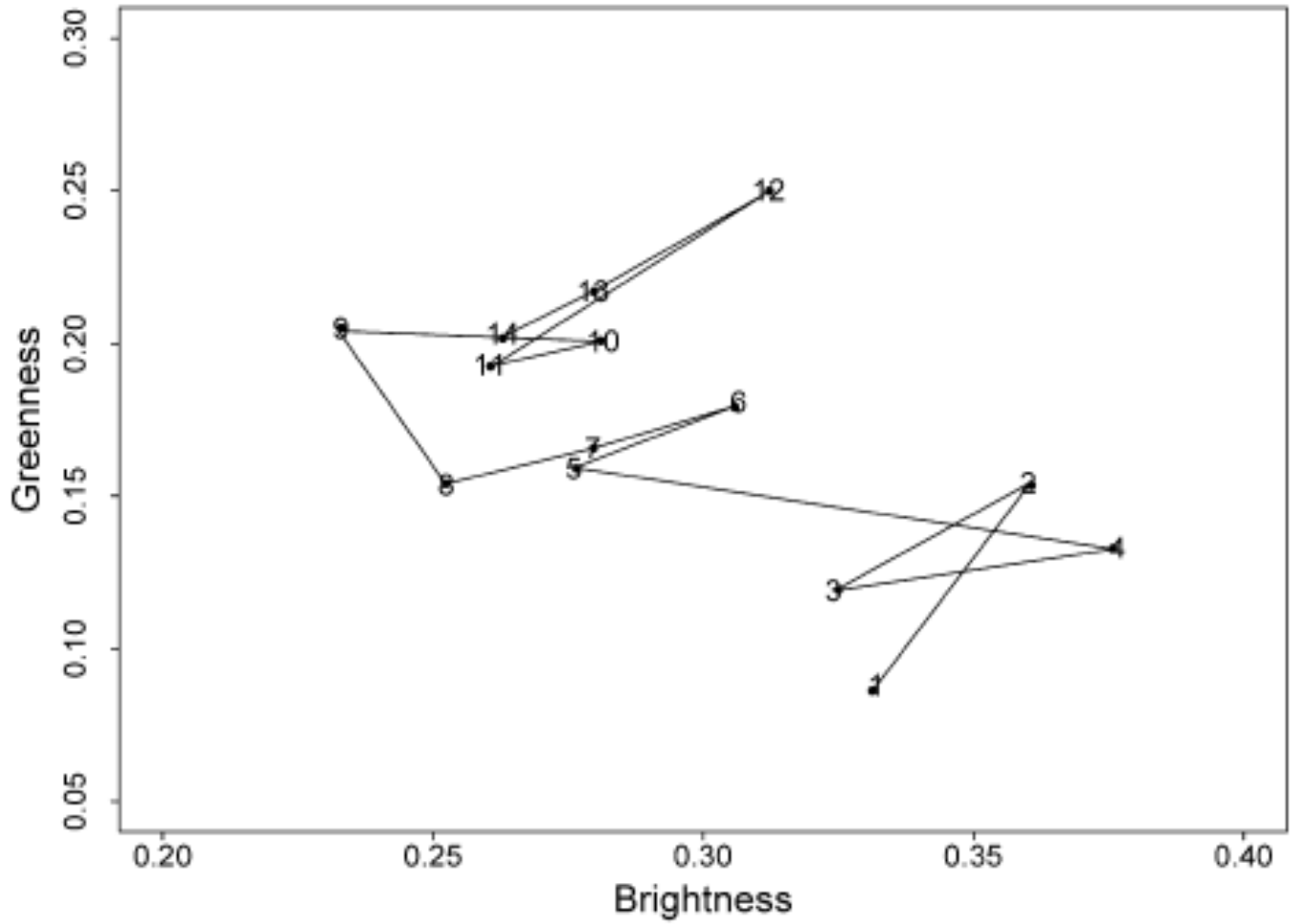
Received 10 August 2001; received in revised form 26 March 2002; accepted 30 March 2002

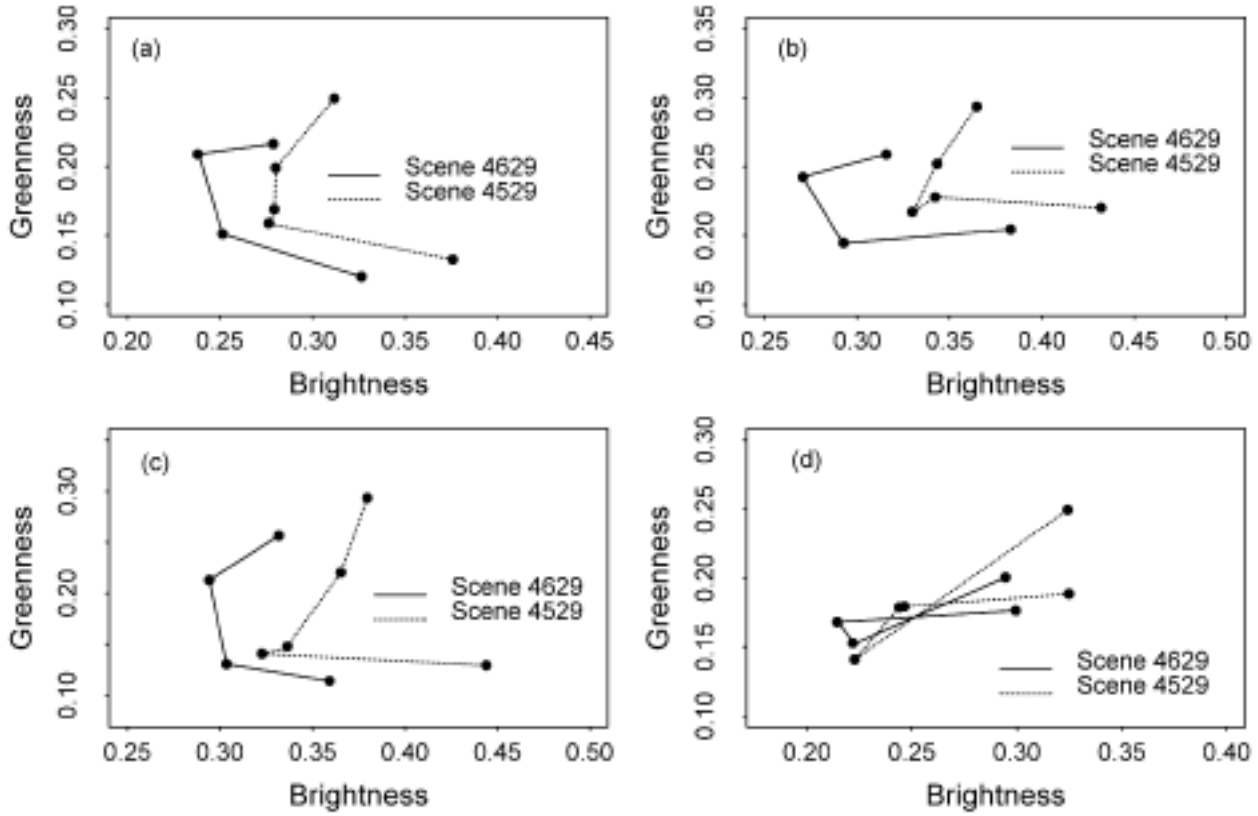
Forest growth and succession (age) have nonlinear trends in spectral indices (result from models)



Hmmm… observations are more messy – how can we make sense of this pattern?

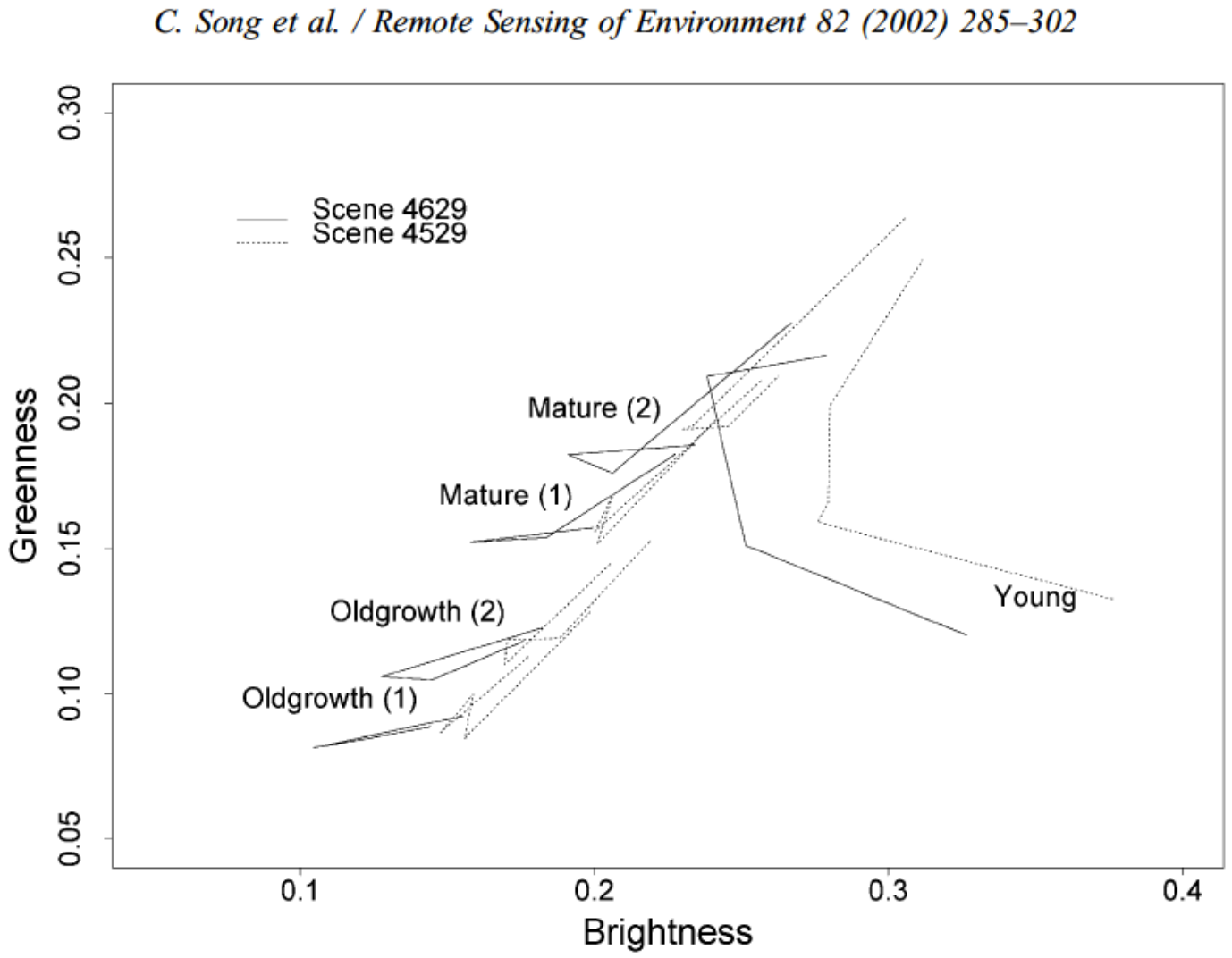


View angles matter – when sorted by view angles, the patterns are clearer

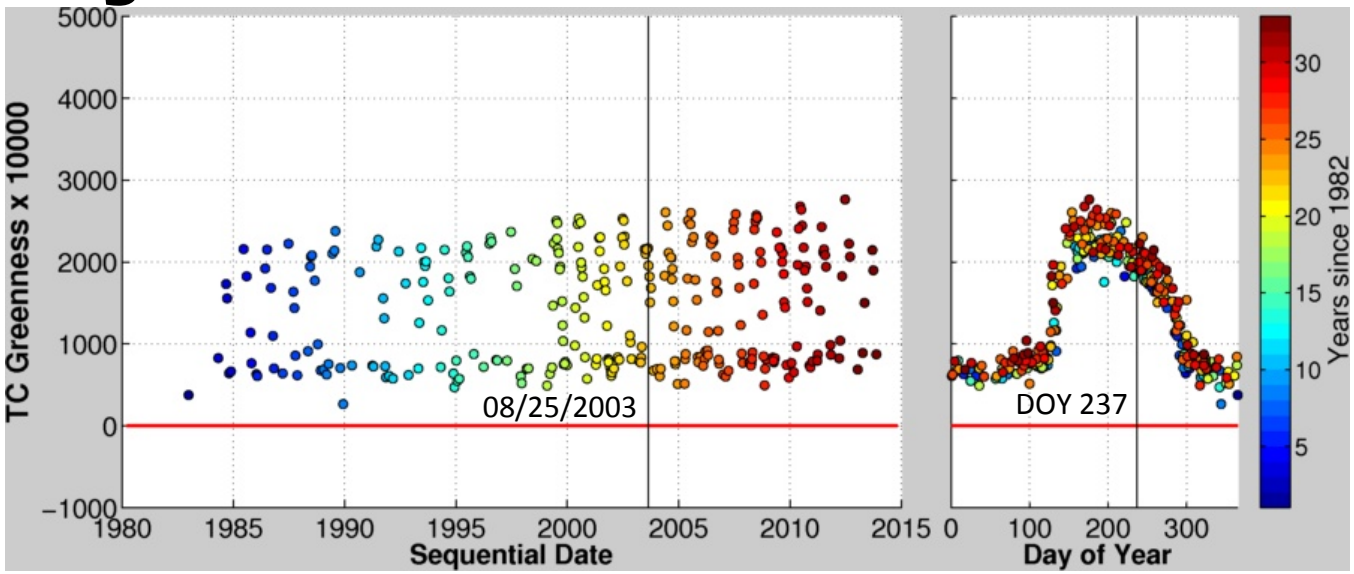


A,B and C are successfully regenerating as forests, D is not

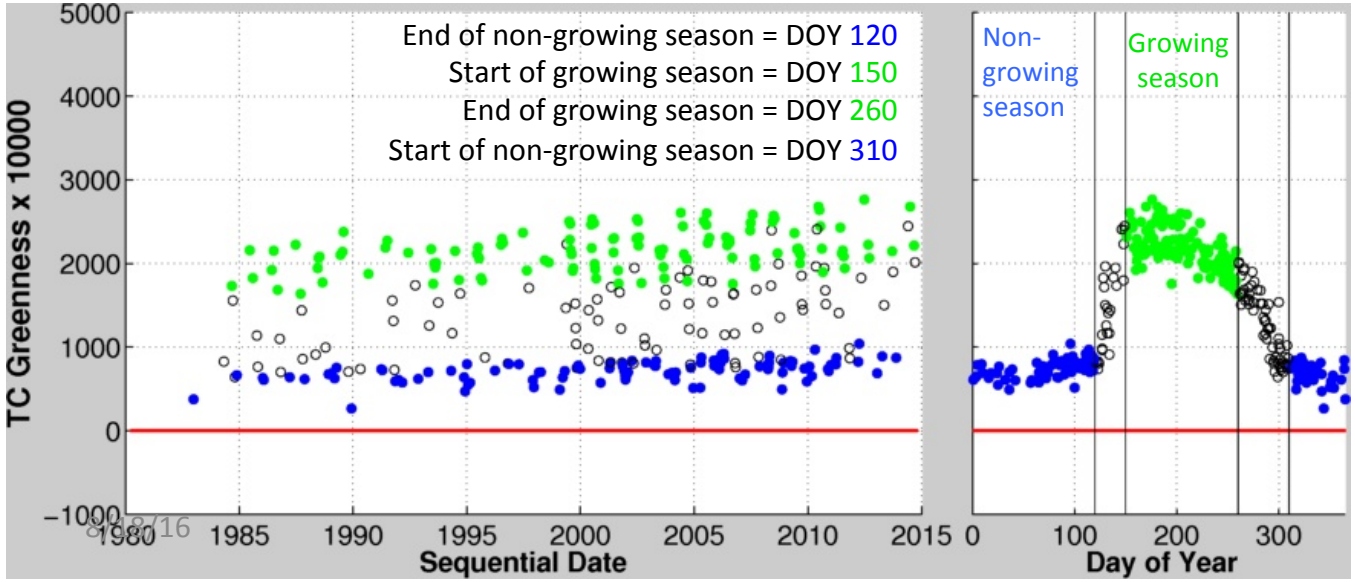
At the time we were thrilled to pull together 15 images of the same place!



By Year

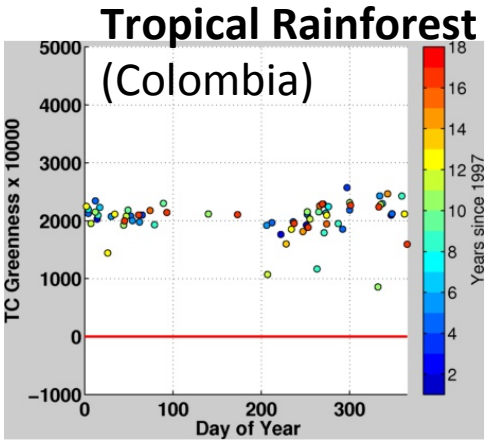


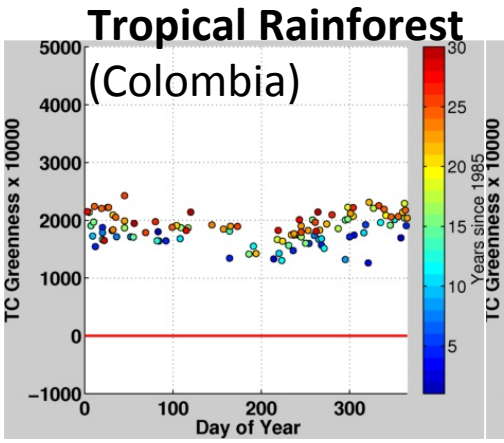
By Season

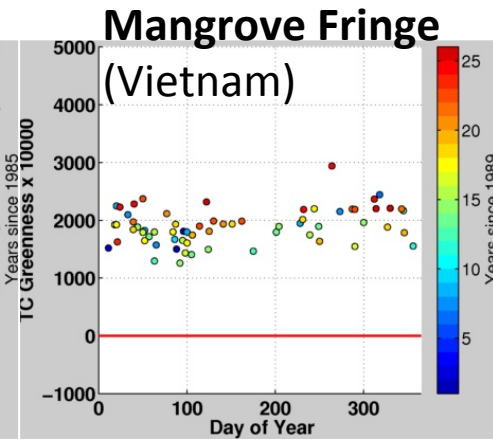


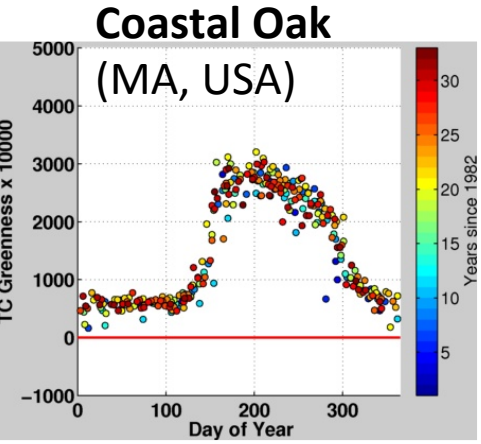
Global Forests

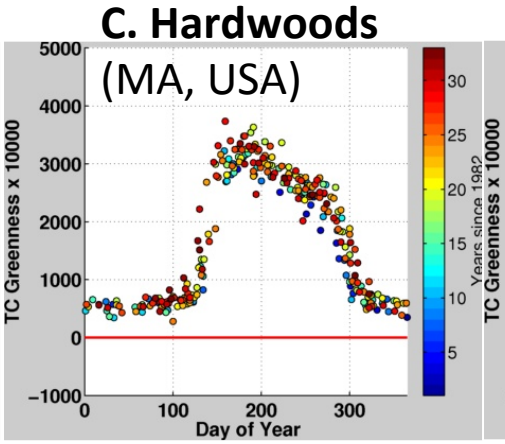
(TC Greenness)

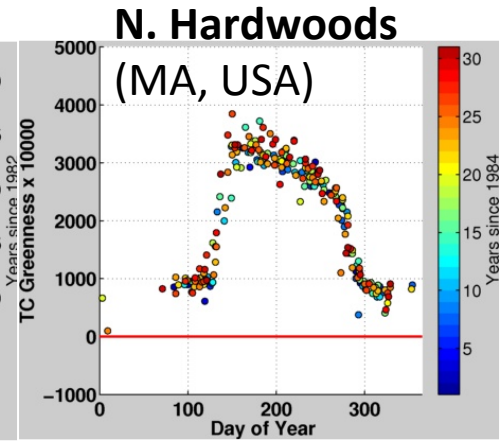


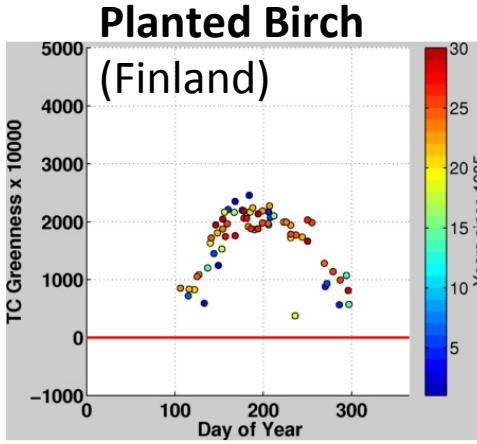


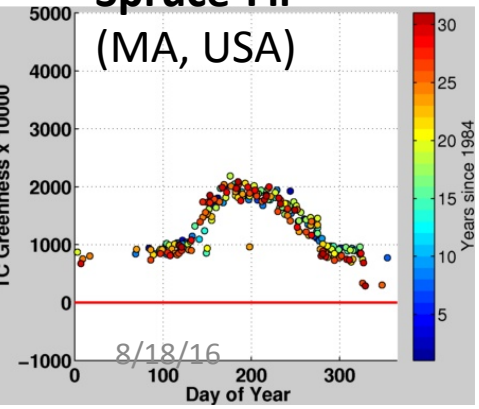


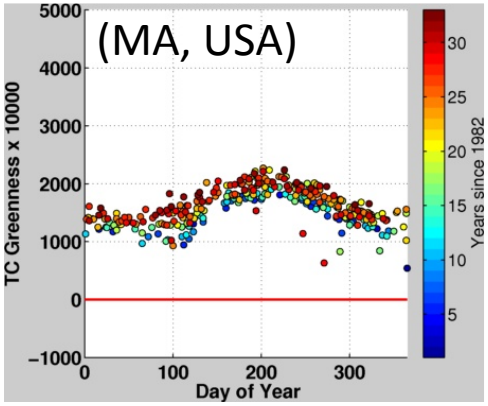


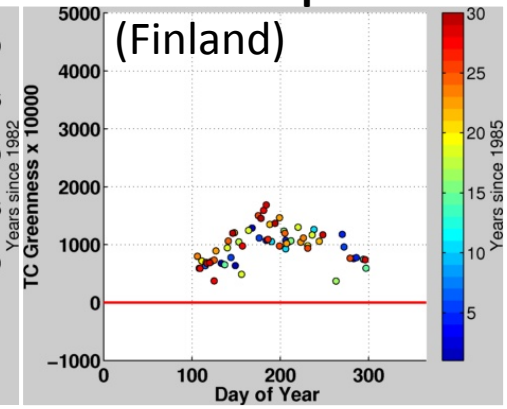


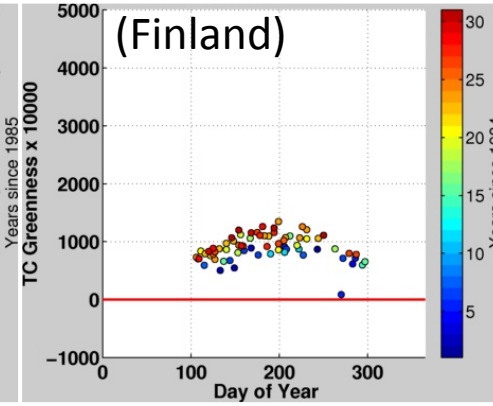






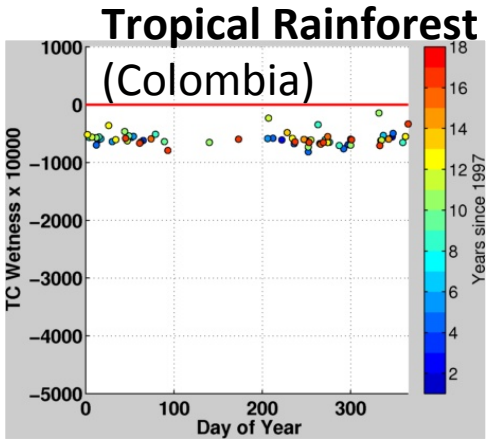


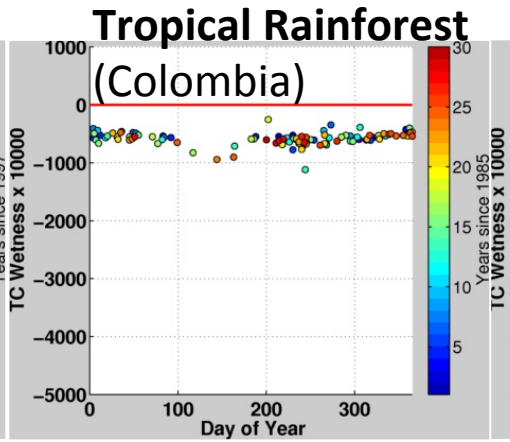


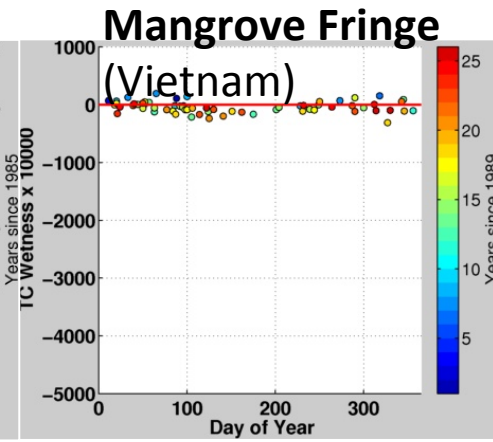


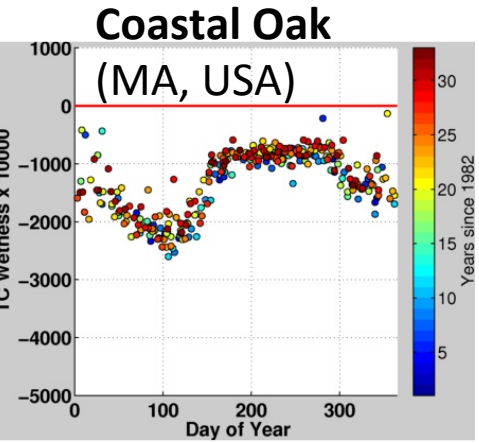
Global Forests

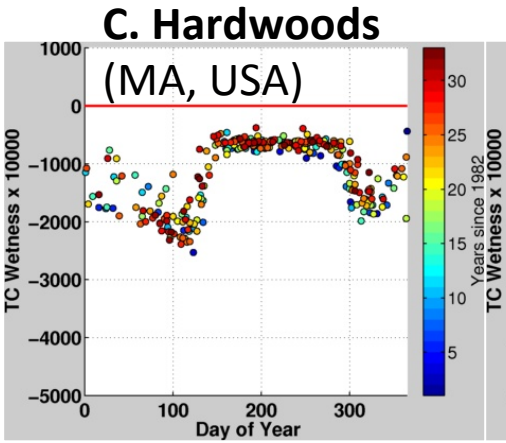
(TC Wetness)

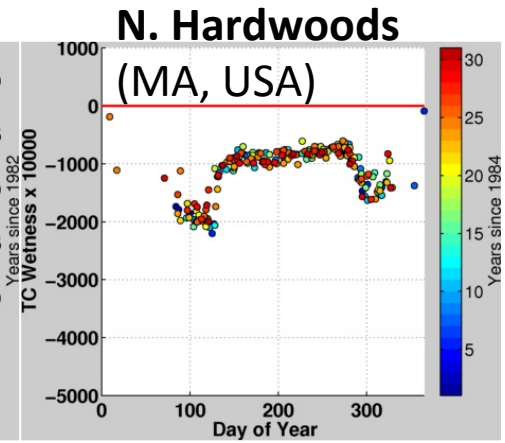


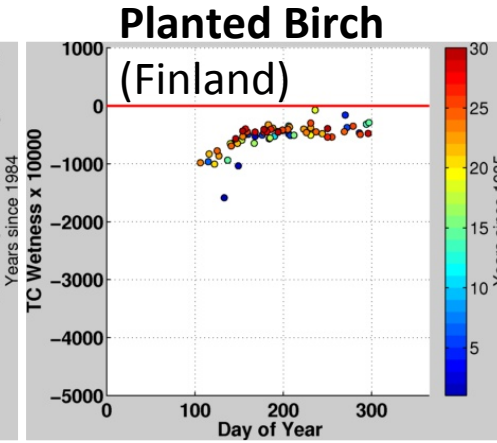


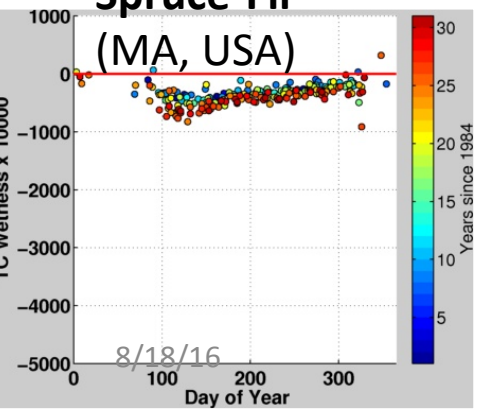


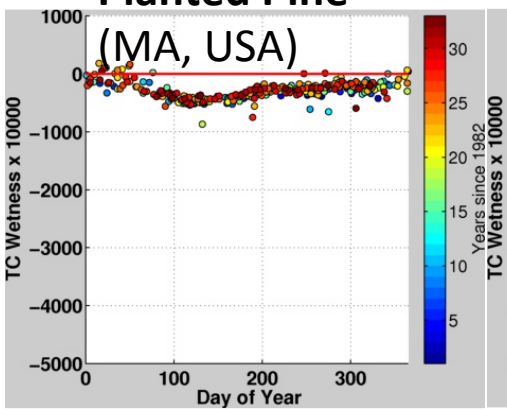


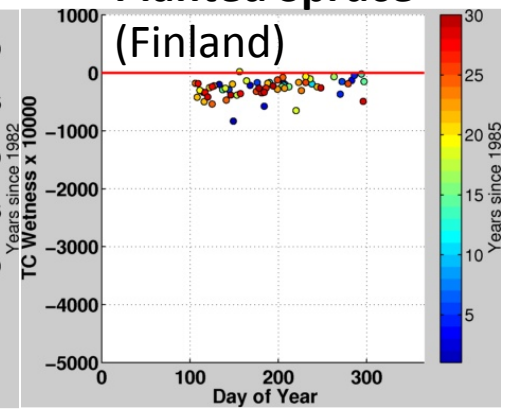


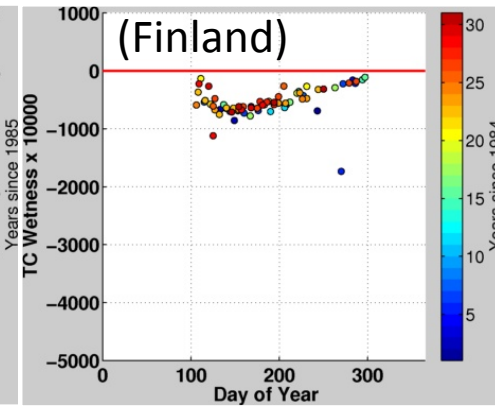




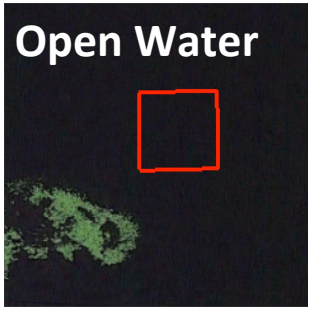


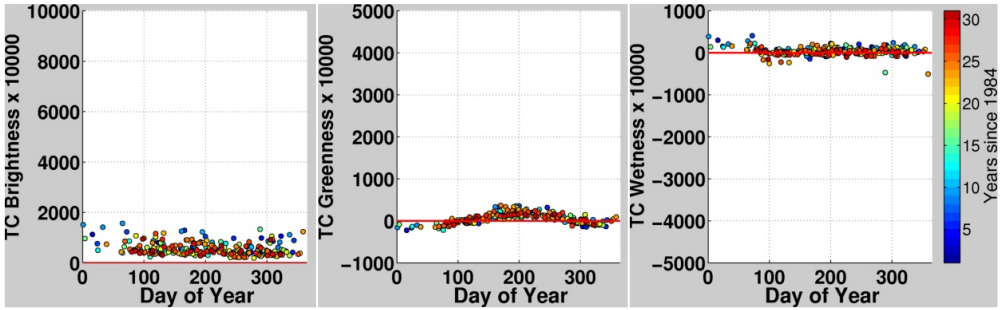


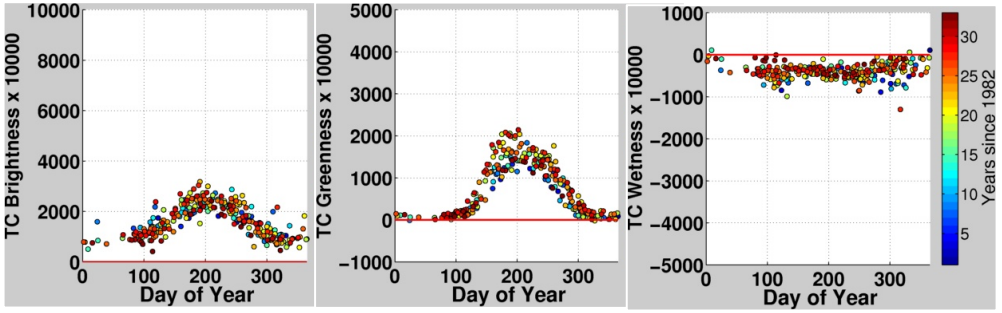


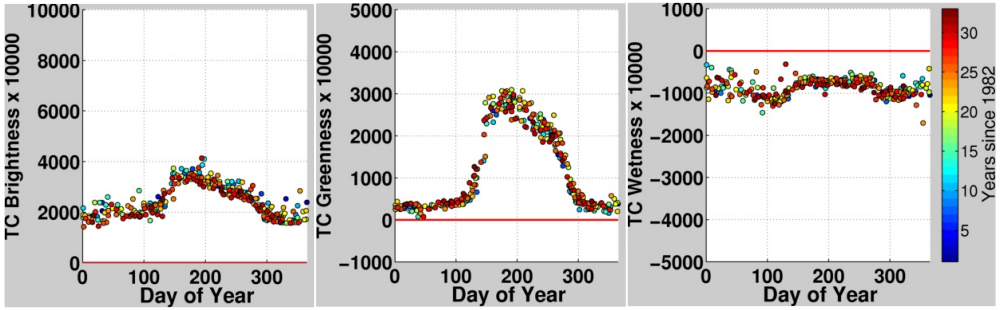


Wetland Gradient



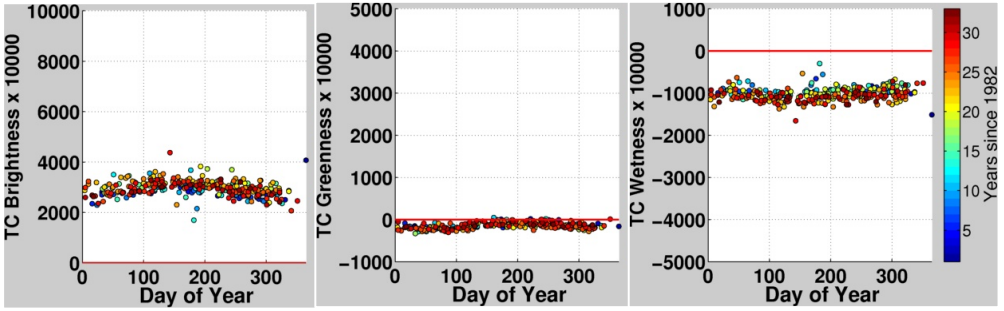


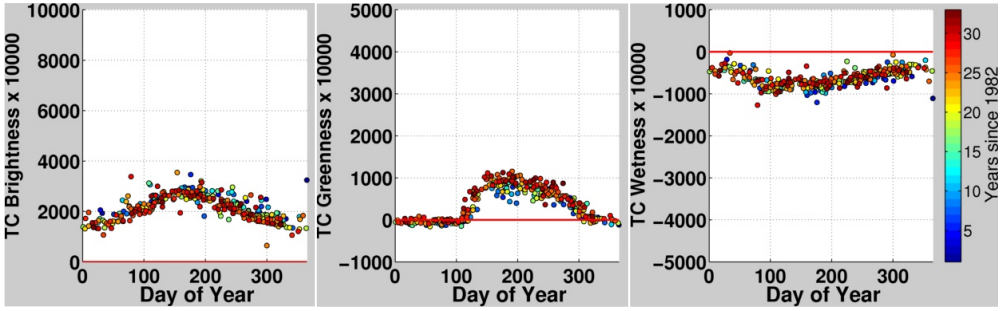


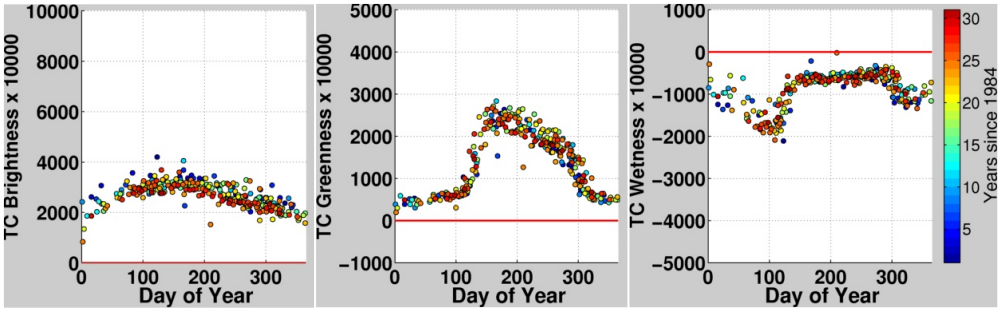


Brightness *Greenness* *Wetness*

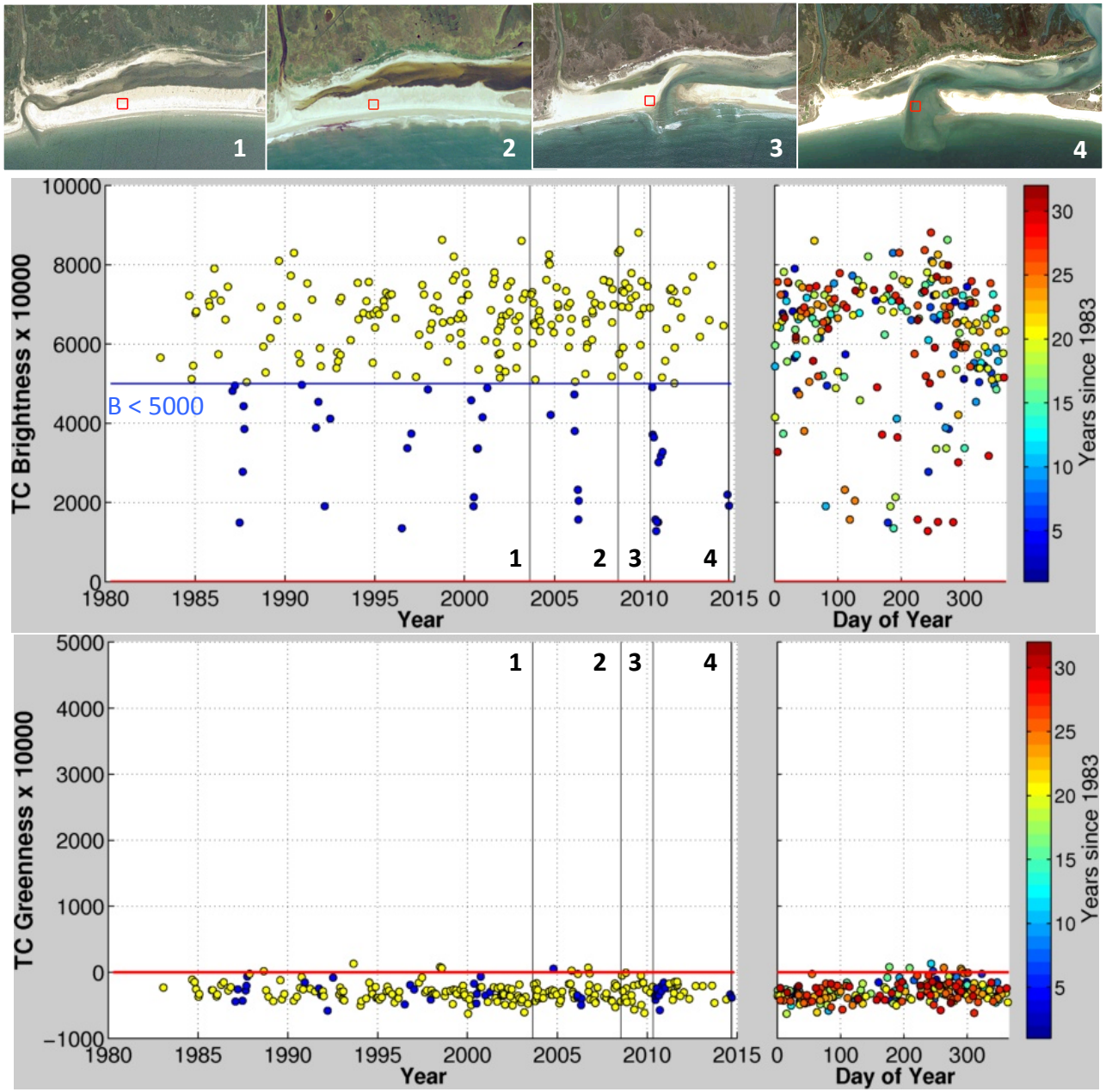
Urban Gradient



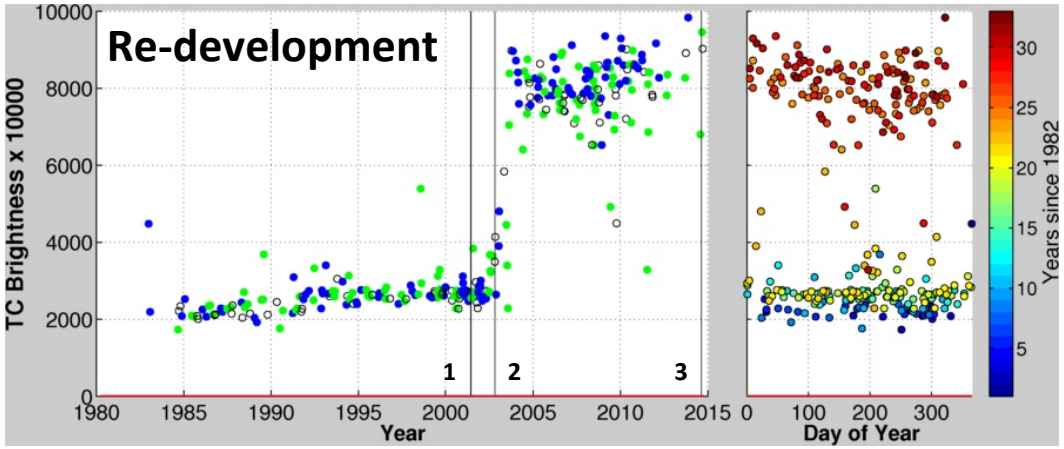


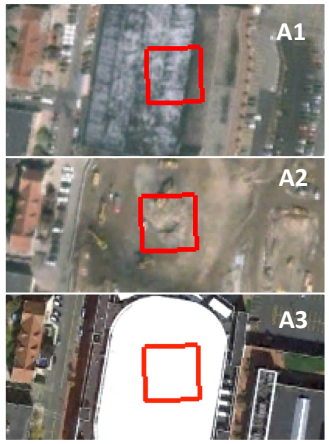


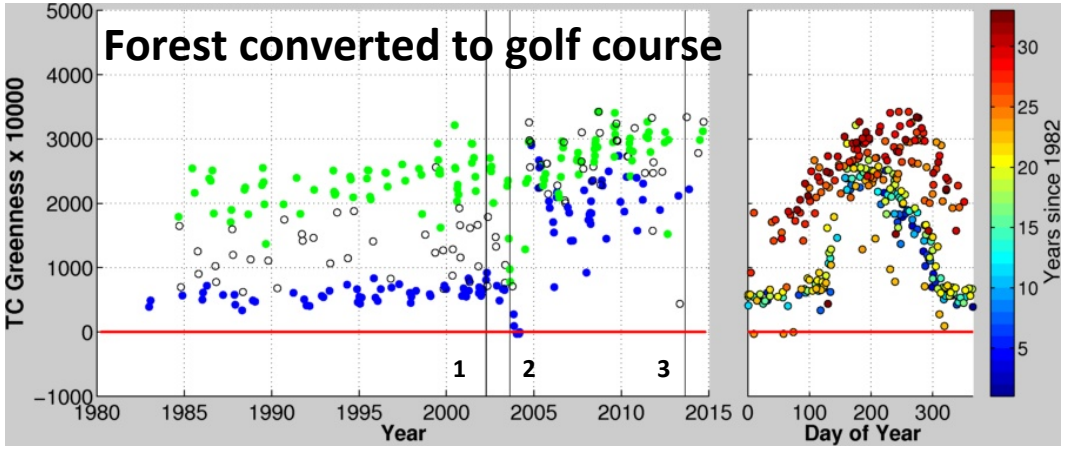
Periodic Change

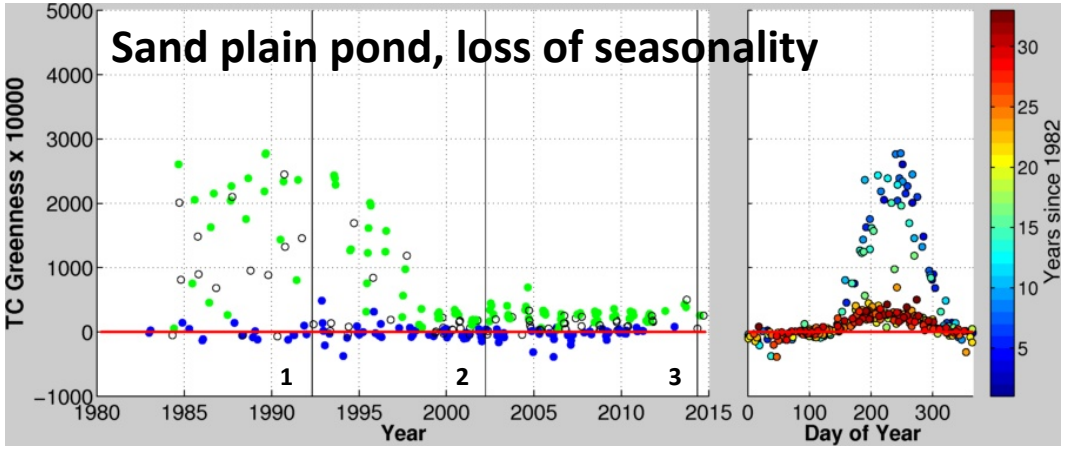


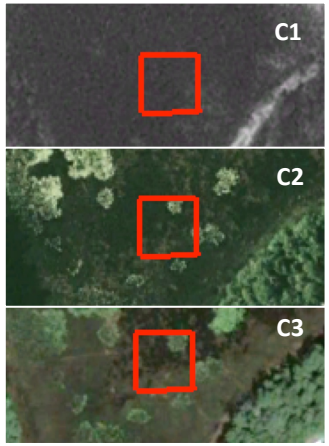
Abrupt Change



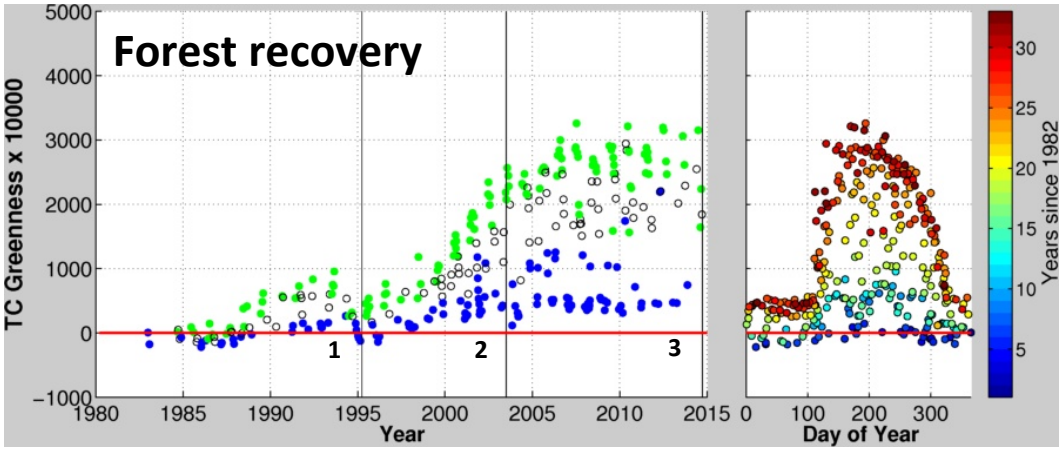


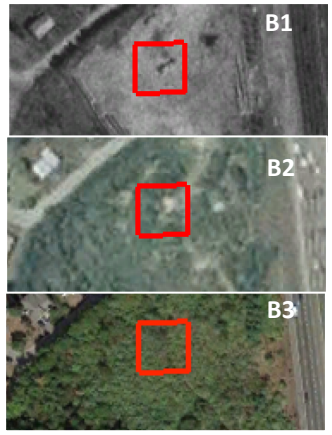


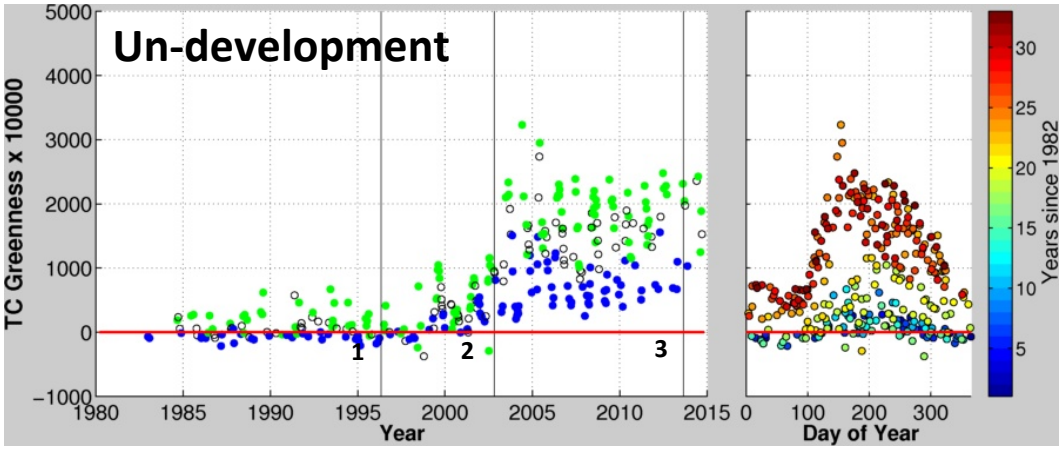


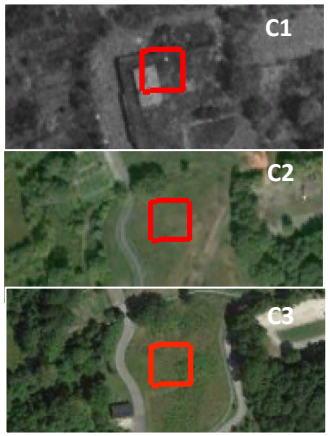


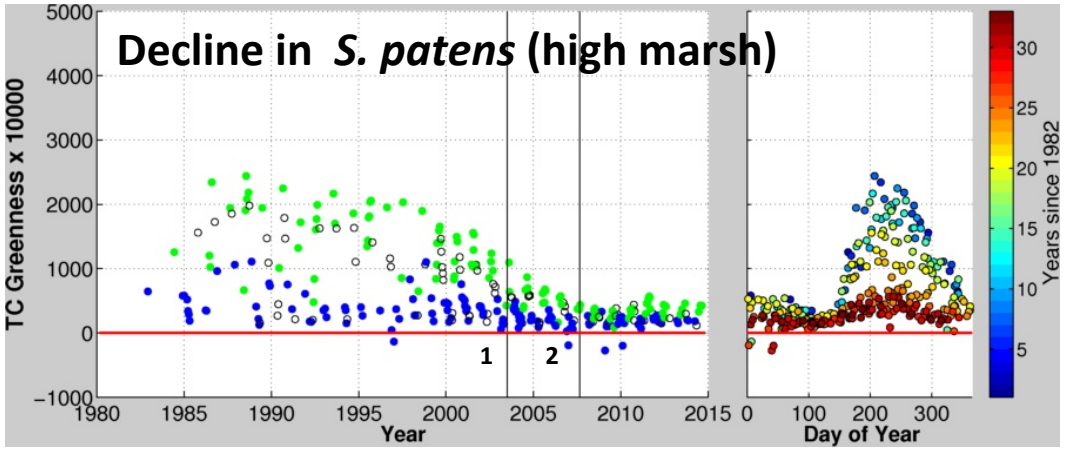
Gradual Change





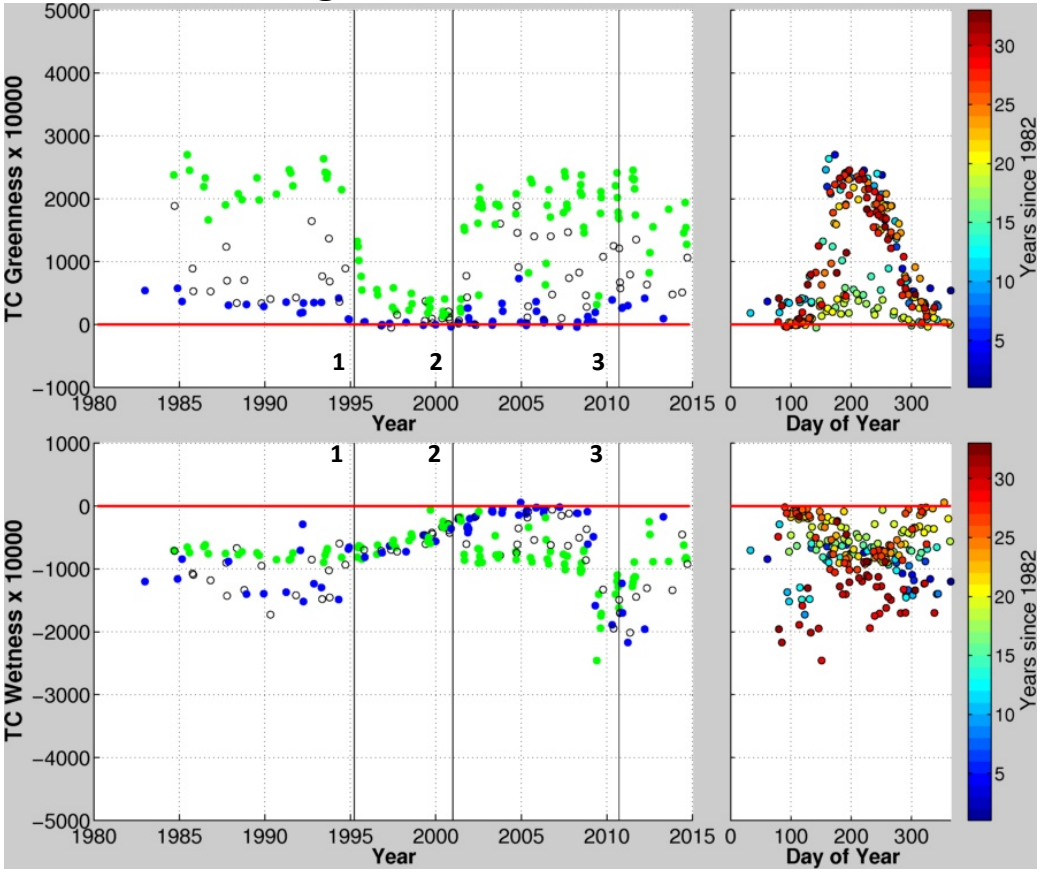


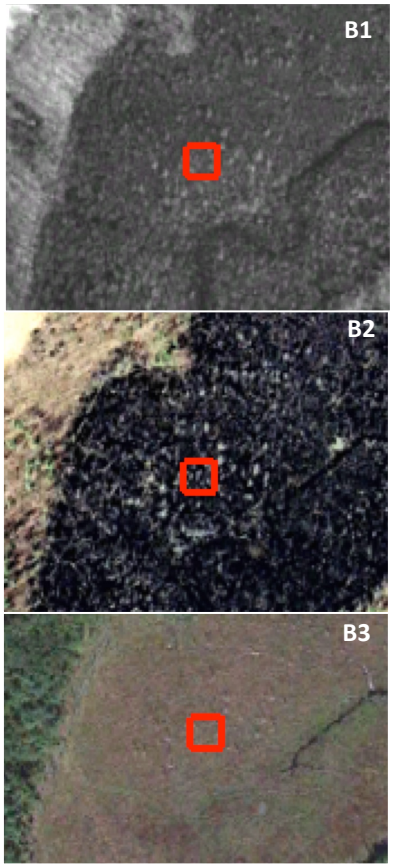




Change and Recovery

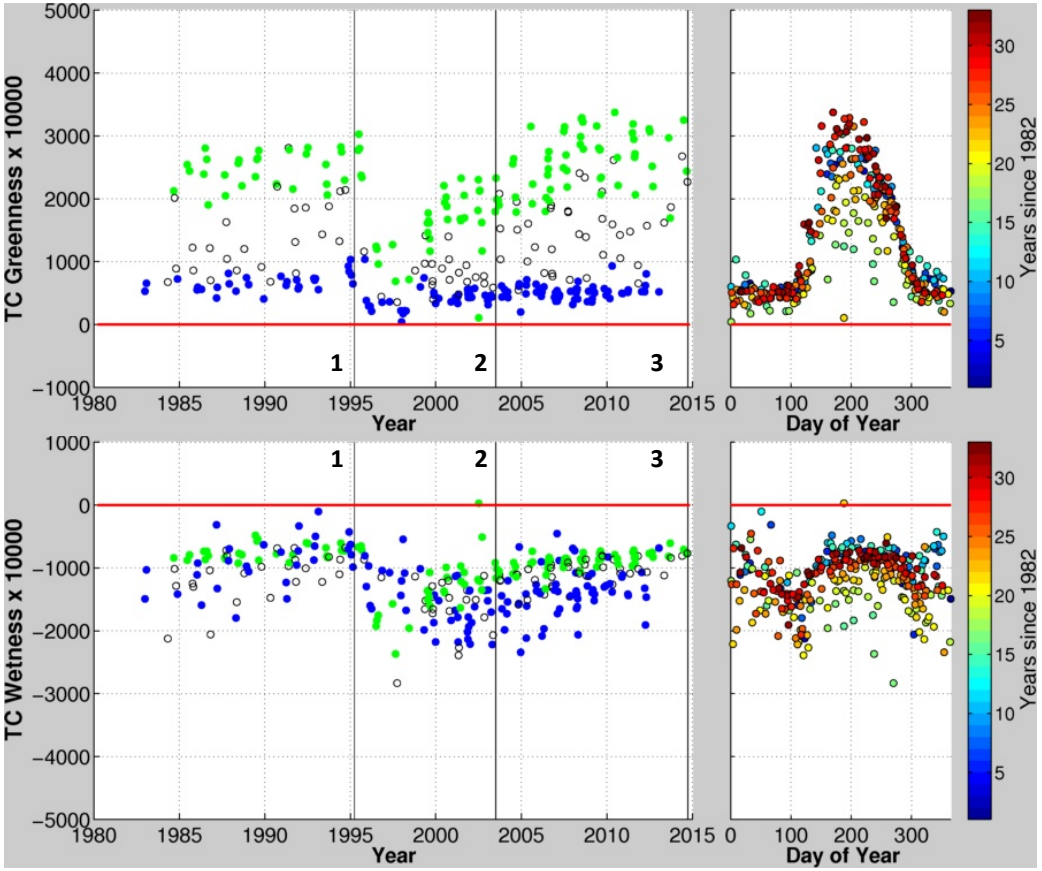
Beaver flooding and wetland succession

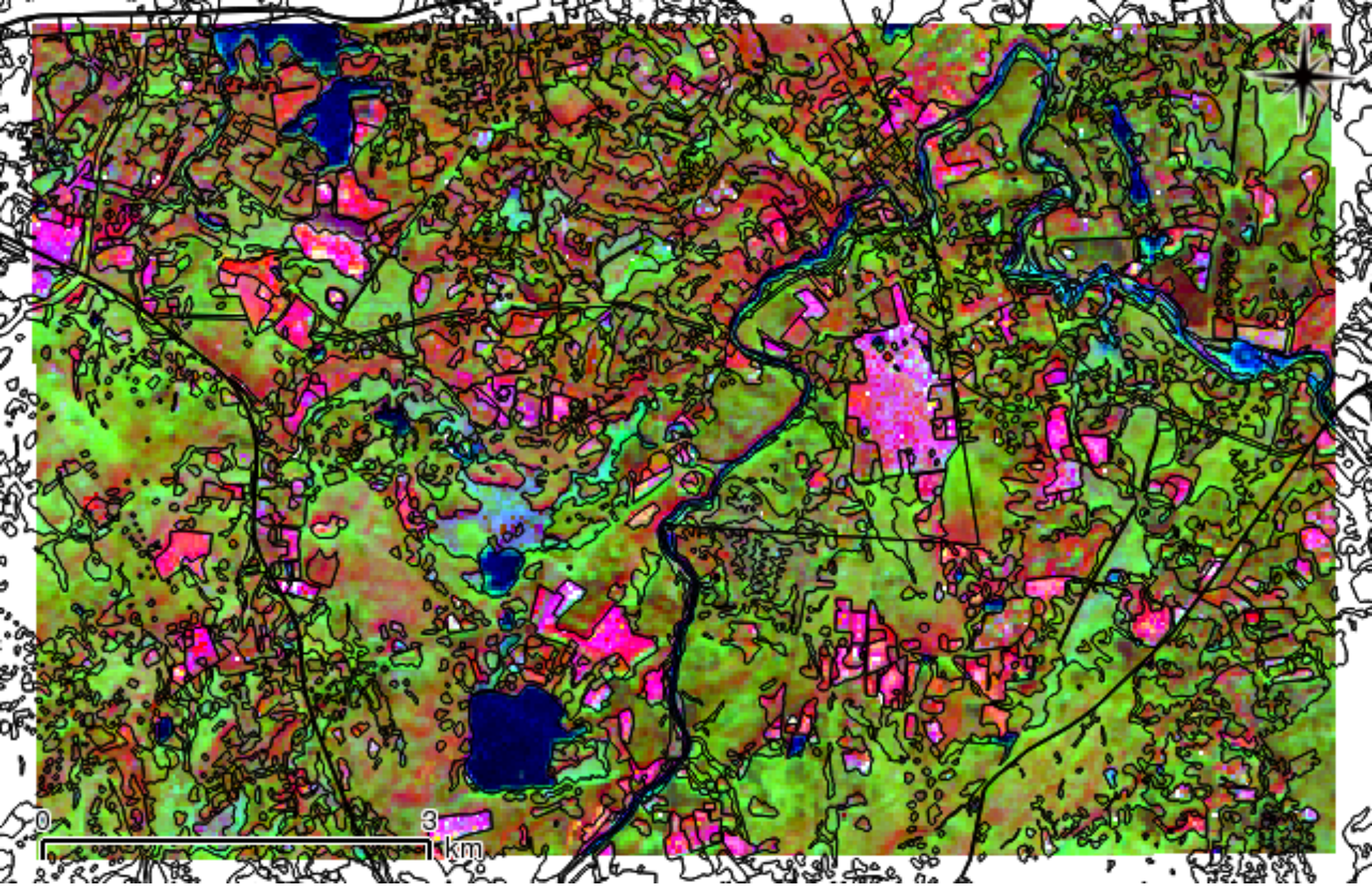




Change and Recovery

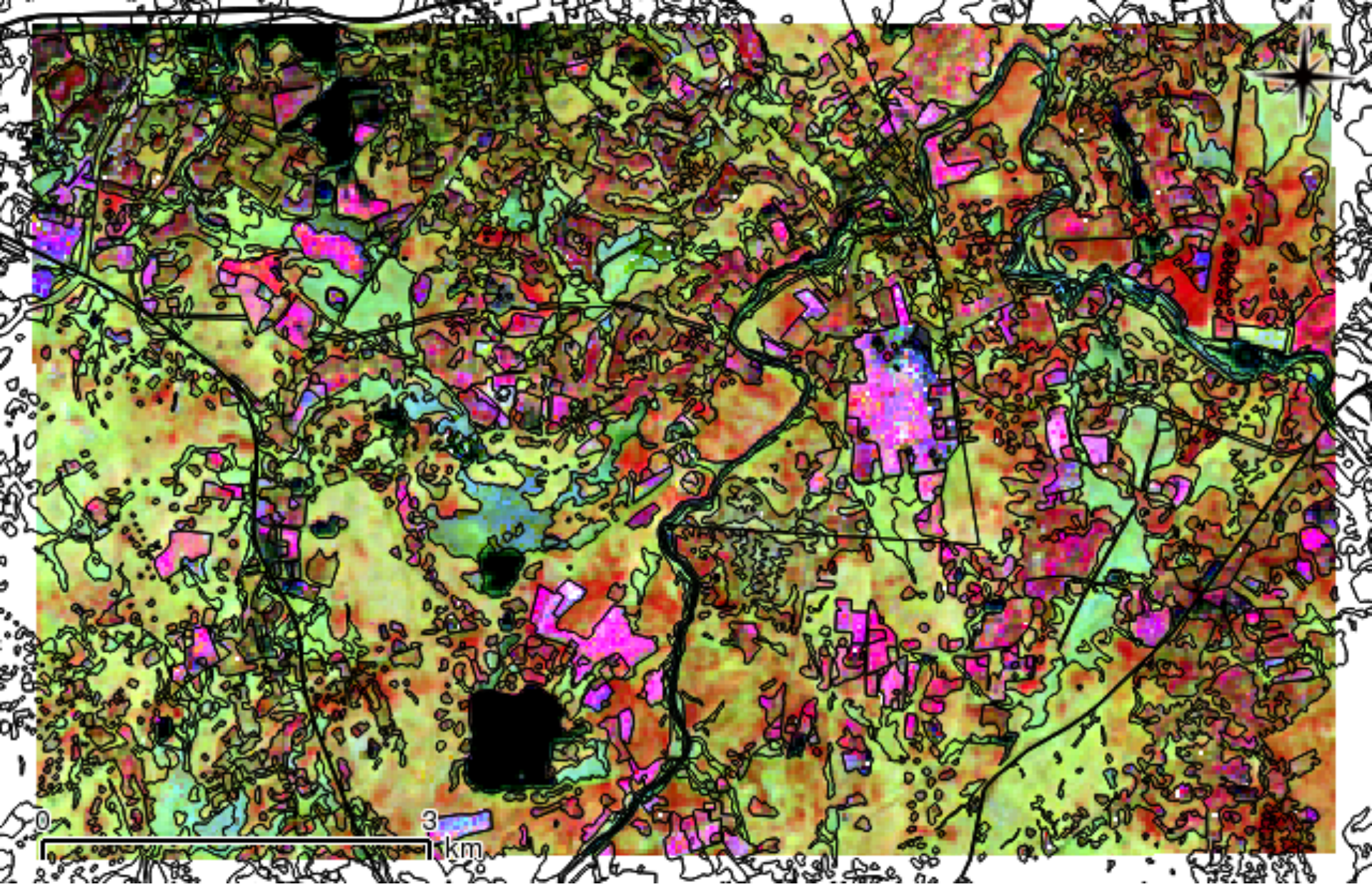
Failed development, forest succeeds





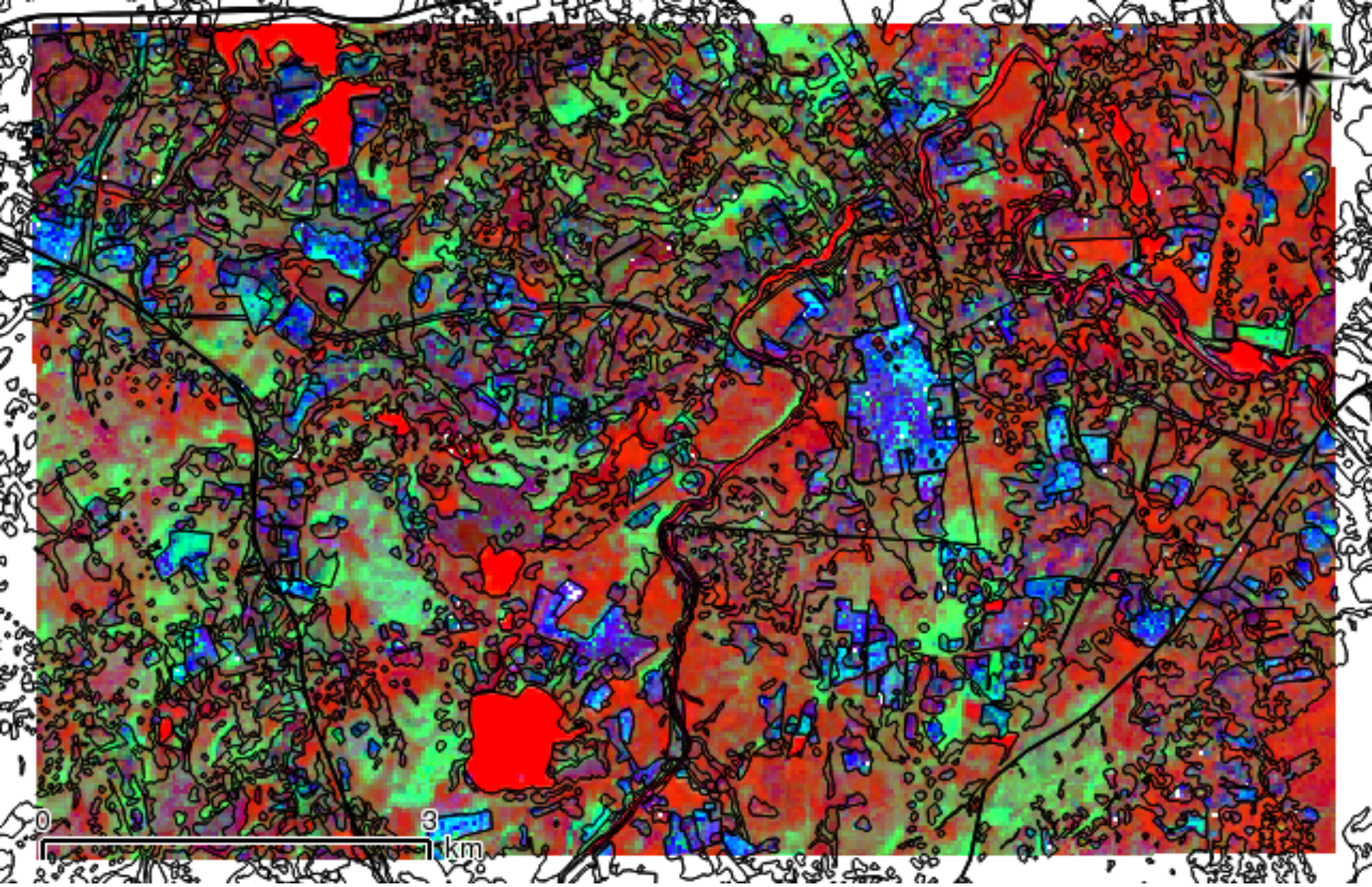
R – Intercept
G – Annual amplitude
B - RMSE

TC Brightness



R – Intercept
G – Annual amplitude
B - RMSE

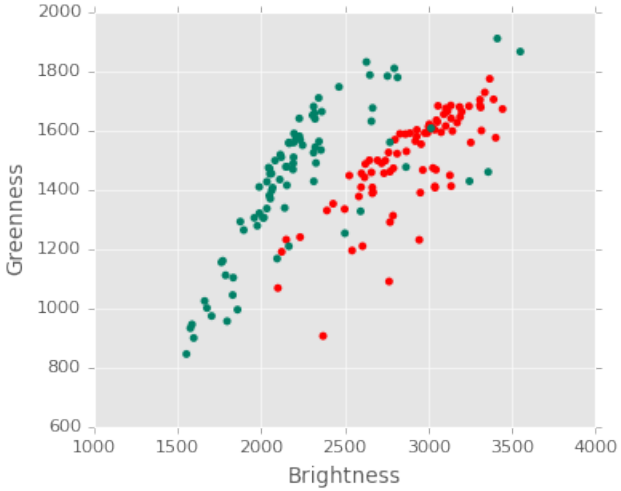
TC Greenness

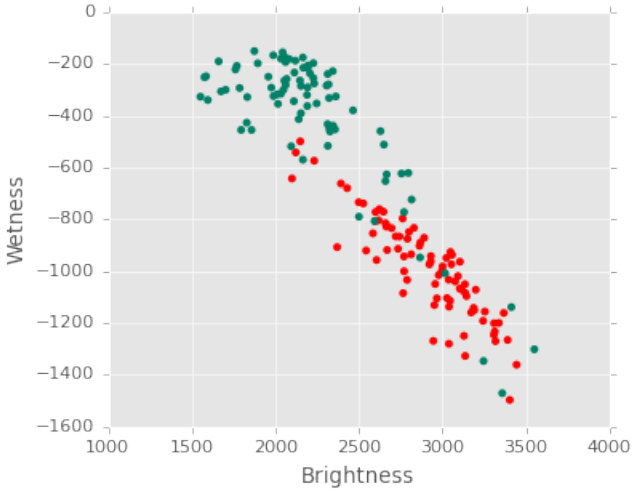


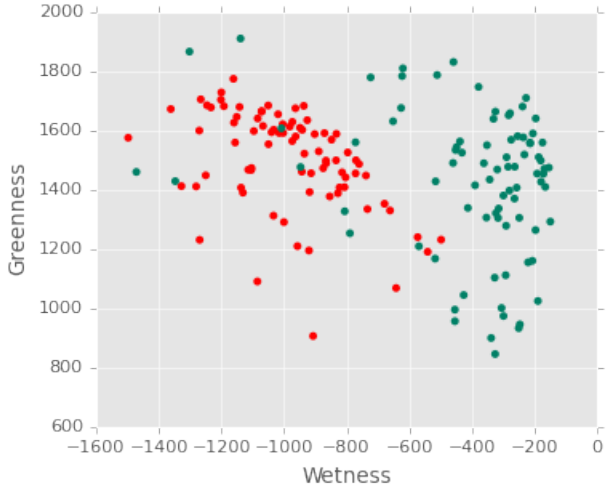
R – Intercept
G – Annual amplitude
B - RMSE

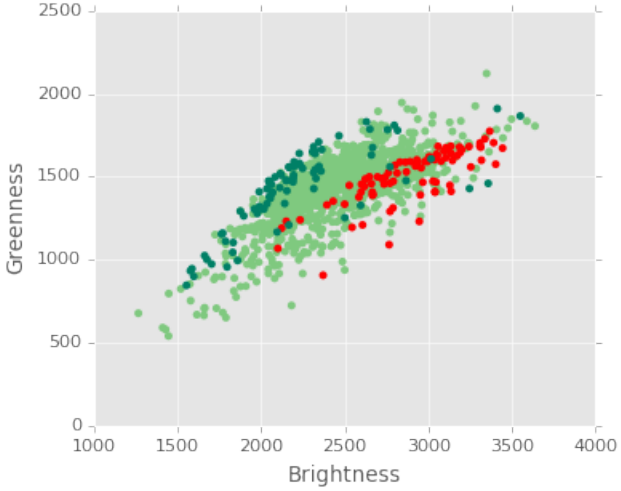
TC Wetness

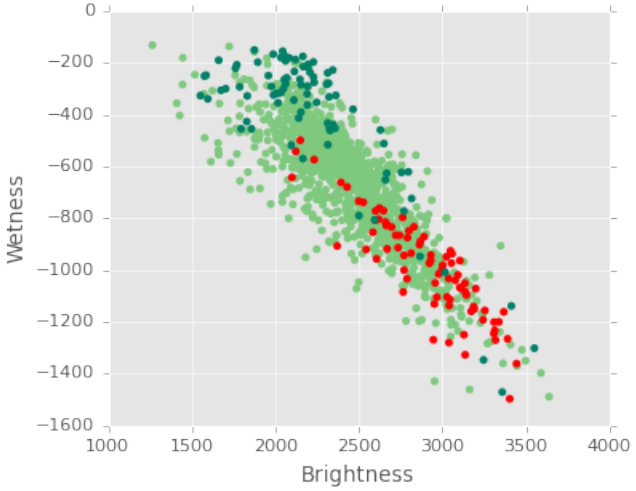
Intercept









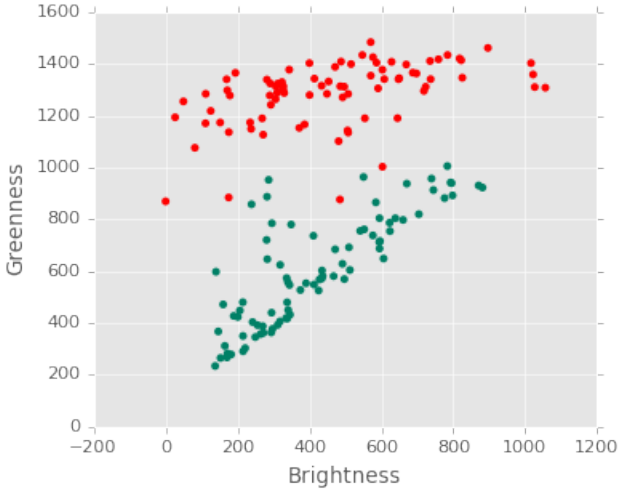


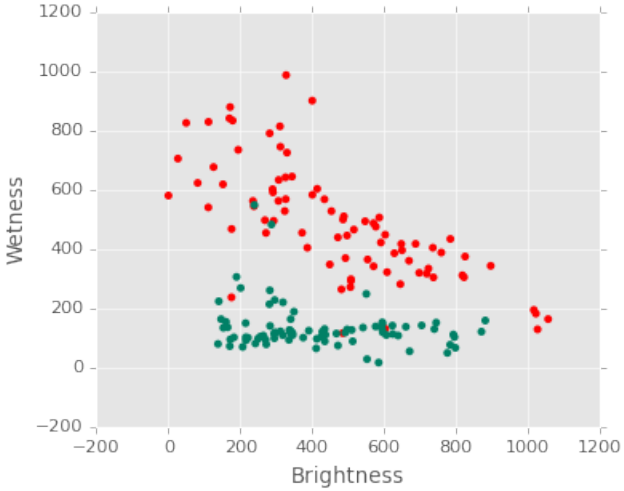
Oak

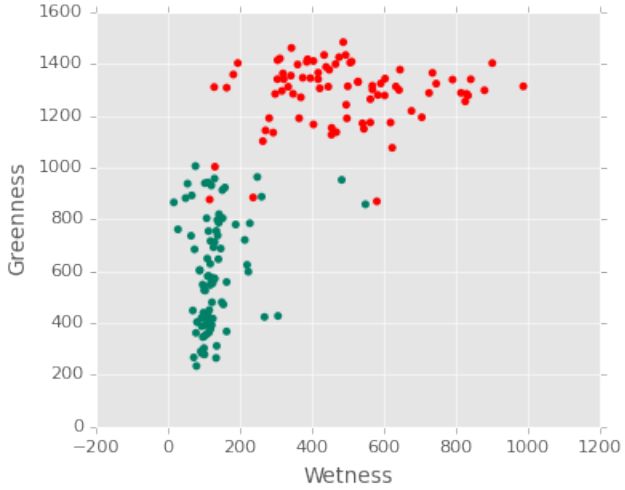
White Pine

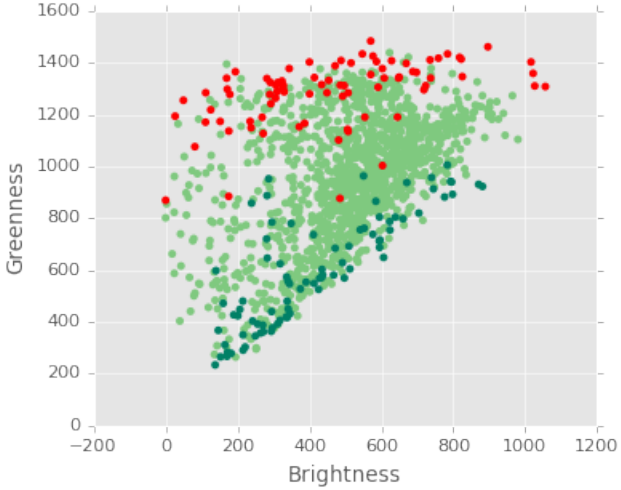
Mixed

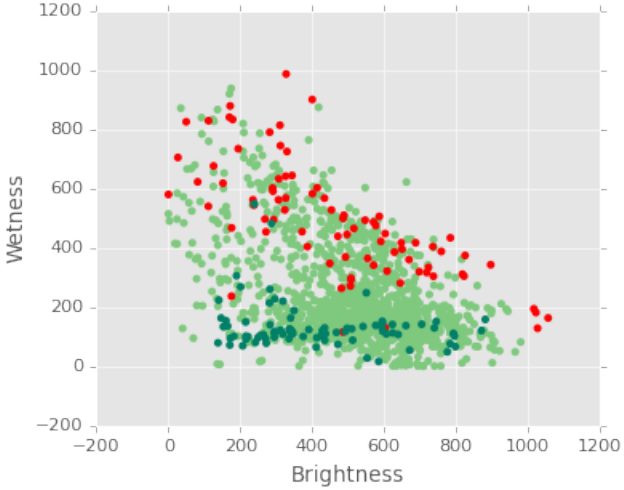
Annual Amplitude

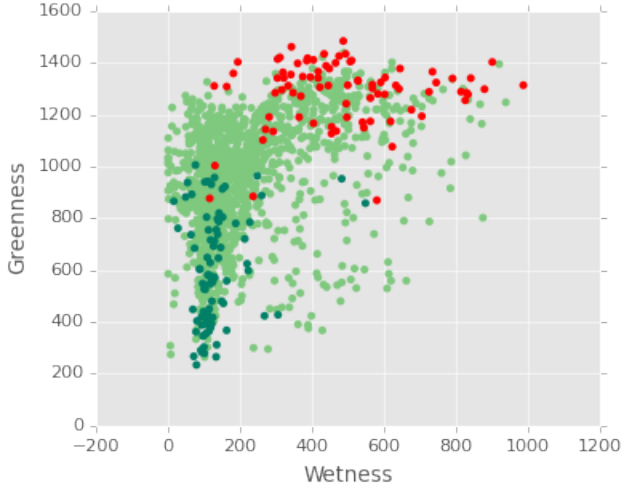










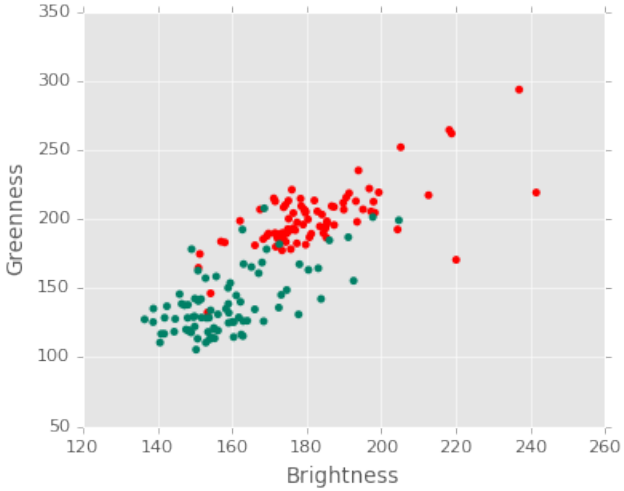


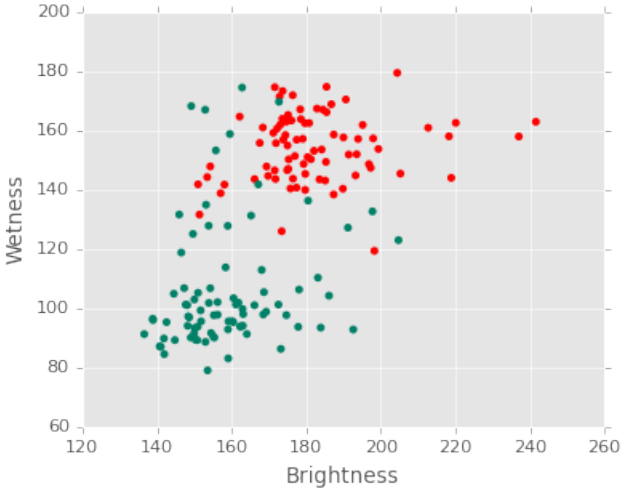
Oak

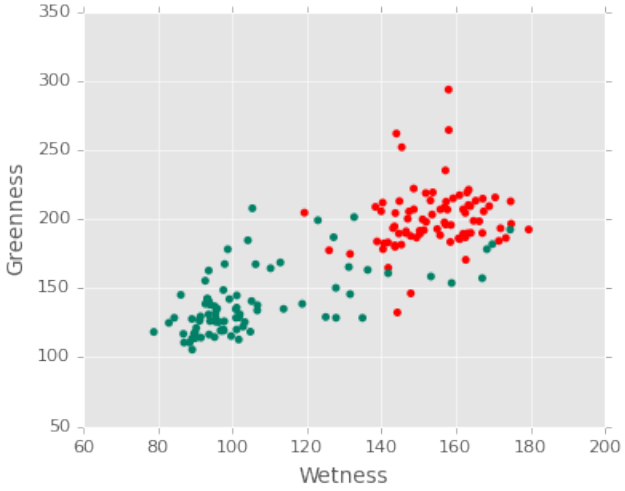
White Pine

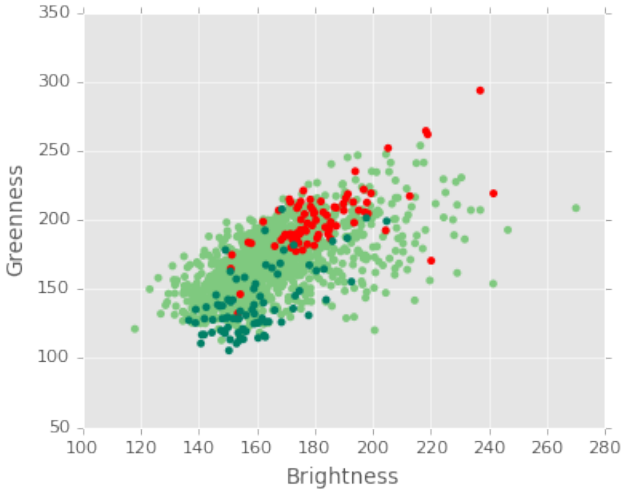
Mixed

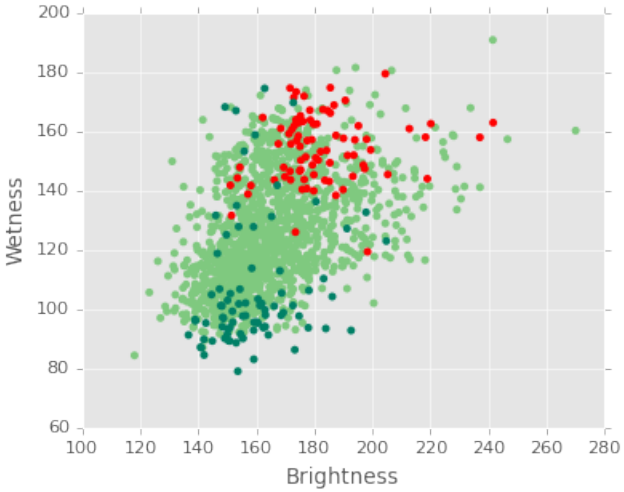
RMSE

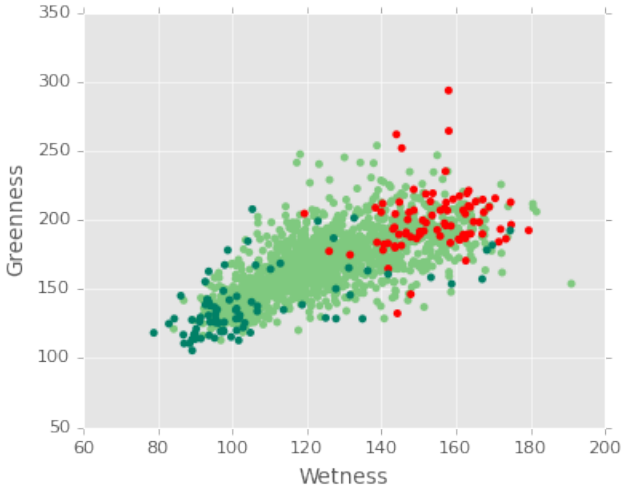












Oak

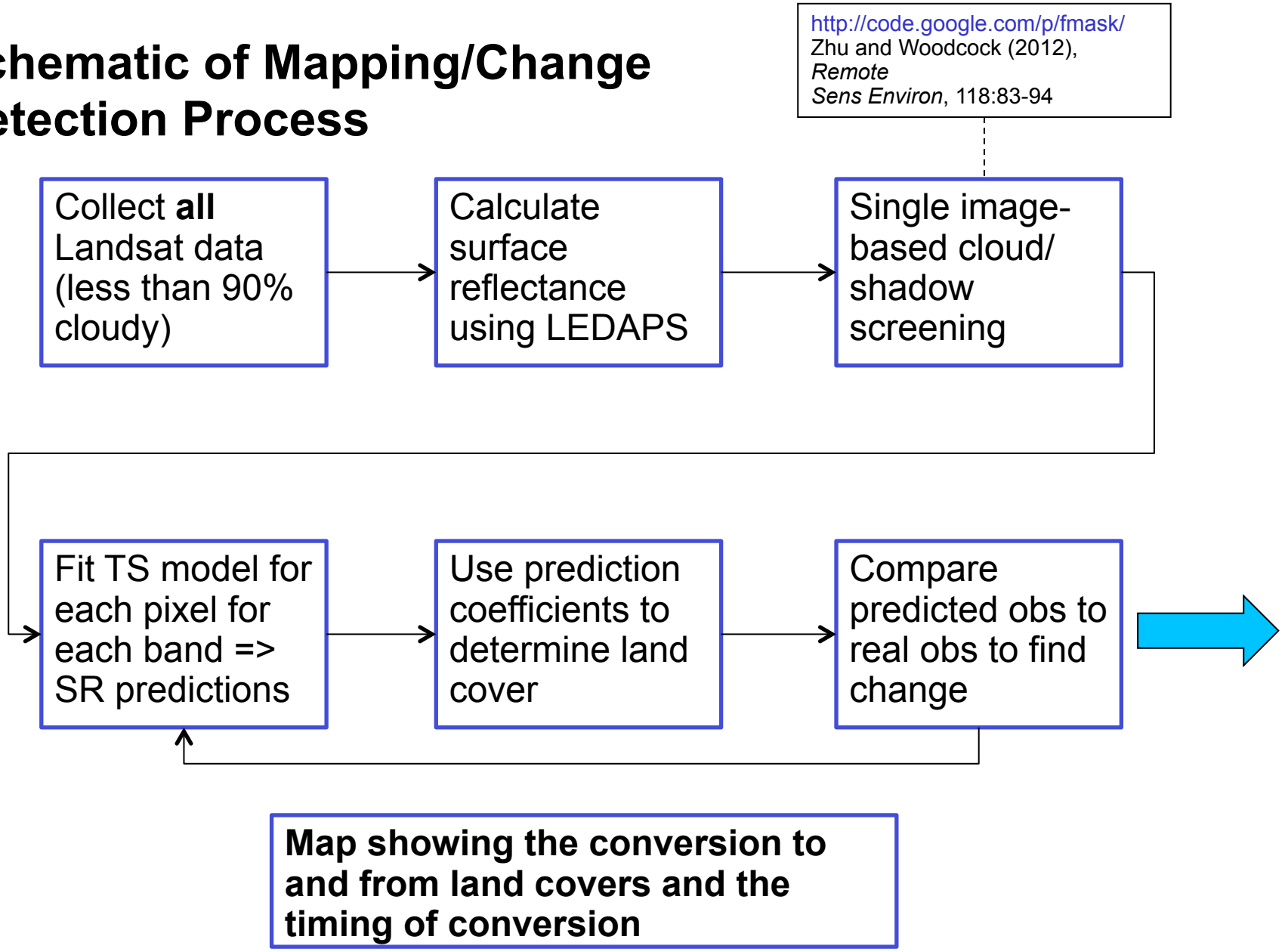
White Pine

Mixed

Continuous Change Detection and Classification (Zhu and Woodcock, RSE 2014)

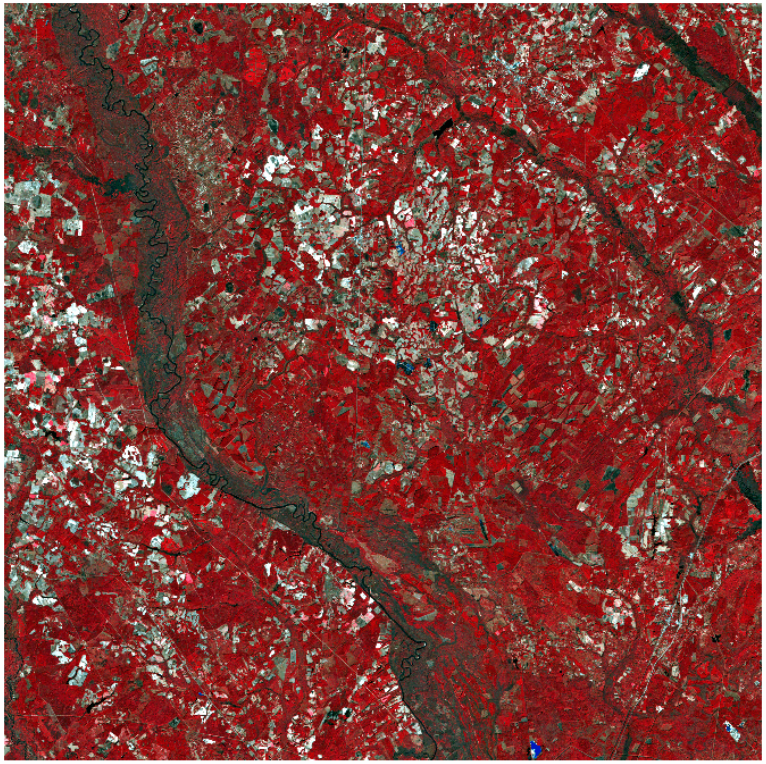
- Use all available Landsat Data, removing clouds, cloud shadows, and snowy observations
- Treat each pixel as a time series
- Fit empirical models (usually based on sinusoids) and compare new observations with those predicted by the existing time series model to find change
- Treat image data as noisy and require seeing change multiple consecutive times before mapping
- Result is maps for any time period that can be compared between time periods to find change

Schematic of Mapping/Change Detection Process

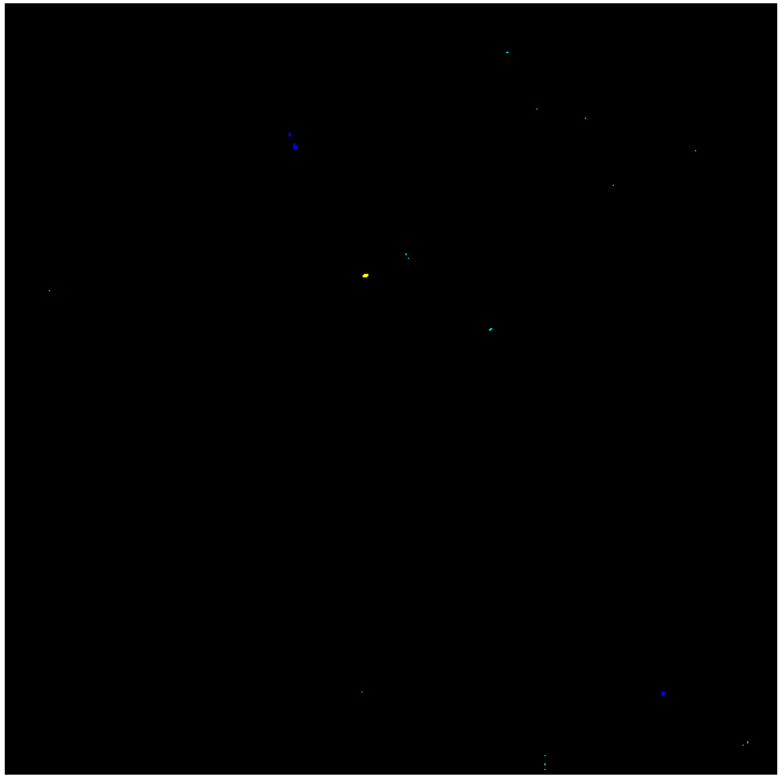


Zhu, Woodcock and Olofsson (2012), *Remote Sens Environ*, http://dx.doi.org/10.1016/j.rse.2011.10.030

2001/1/4 Landsat SR imagery

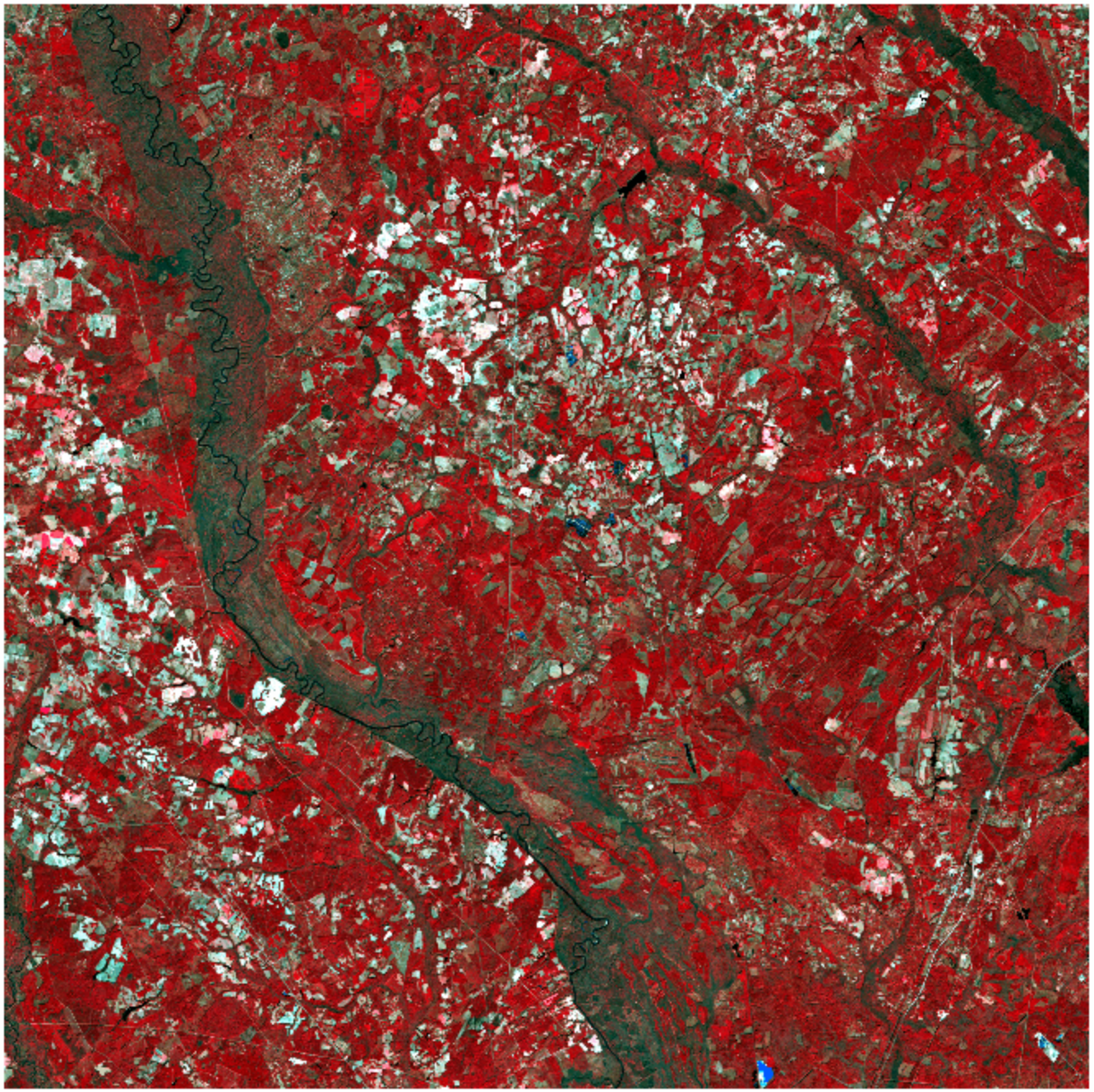


0.00305 percent of cloud cover



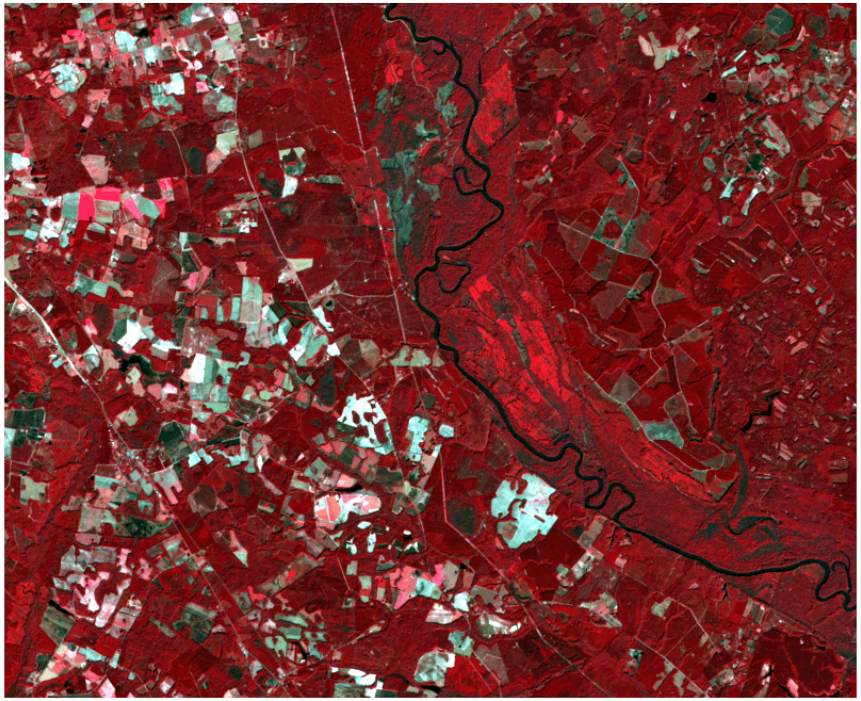
- Study area (all available Landsat ETM+ image from 2001 to 2002 with cloud cover less than 90%)

Predicted daily (1) Landsat SR imagery



8/18/16

Example of continuous monitoring of forest disturbance using all available Landsat images in 2003



2002/11/23 Landsat SR

2002/11/23 deforestation

Results of multi-date differencing
Testing unseen data

1. Spatial accuracies

Reference data				
Single-date differencing	Forest disturbance	Others	Total	User's (%)
Forest disturbance	**7653**	333	7985	95.83
Others	261	**242159**	242420	99.89
Total	7914	242492	250406	
Producer's (%)	96.70	99.86	Overall (%)	**99.76**

2. Temporal accuracy = 94%

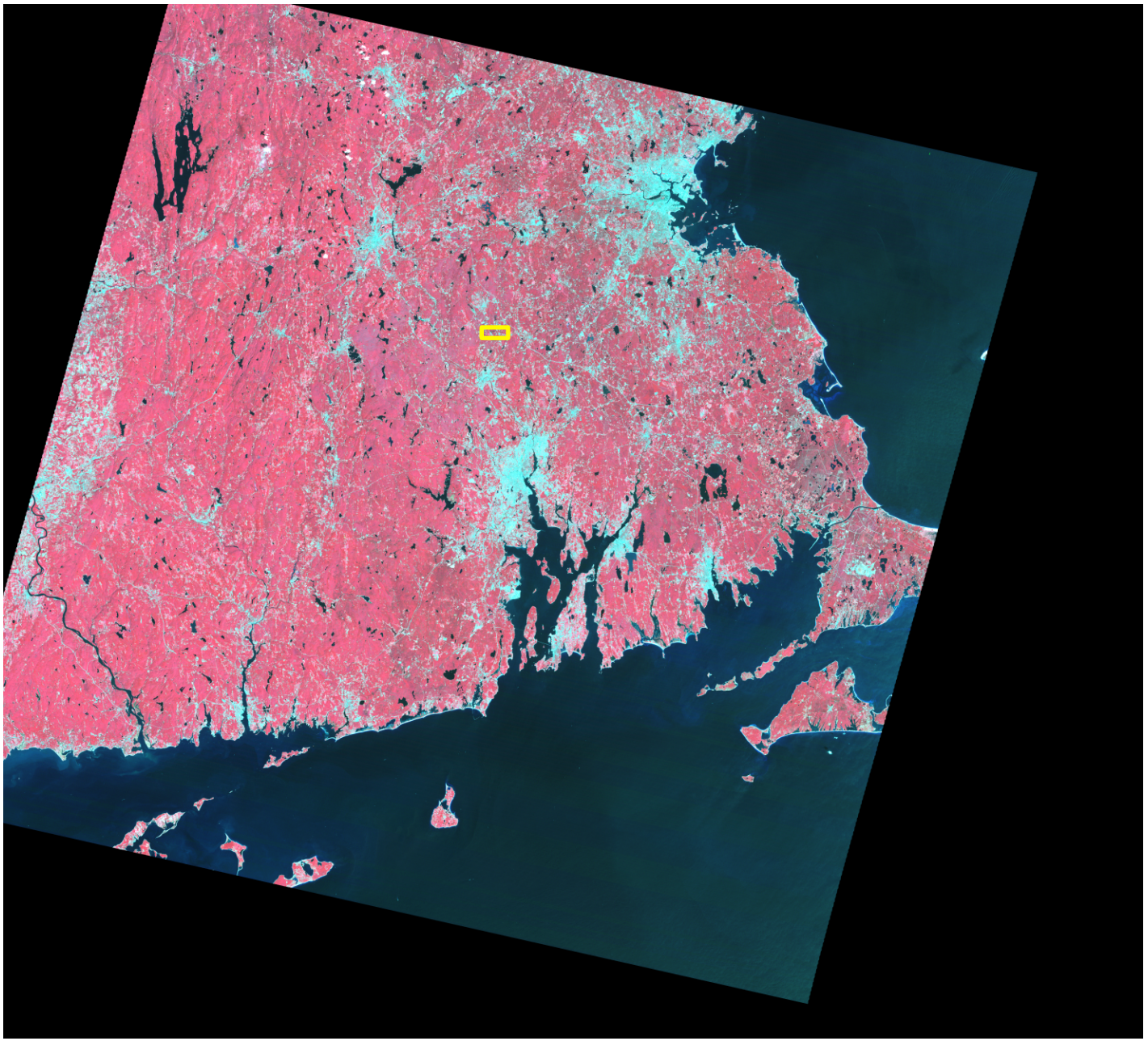
This table shows the confusion matrix for the accuracy assessment of the single-date differencing algorithm. The overall accuracy results are not terribly revealing, as after excluding the edges of the change polygons, the change pixels left are only about 3% of the total interpreted pixels.

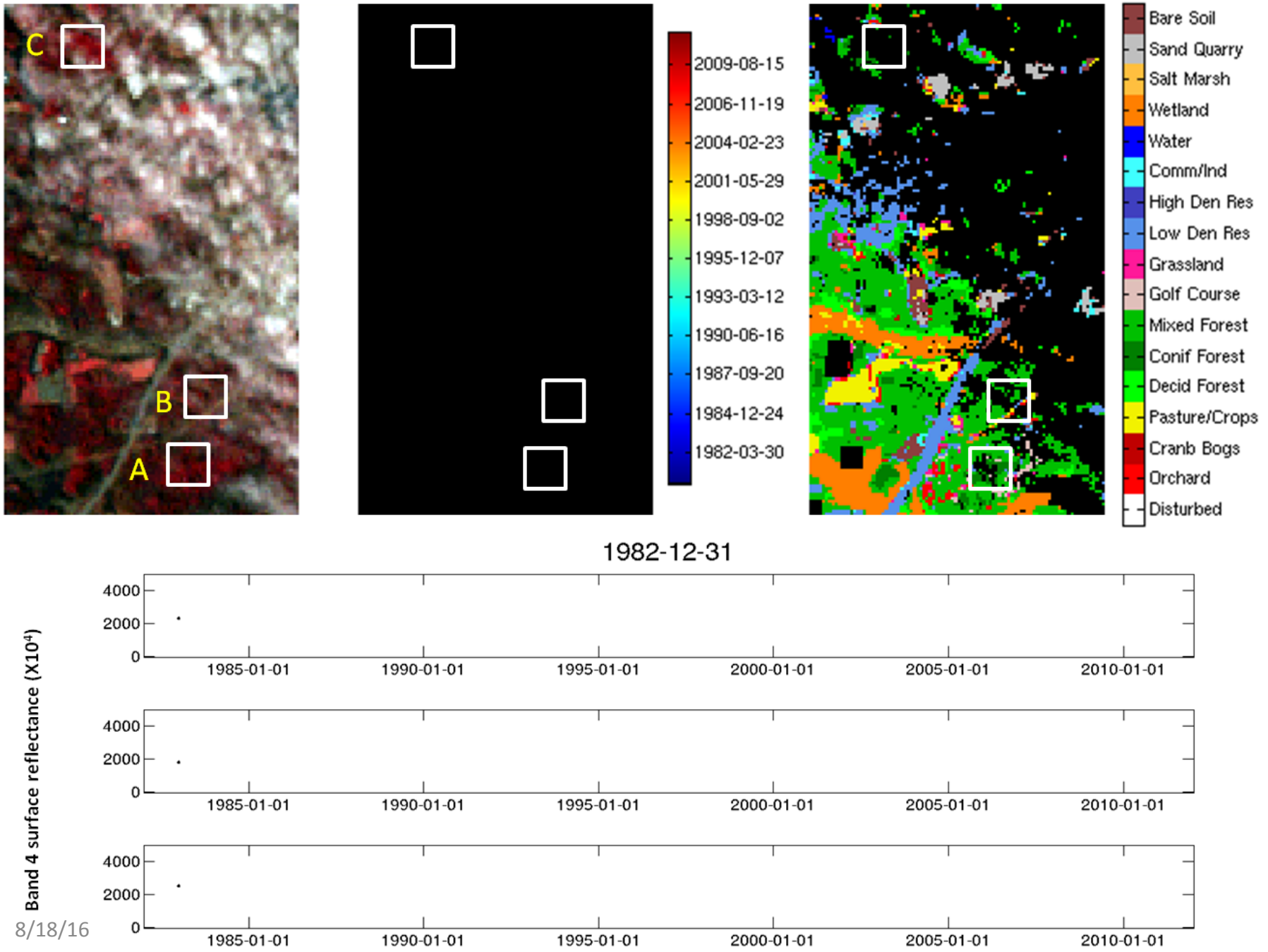
Zhu, Z., Woodcock, C. E., and Olofsson, P., 2012. Continuous Monitoring of Forest Disturbance Using All Available Landsat Imagery, *Remote Sensing of Environment*, 122:75-91.

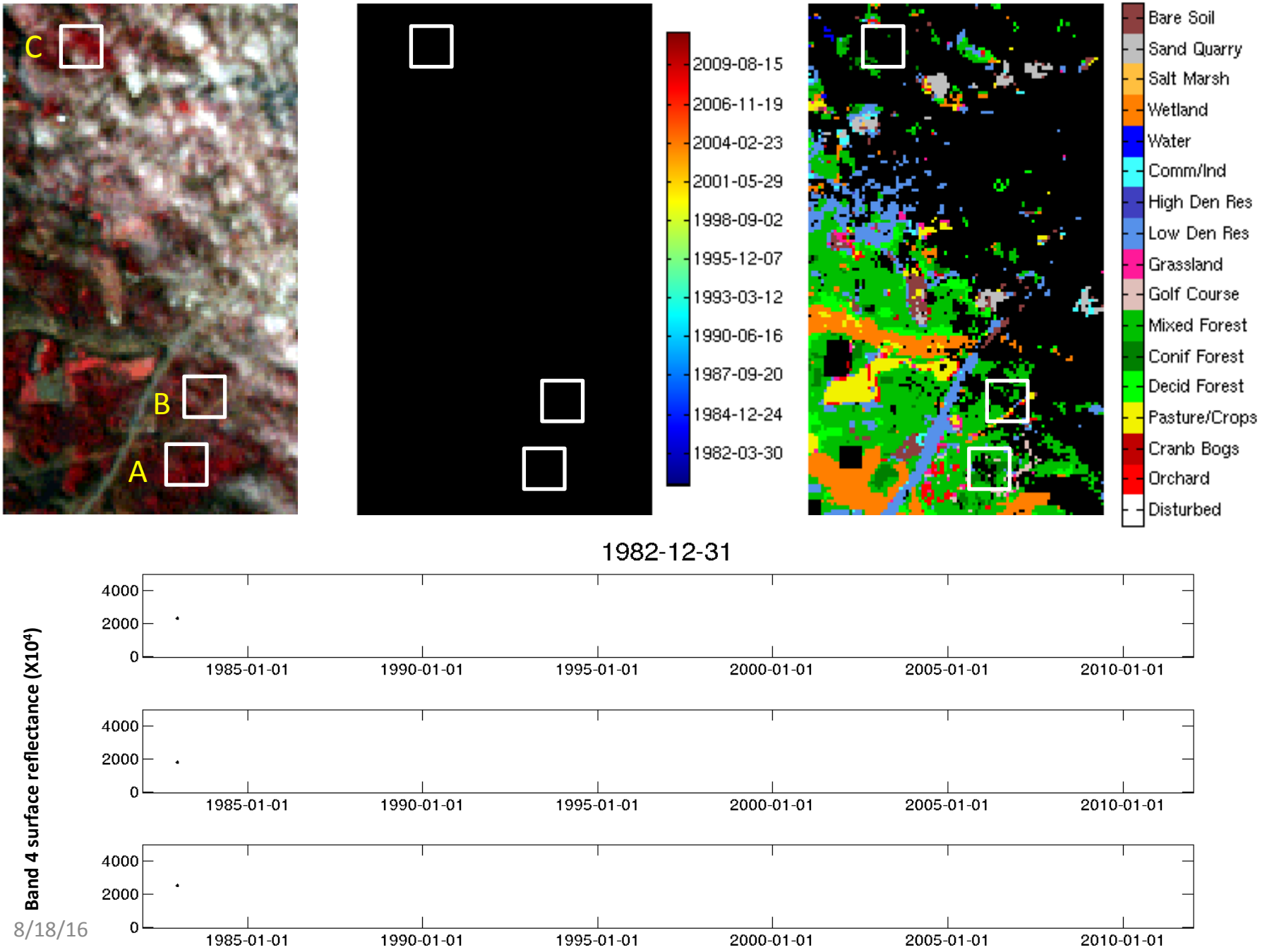
Continuous land cover classification and change detection: An example

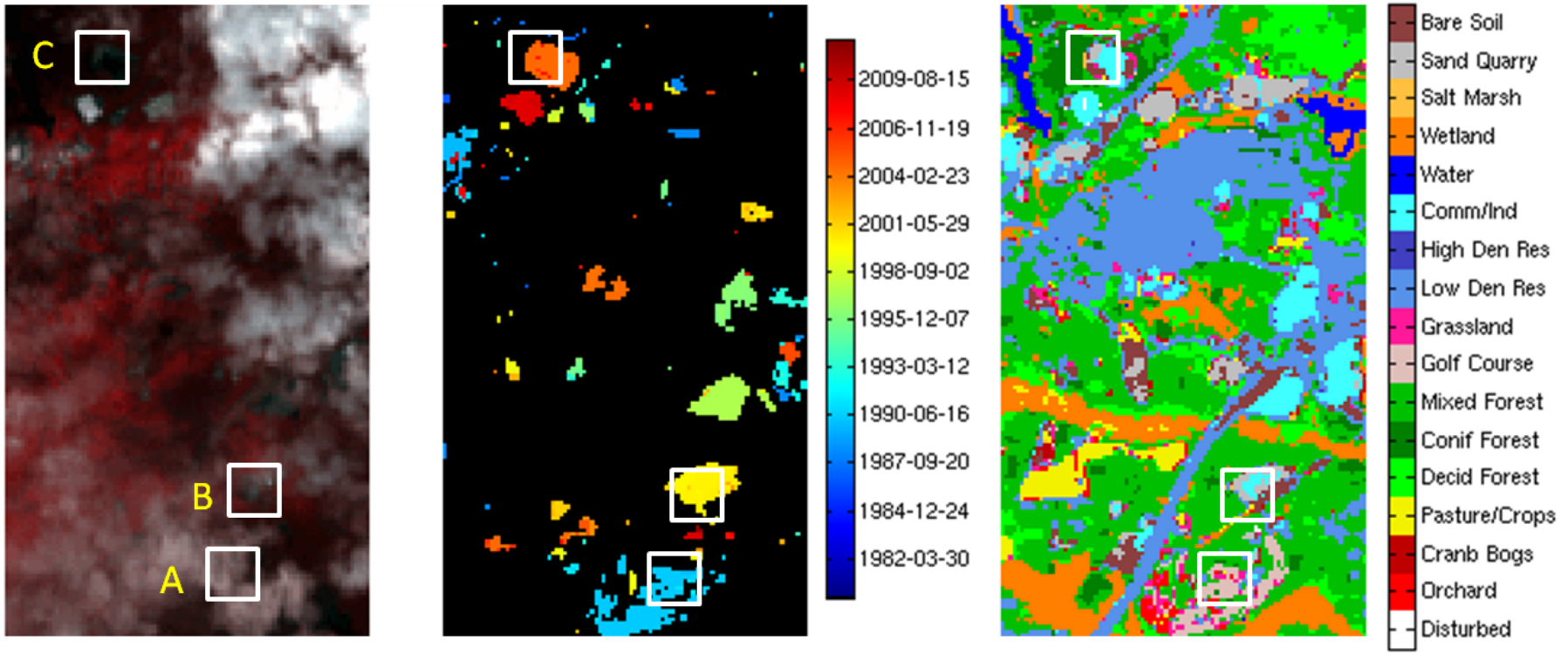
- We processed a total of 532 Landsat TM/ETM+ images for path 12 row 31 at Eastern Massachusetts started from 1982 to 2011.
- Land cover changes are detected continuously using all spectral bands.
- The type of land cover for each curve are classified using the parameters of the time series model.

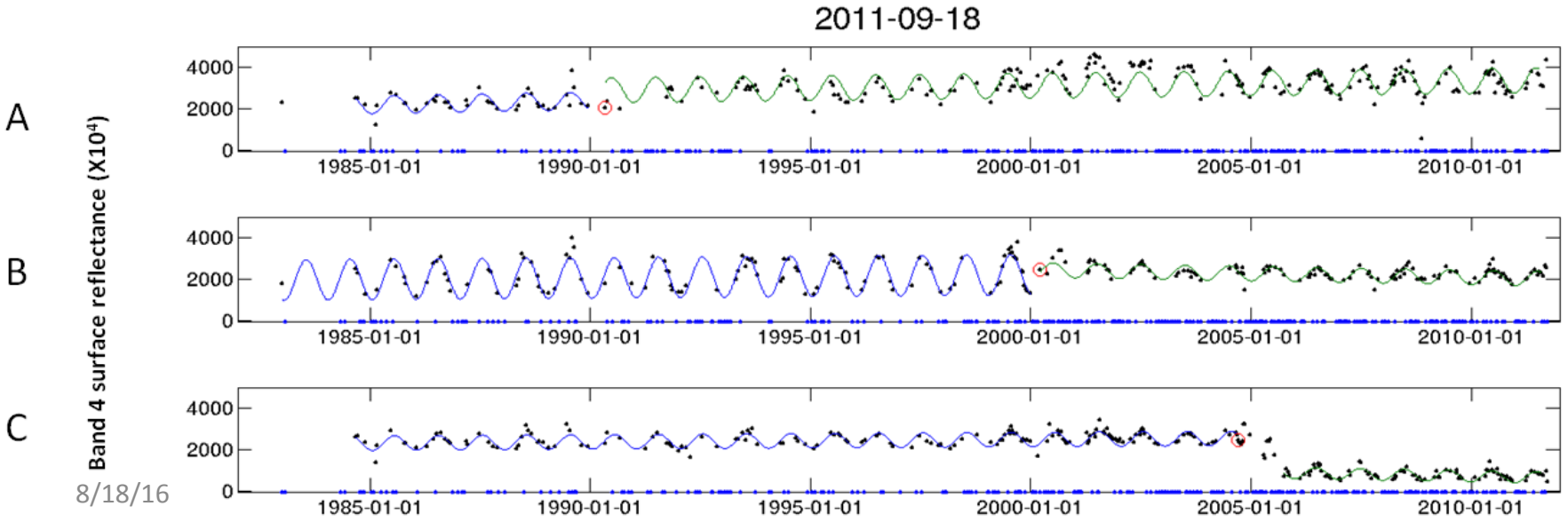
Massachusetts, Sept. 7th 1984, Path/Row =12/31, Band 4, 3, and 2 composite



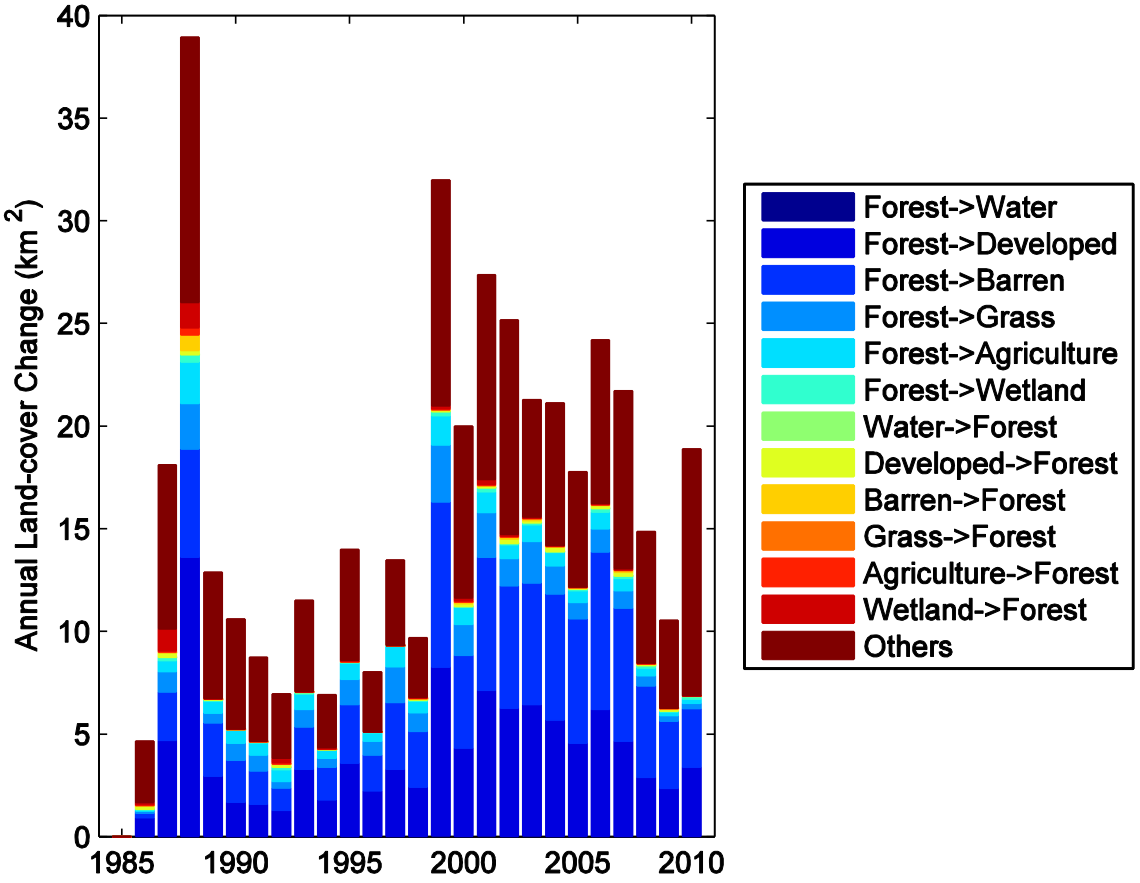

Landsat surface reflectance
Land cover change map
Land cover classification map
C
B
A
2009-08-15
2006-11-19
2004-02-23
2001-05-29
1998-09-02
1995-12-07
1993-03-12
1990-06-16
1987-09-20
1984-12-24
1982-03-30
Bare Soil
Sand Quarry
Salt Marsh
Wetland
Water
Comm/Ind
High Den Res
Low Den Res
Grassland
Golf Course
Mixed Forest
Conif Forest
Decid Forest
Pasture/Crops
Cranb Bogs
Orchard
Disturbed
1982-12-31
A
B
C
Band 4 surface reflectance (X10⁴)
4000
2000
0
1985-01-01
1990-01-01
1995-01-01
2000-01-01
2005-01-01
2010-01-01


Landsat surface reflectance
Land cover change map
Land cover classification map
C
B
A
2009-08-15
2006-11-19
2004-02-23
2001-05-29
1998-09-02
1995-12-07
1993-03-12
1990-06-16
1987-09-20
1984-12-24
1982-03-30
Bare Soil
Sand Quarry
Salt Marsh
Wetland
Water
Comm/Ind
High Den Res
Low Den Res
Grassland
Golf Course
Mixed Forest
Conif Forest
Decid Forest
Pasture/Crops
Cranb Bogs
Orchard
Disturbed
1982-12-31
A
B
C
Band 4 surface reflectance (X10⁴)
4000
2000
0
1985-01-01
1990-01-01
1995-01-01
2000-01-01
2005-01-01
2010-01-01


Landsat surface reflectance
Land cover change map
Land cover classification map
C
B
A
2009-08-15
2006-11-19
2004-02-23
2001-05-29
1998-09-02
1995-12-07
1993-03-12
1990-06-16
1987-09-20
1984-12-24
1982-03-30
Bare Soil
Sand Quarry
Salt Marsh
Wetland
Water
Comm/Ind
High Den Res
Low Den Res
Grassland
Golf Course
Mixed Forest
Conif Forest
Decid Forest
Pasture/Crops
Cranb Bogs
Orchard
Disturbed


2011-09-18
A
B
C
Band 4 surface reflectance (X10⁴)
4000
2000
0
1985-01-01
1990-01-01
1995-01-01
2000-01-01
2005-01-01
2010-01-01

Boston Scene Annual Land Cover Change Histogram

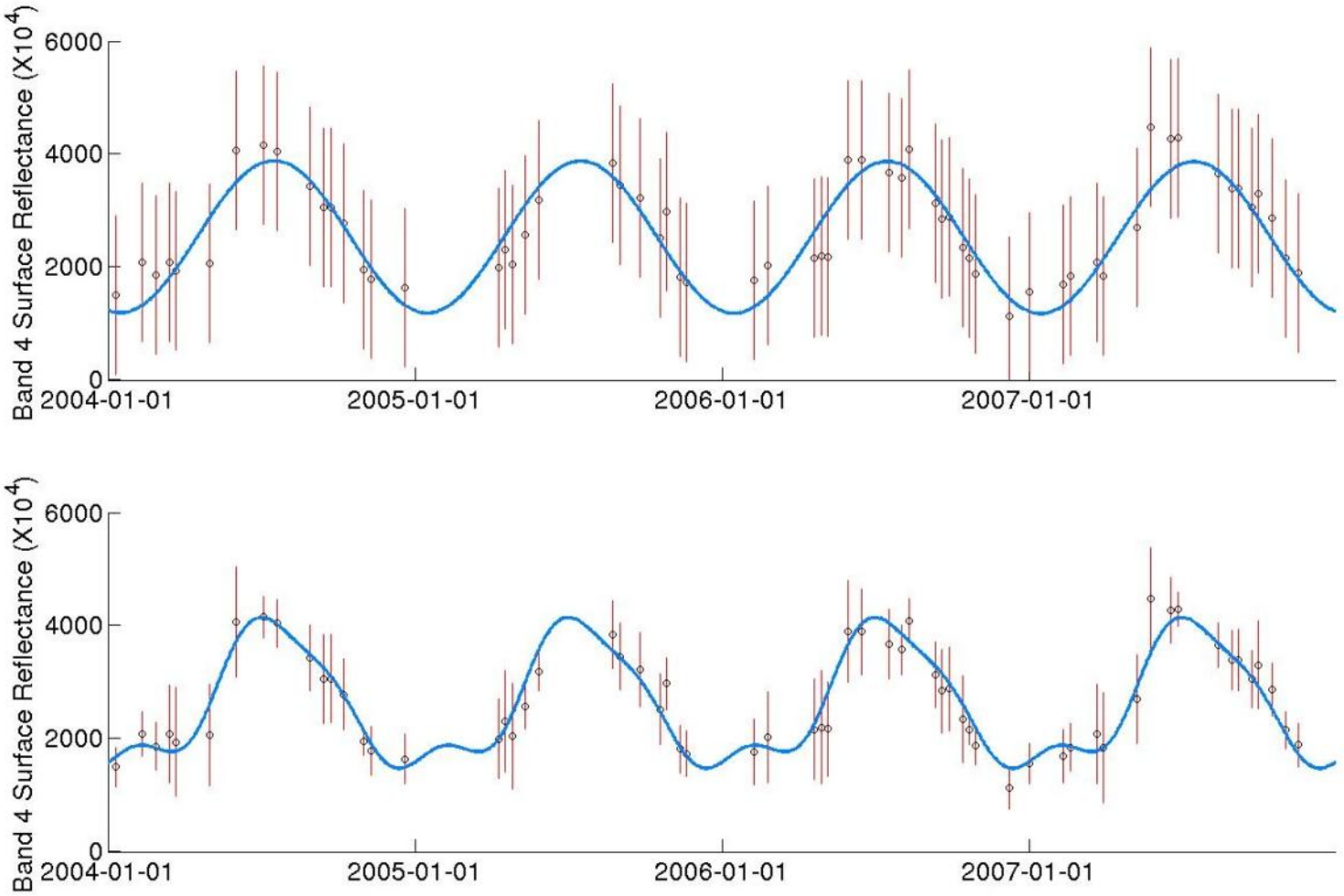


Algorithm refinements

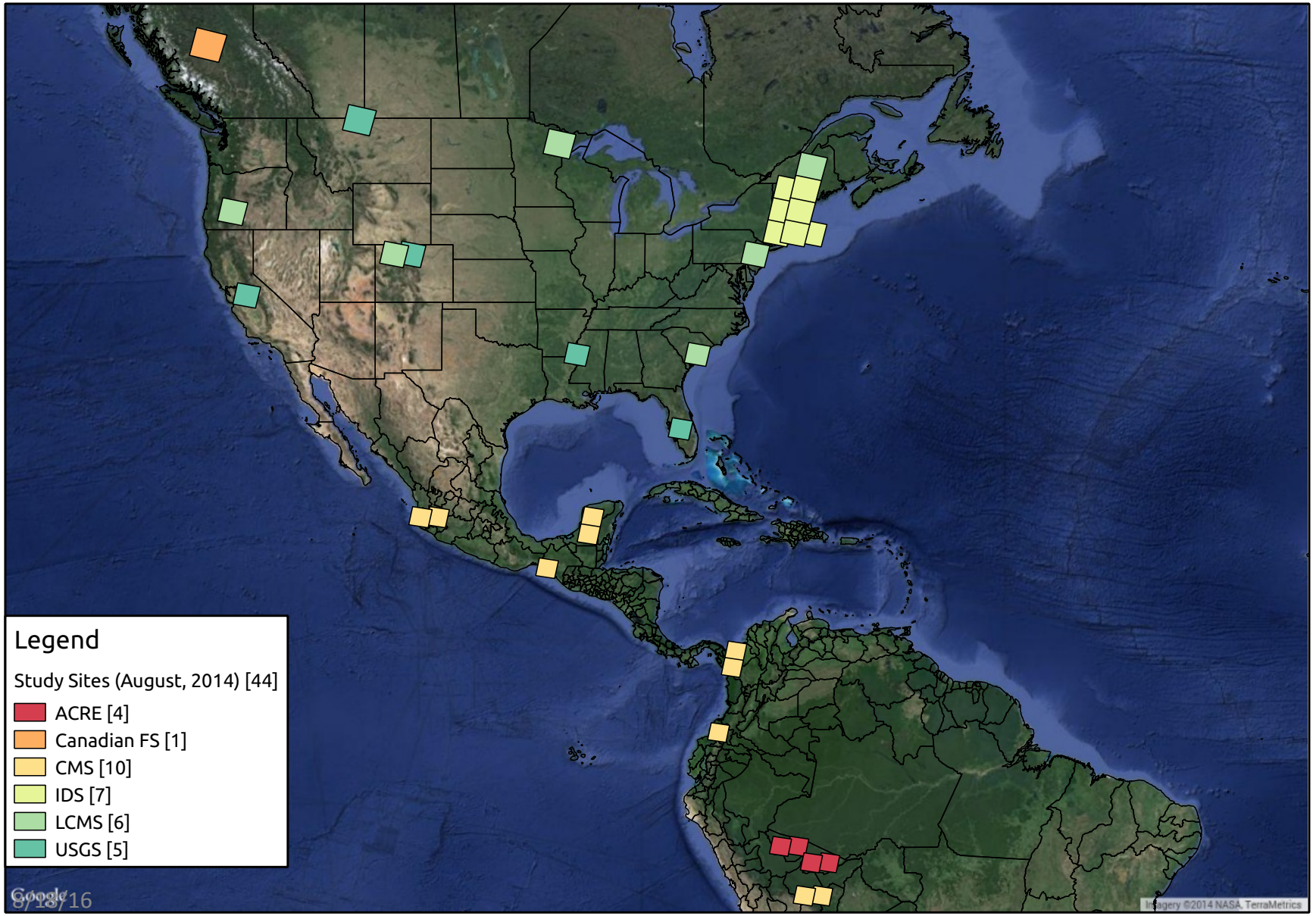
More coefficients

Temporally varying thresholds

LASSO fit

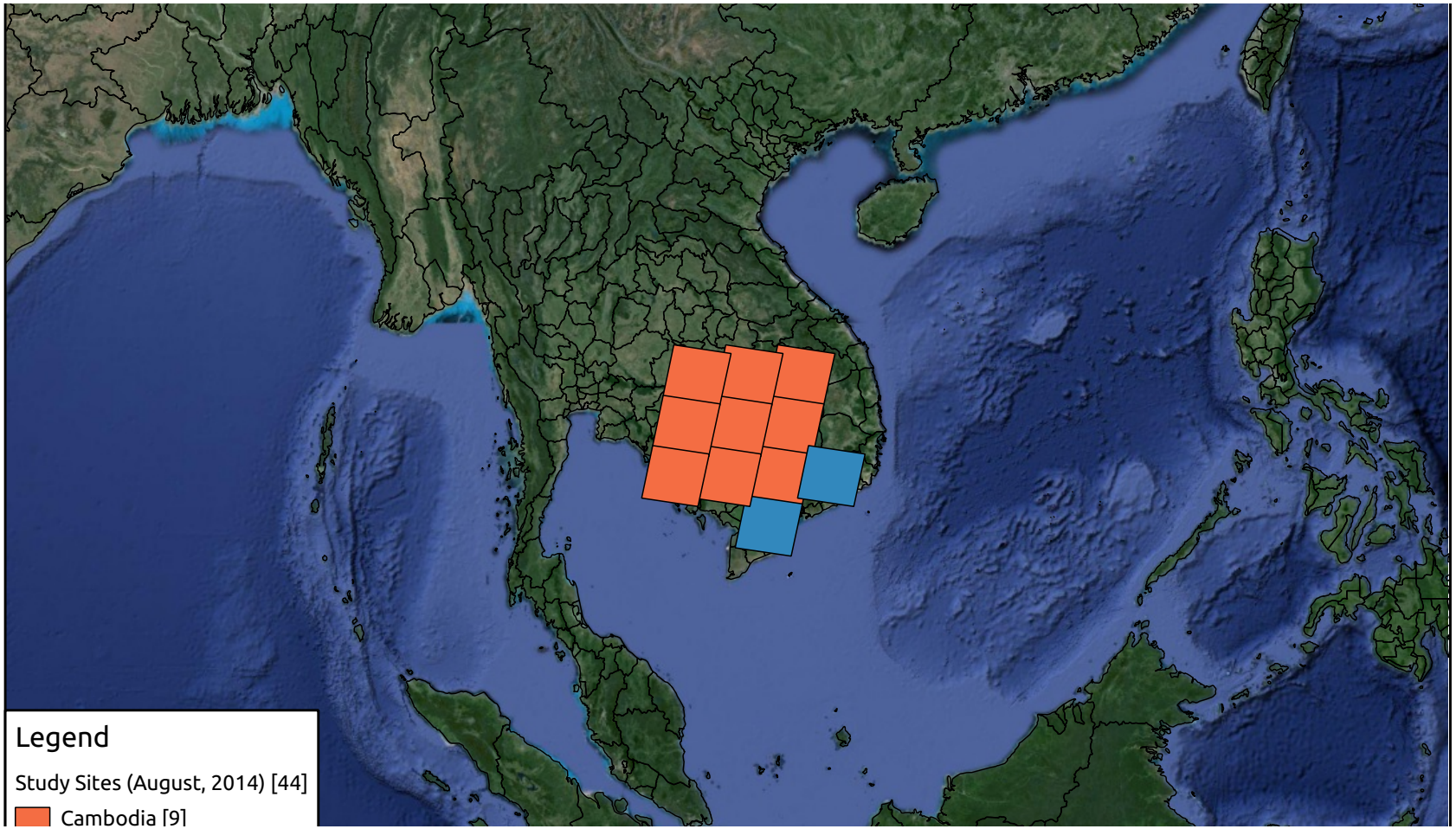


Study areas in western hemisphere

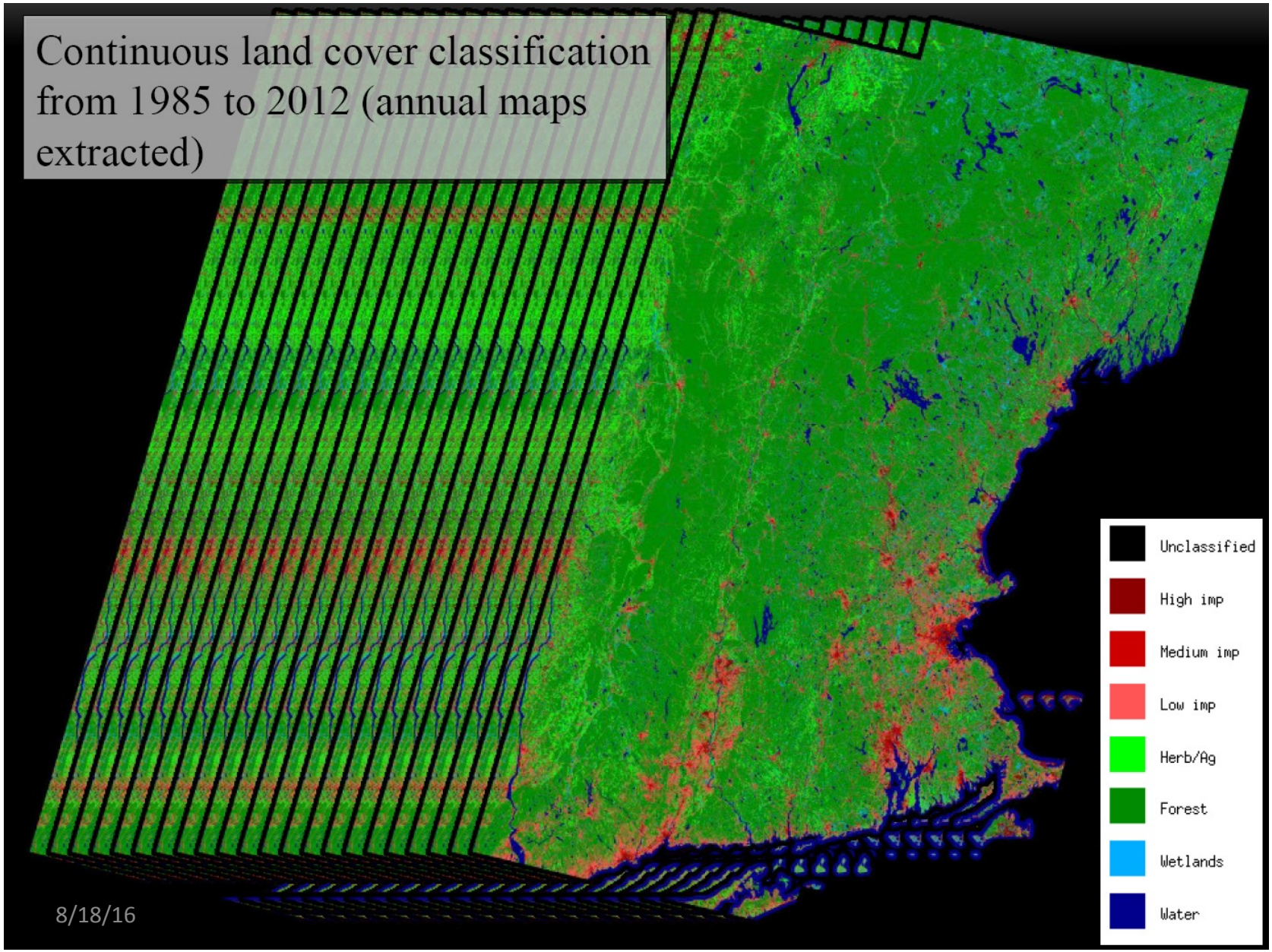


Chris Holden - August 11, 2014

Study Areas in SE Asia



Test in a variety of environments



Mapped land categories, IDS map of NE

Stable categories

- Unclassified* (0.30%)
- High/Medium Imp. (4.1%)
- Low Impervious (8.9%)
- Herb/Ag (8.4%)
- Forest (61%)
- Wetlands (5.4%)
- Water (5.9%)

Change categories

- Forest → High/Medium Imp. (0.51%)
- Forest → Low Imp. (0.53%)
- Forest → Other (0.96%)
- Forest → Forest (3%)
- Herb/Ag → Forest (0.15%)
- Other → Forest (0.49%)

*The area of this stratum should be allocated to the other strata and thus have an accuracy and estimated area of zero

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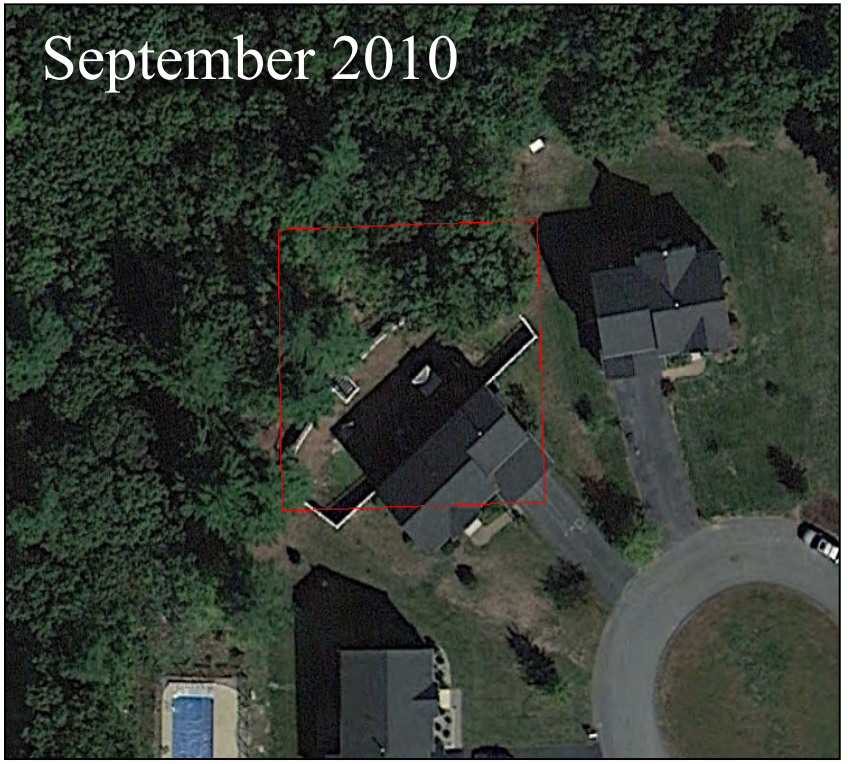
Mixed forest partly cleared for residential development in June 2001.



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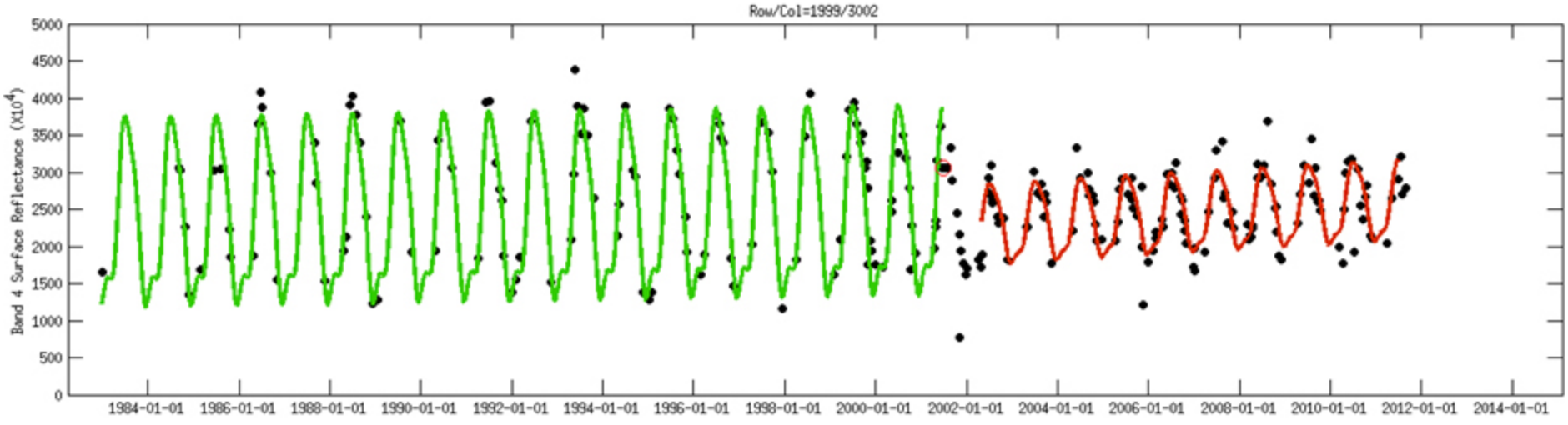
Prediction model applied with predictions classified by land cover



Mixed Forest

Low Density Residential

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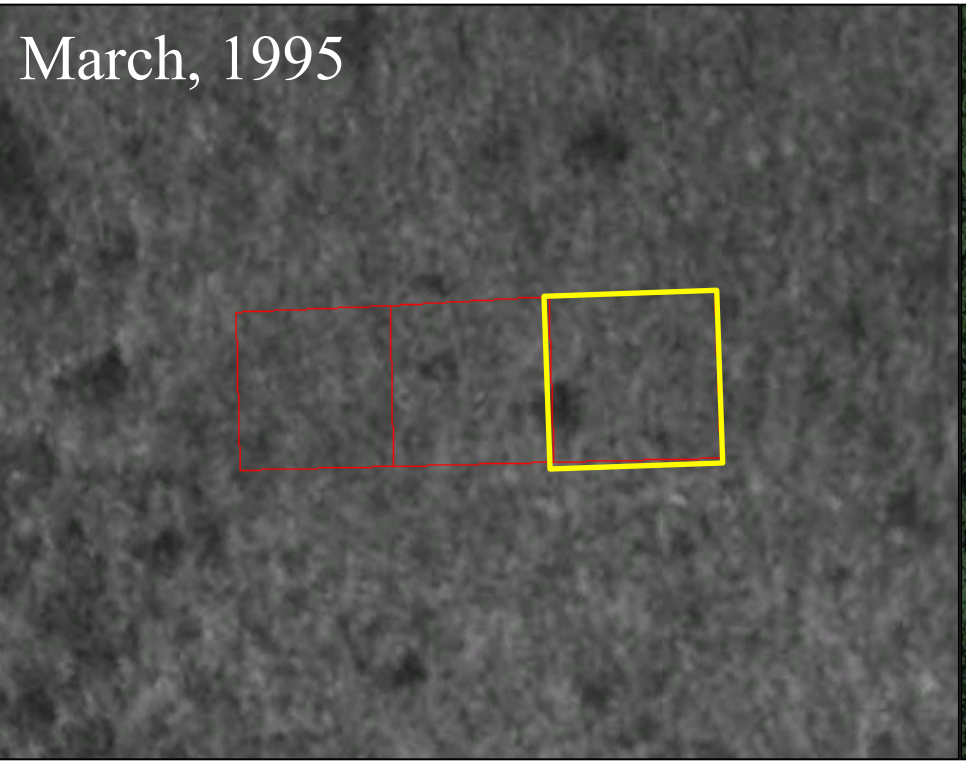
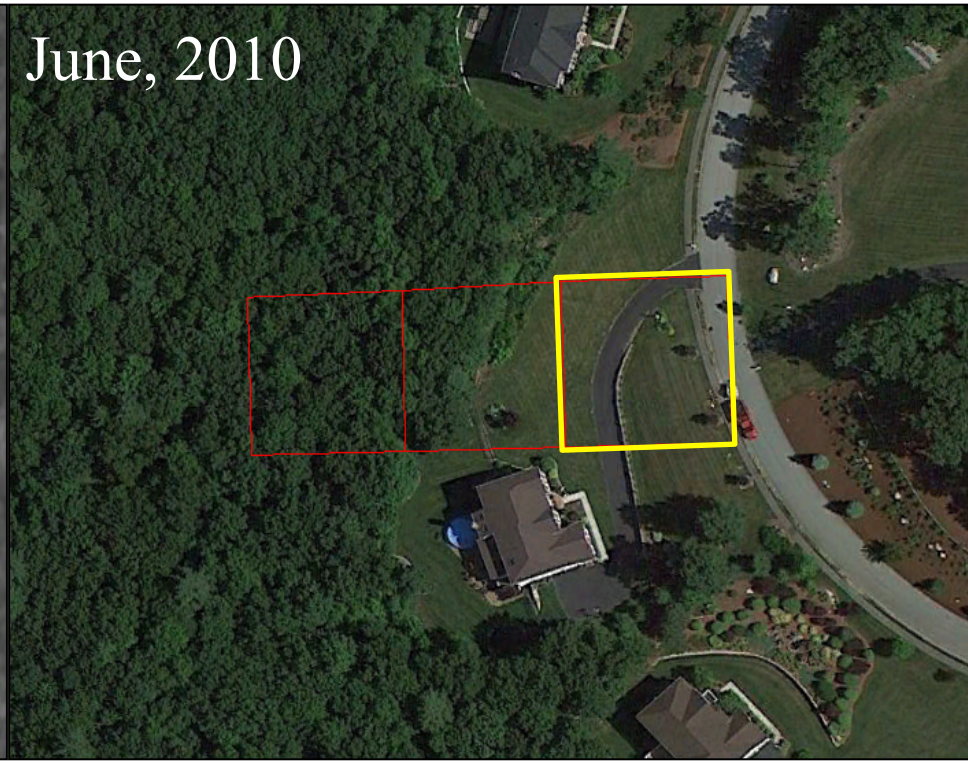
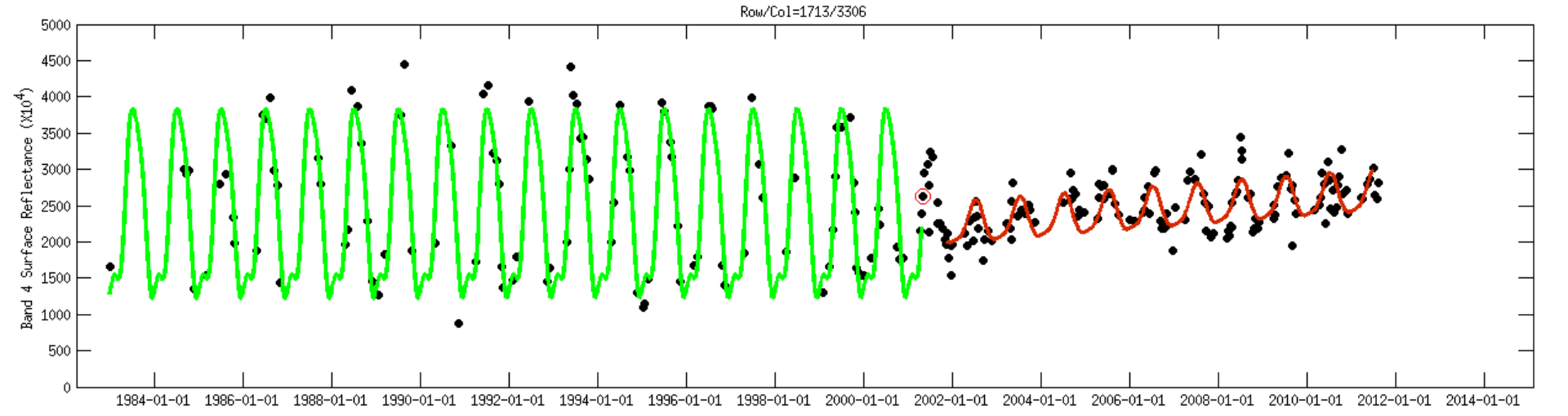
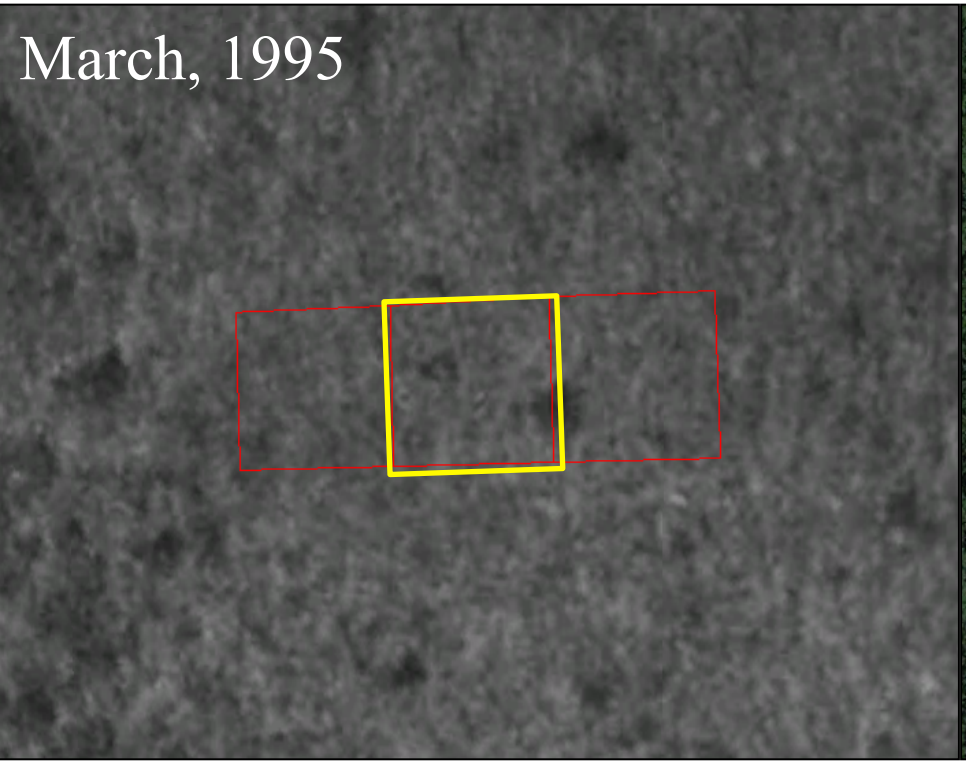
Residential development, Mass. Time-series displayed for pixel represented by yellow square. CCDC classified pixel as ***Dec. Forest*** until April 2001 and then as ***Low Dens. Residential***.

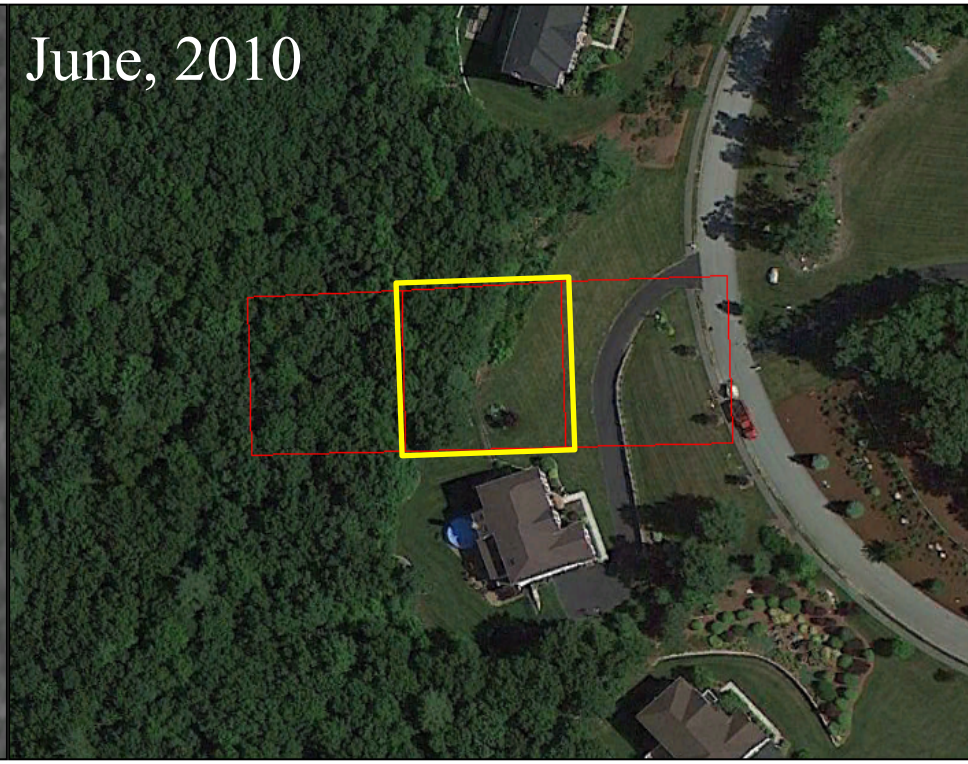


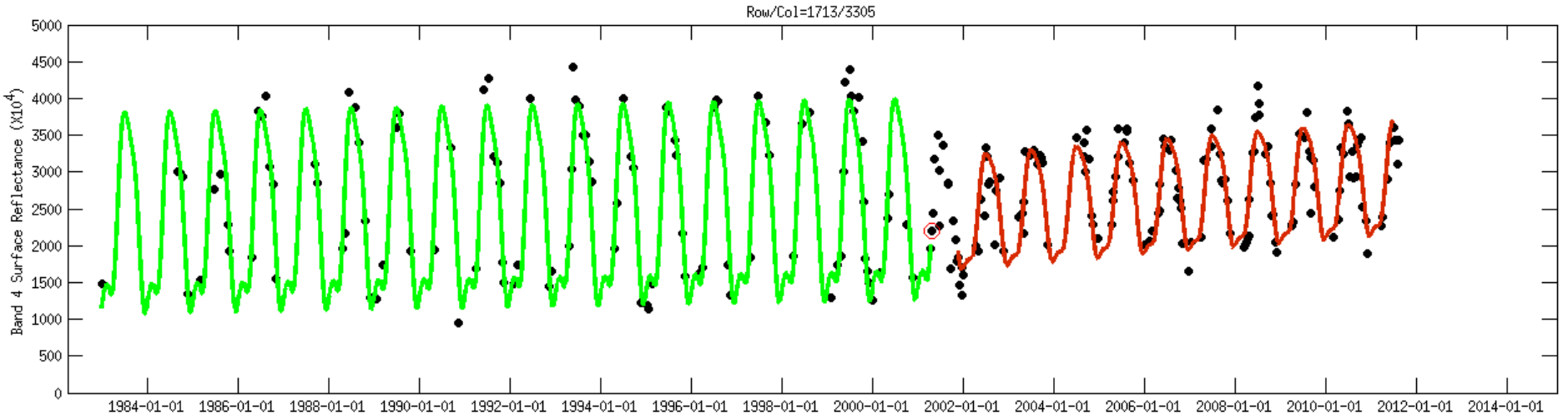




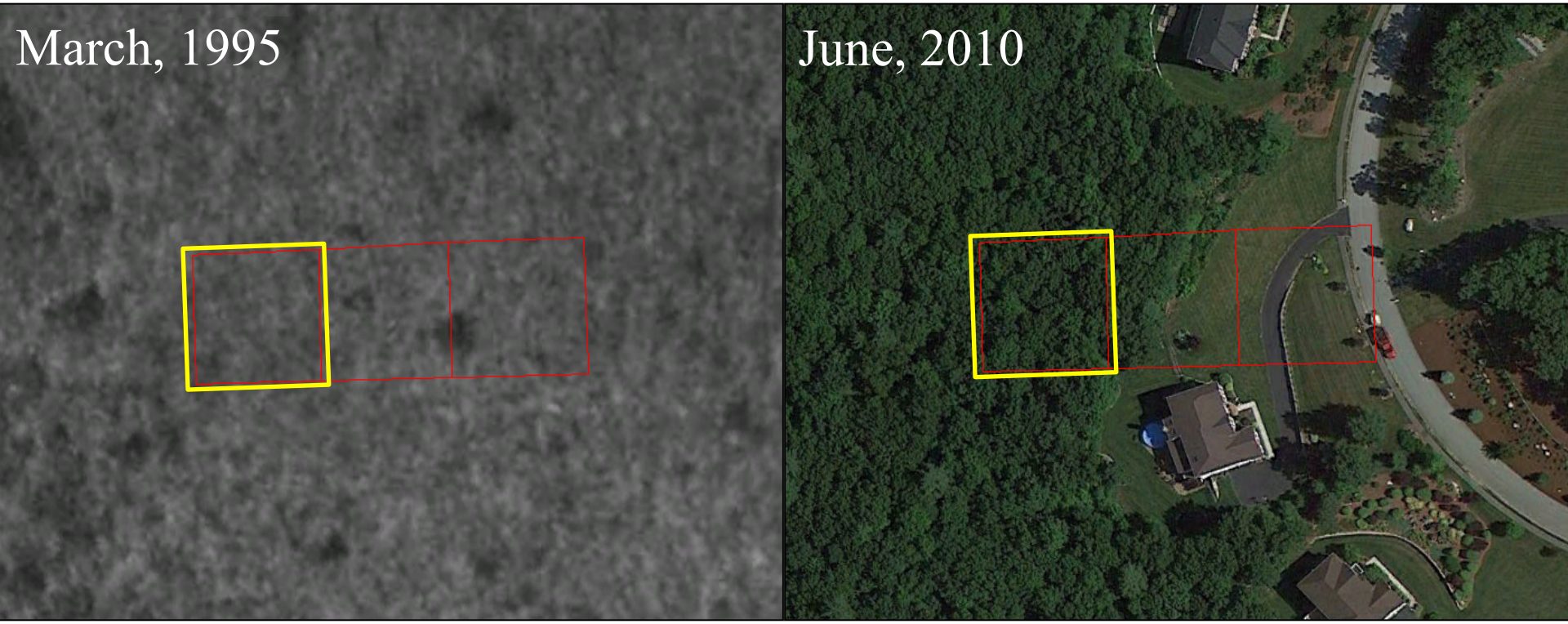
Residential development, Mass. Time-series displayed for pixel represented by yellow square. CCDC classified pixel as ***Dec. Forest*** until May 2001 and then as ***Low Dens. Residential***.

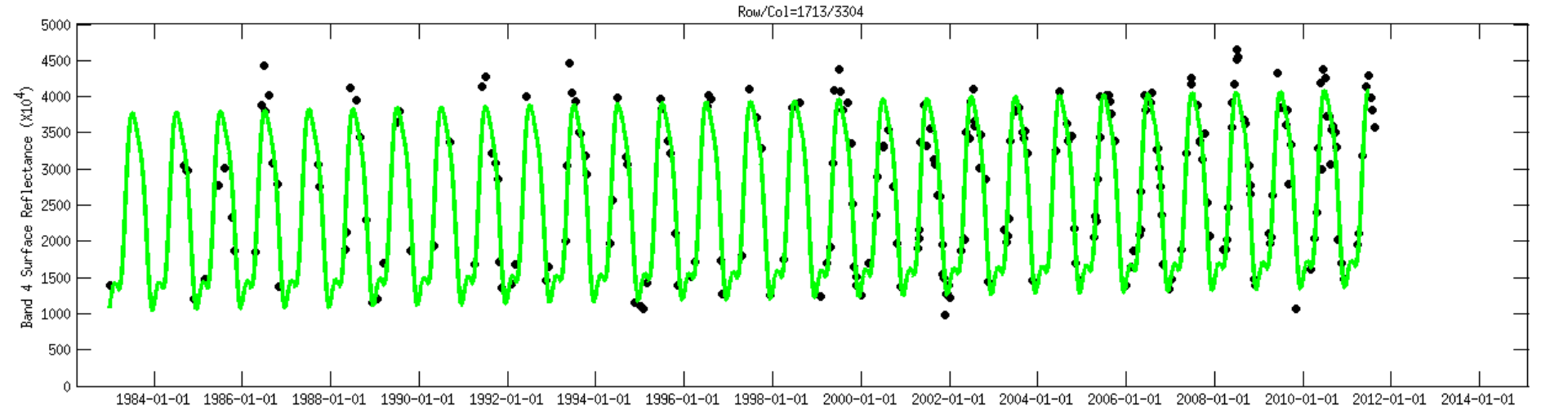




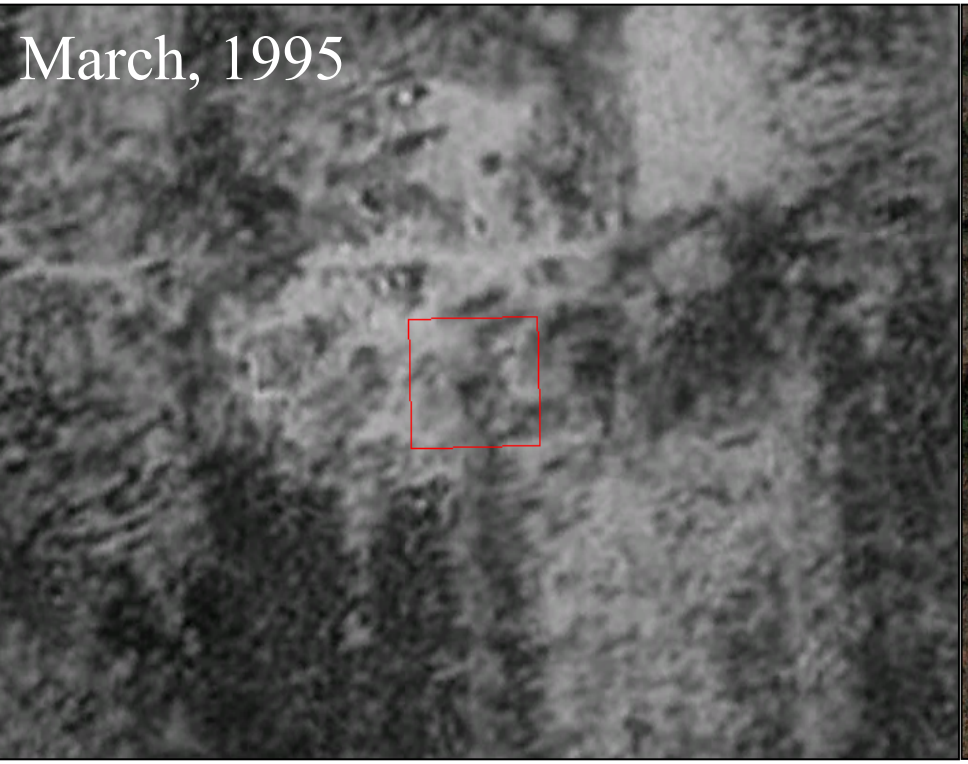


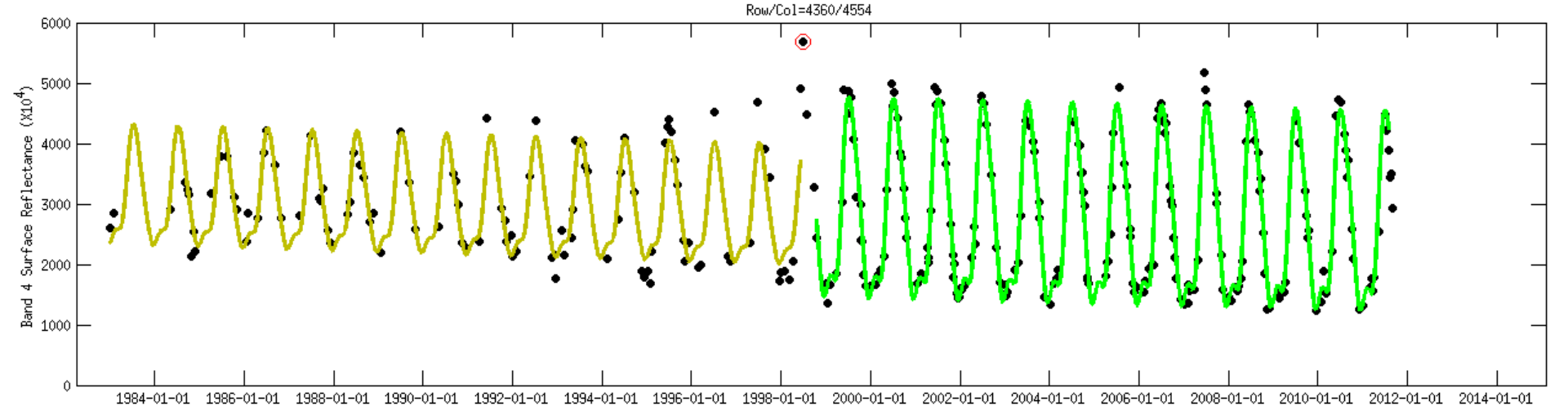
Residential development, Mass. Time-series displayed for pixel represented by the yellow square. CCDC classified pixel as stable ***Dec. Forest***.





Abandoned farmland near New Bedford, MA. Time-series displayed for the pixel represented by the red square. CCDC classified pixel as ***Pasture/Row Crops*** until Jun 1998 and then as ***Dec. Forest***.





Forest degradation, Mexico

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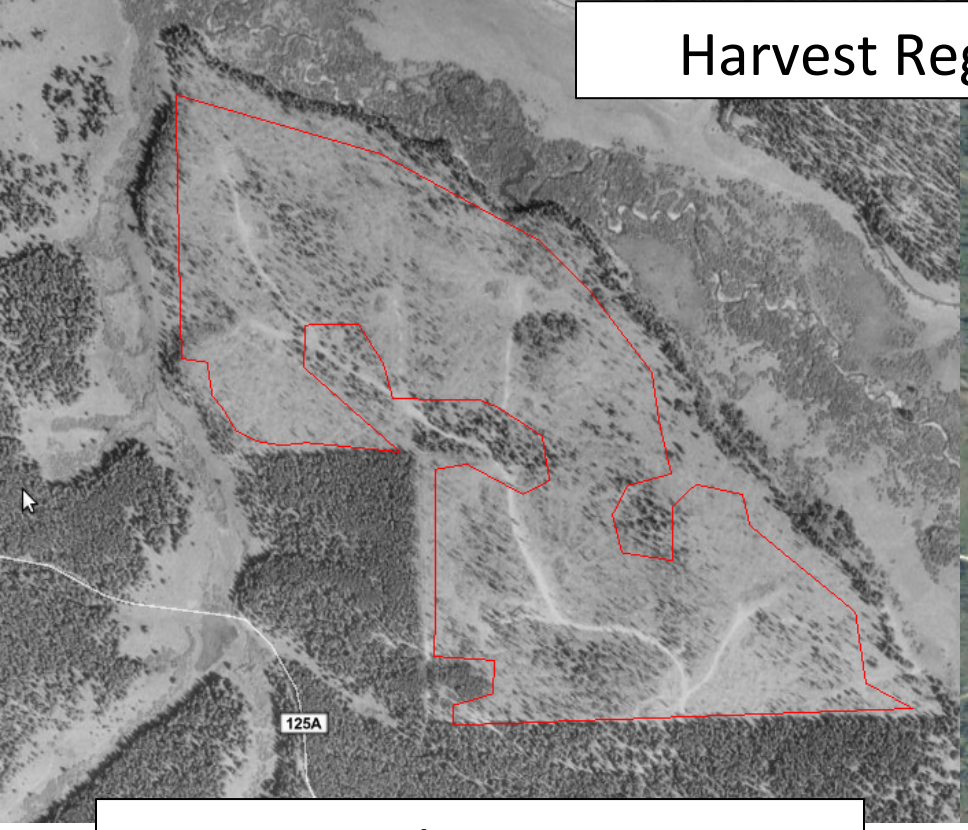
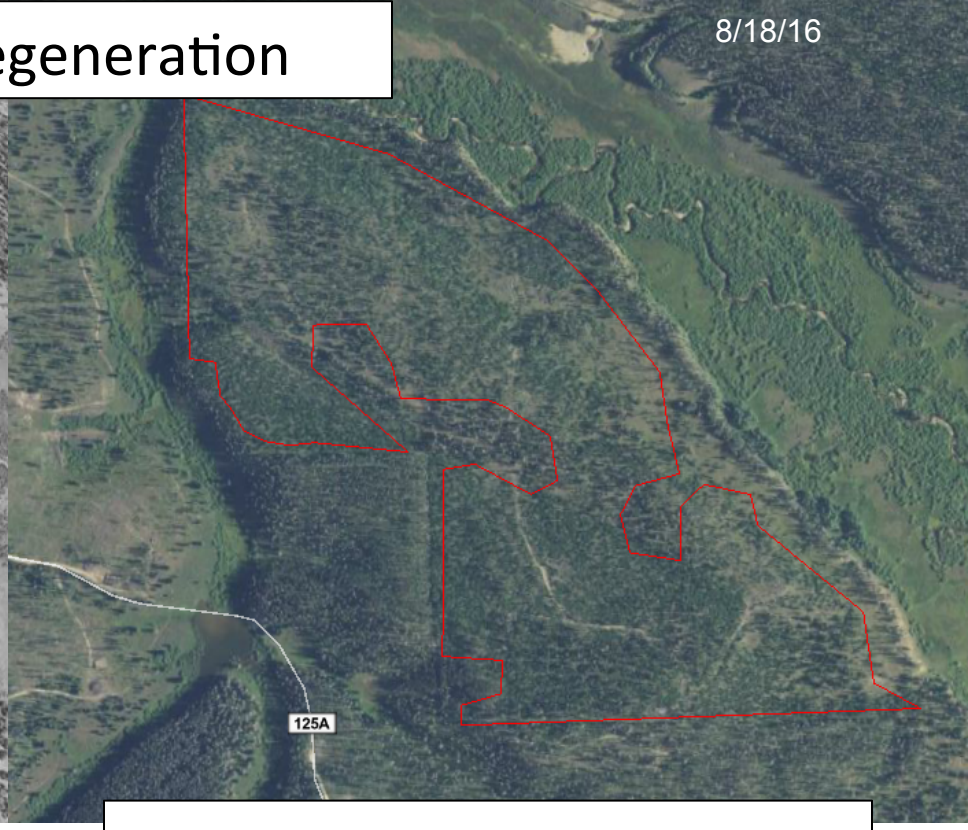
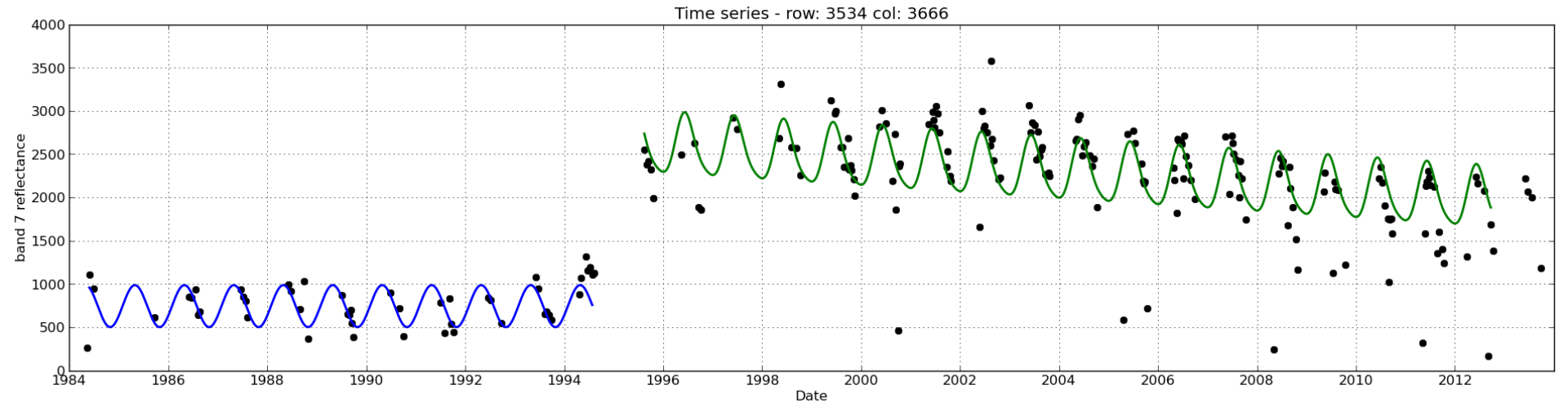
Harvest Regeneration

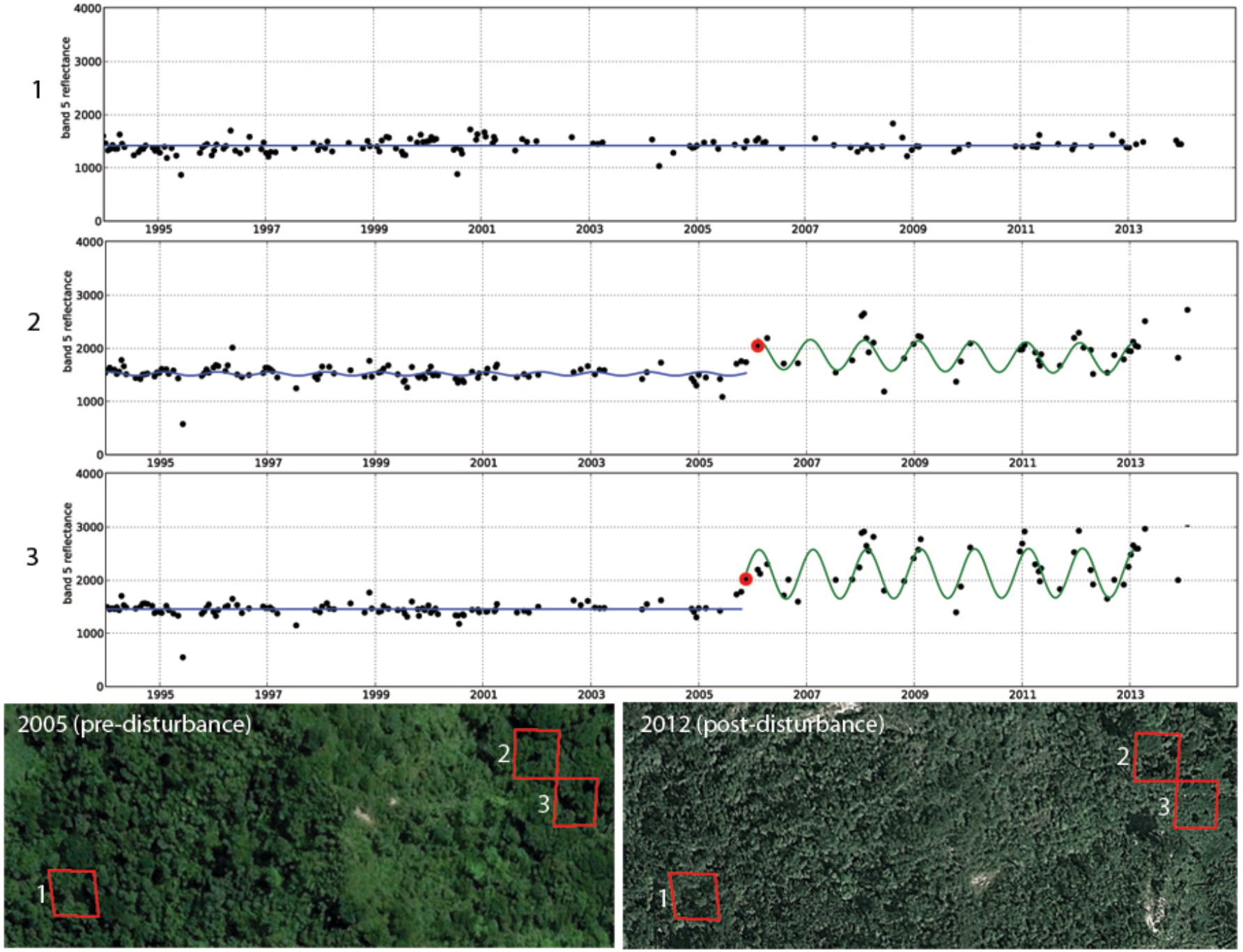


September 07, 1999



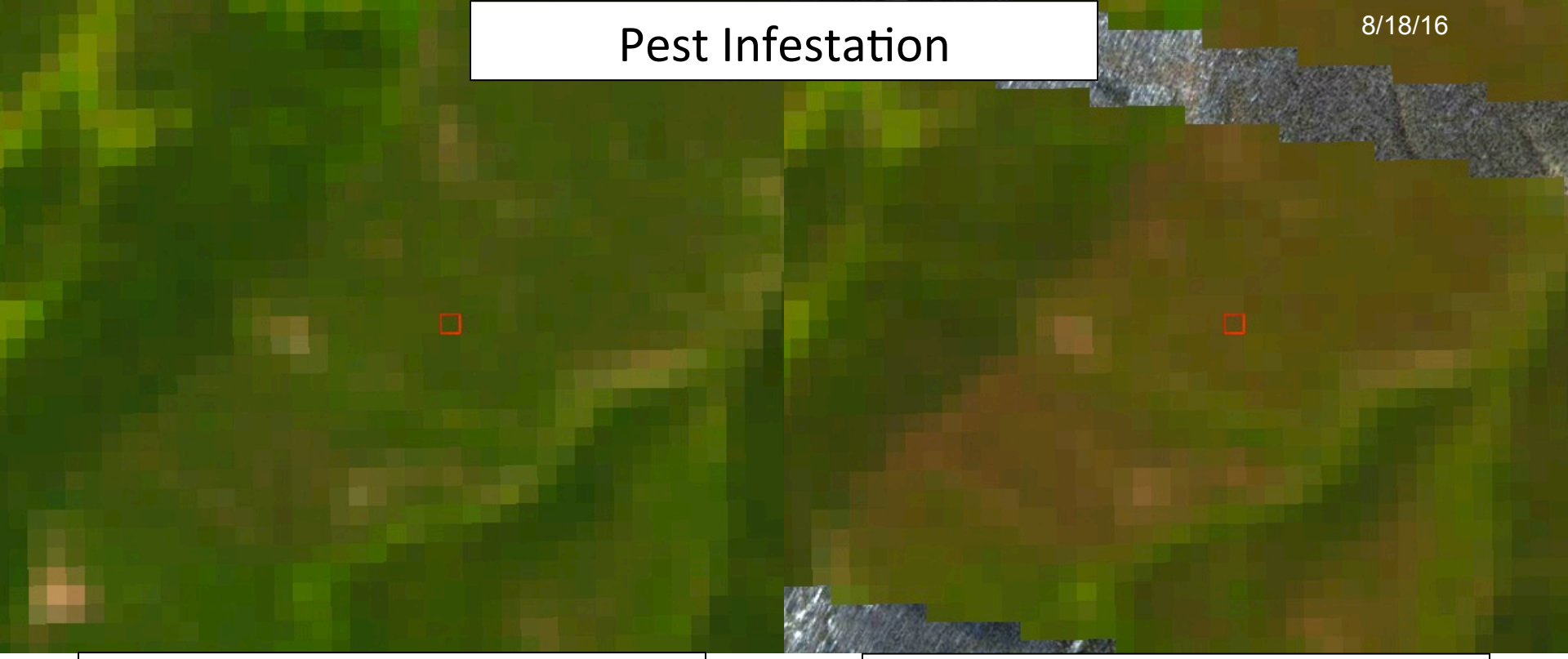
October 27, 2011




1
2
3
band 5 reflectance
0
1000
2000
3000
4000
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2005 (pre-disturbance)
2012 (post-disturbance)
1
2
3

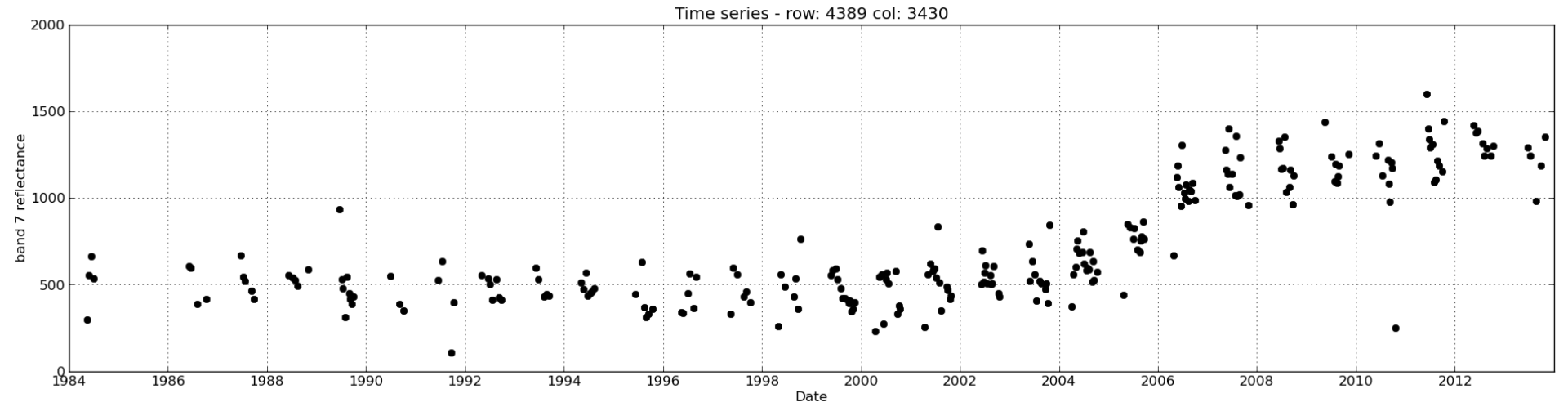
Pest Infestation

8/18/16



June 2, 1984

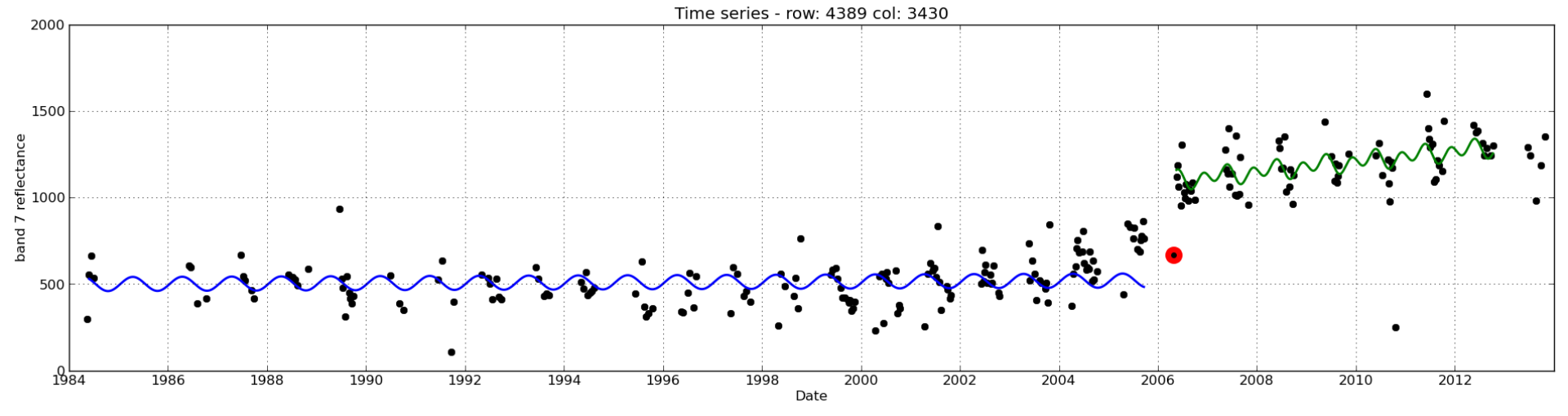
June 21, 2013



Pest Infestation

September 07, 1999

October 27, 2011



Examples from boreal Canada of fire (top), harvest and fire (middle) and thinning (bottom)

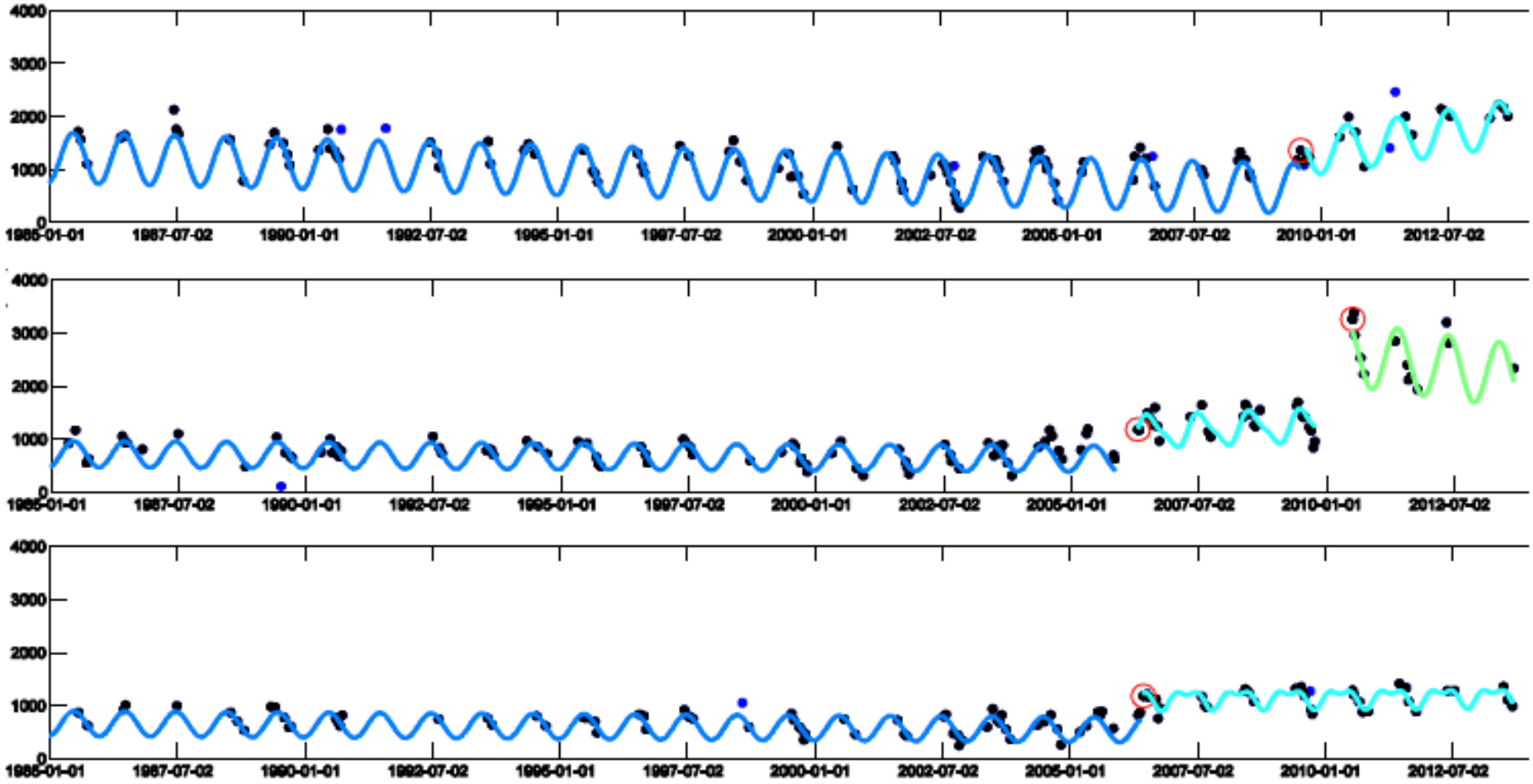
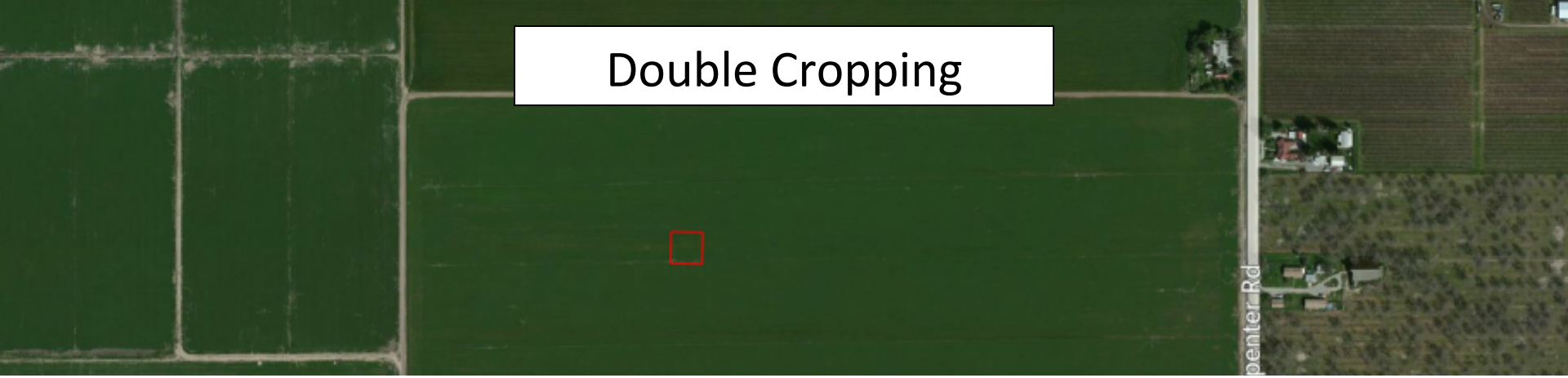


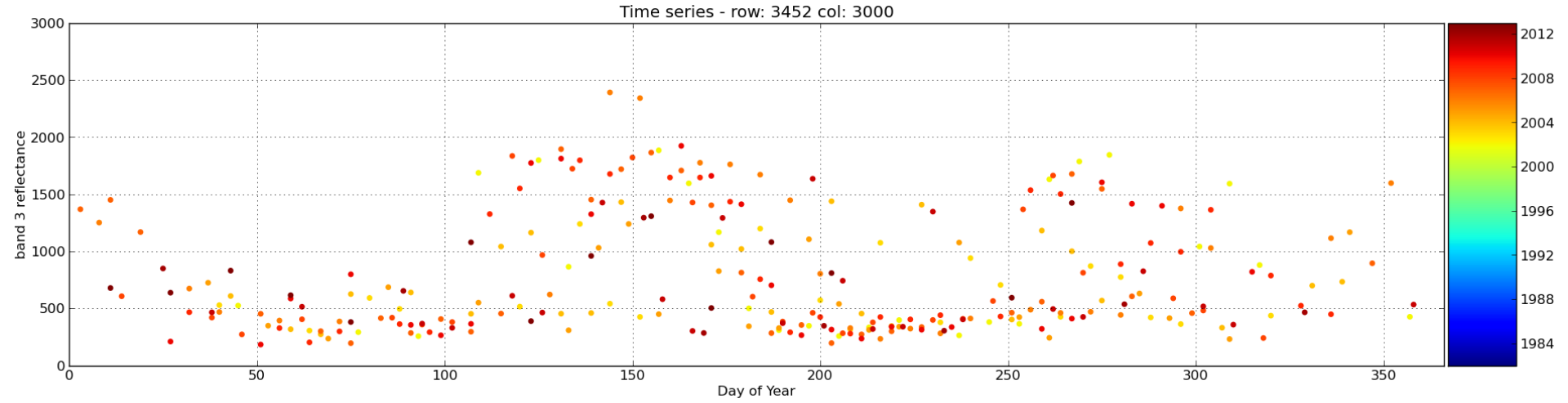
Figure 2. Time series results for 3 pixels with different combinations of disturbance for a location in Central British Columbia. The vertical axis is the Landsat SWIR Band 5 reflectance and is scaled by 10000. The horizontal axis is time and covers three decades. It is interesting to note the negative slope in the initial time series in the top graph, which is indicative of forest growth

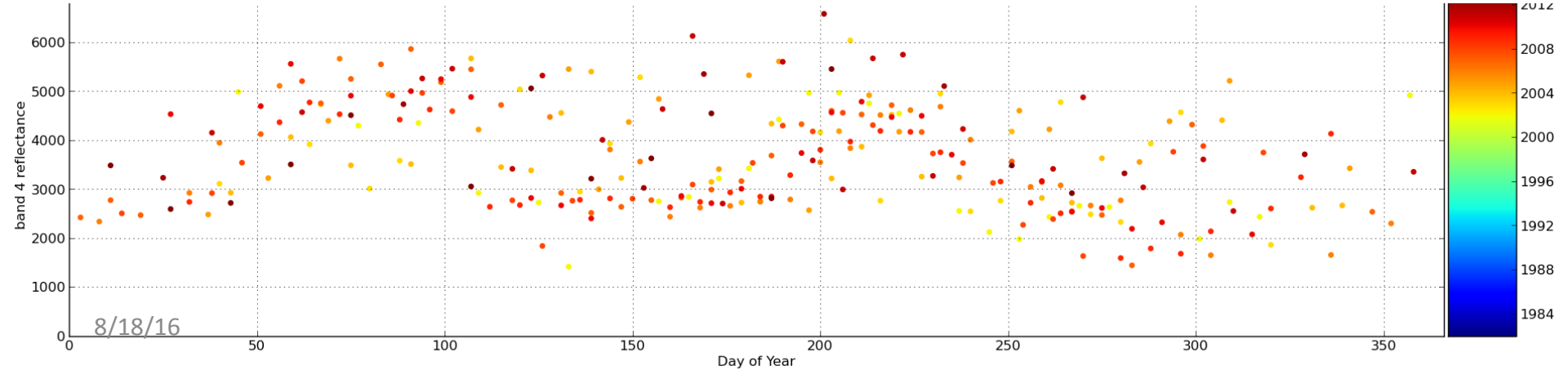
Land Use Histories

- Shifts in agricultural practices within cropland
- Strip cropping to "Conservation Reserve Program" (CRP)?
  - Change in NIR reflectance amplitude
  - Change in NIR phenology signal
  - CRP enrollment time series shows large increases in acreage in late 1990's and large decrease in late 2000's (gas prices)

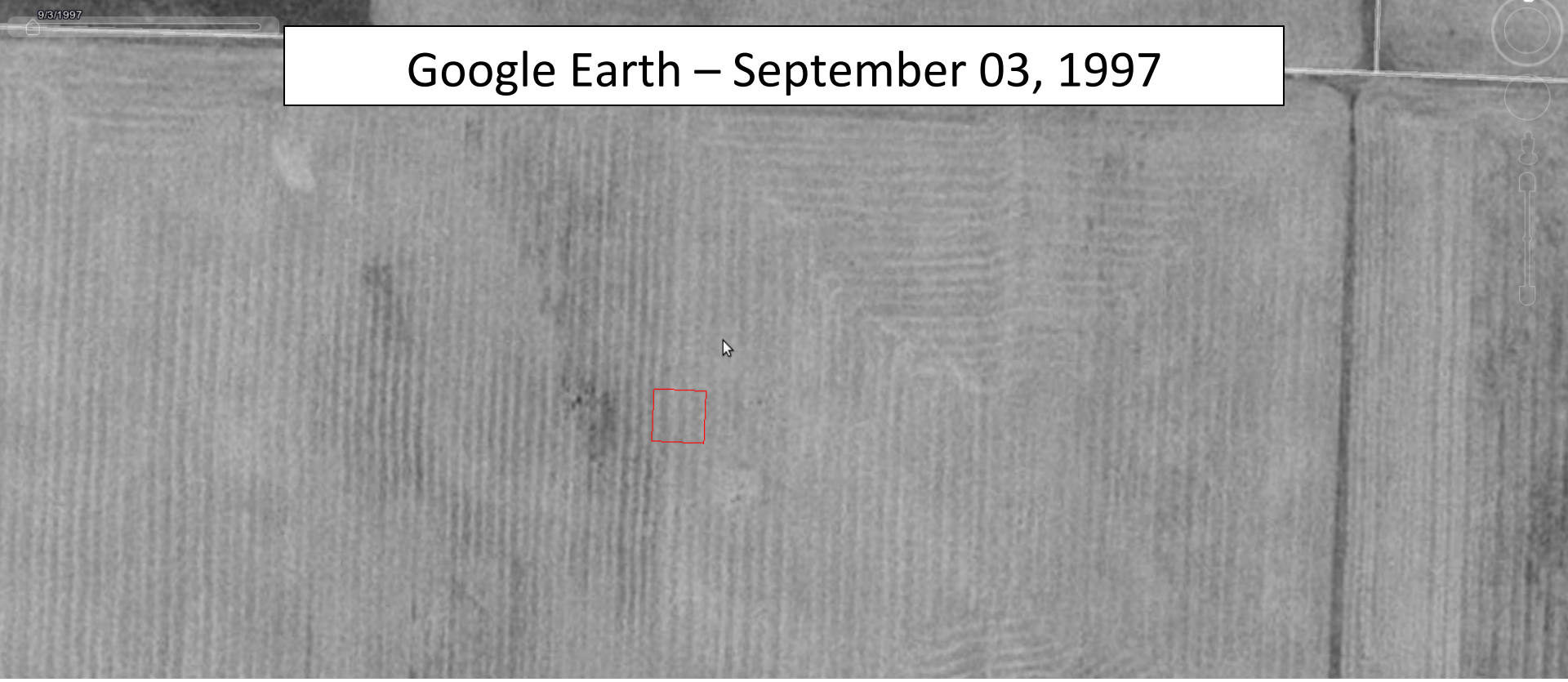
Double Cropping

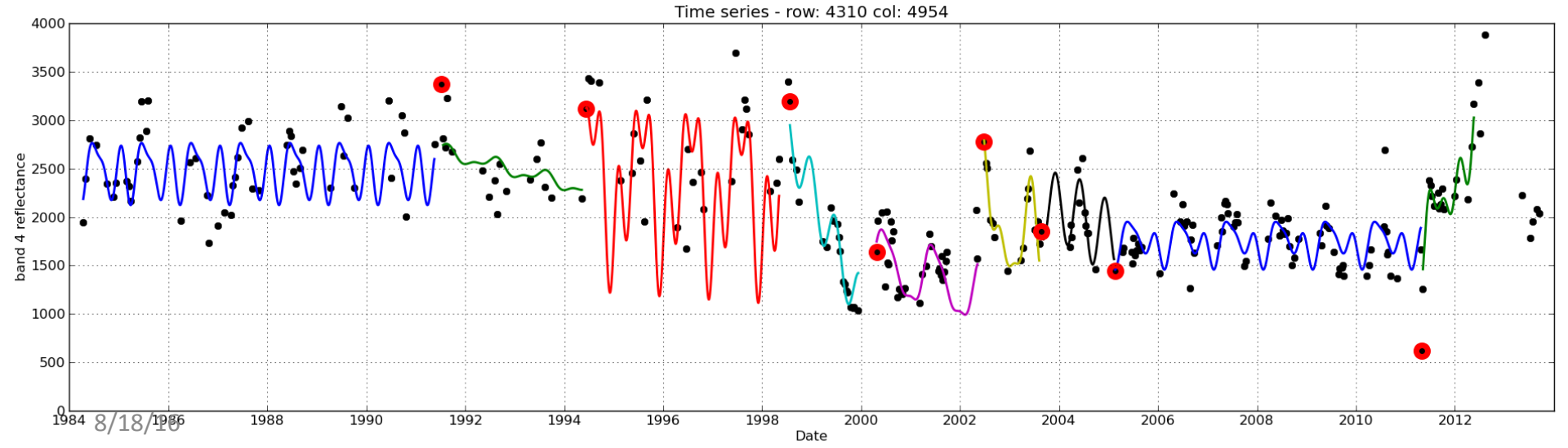




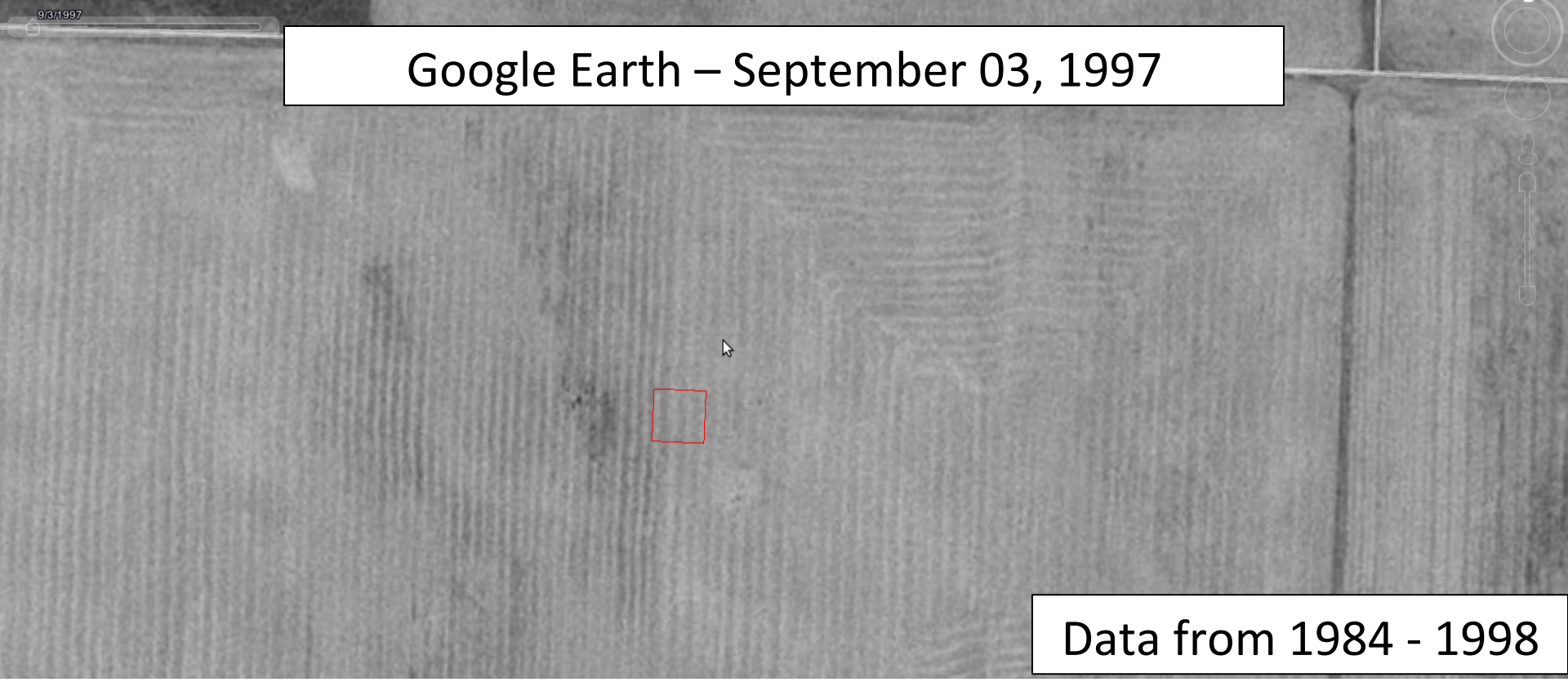


Google Earth – September 03, 1997

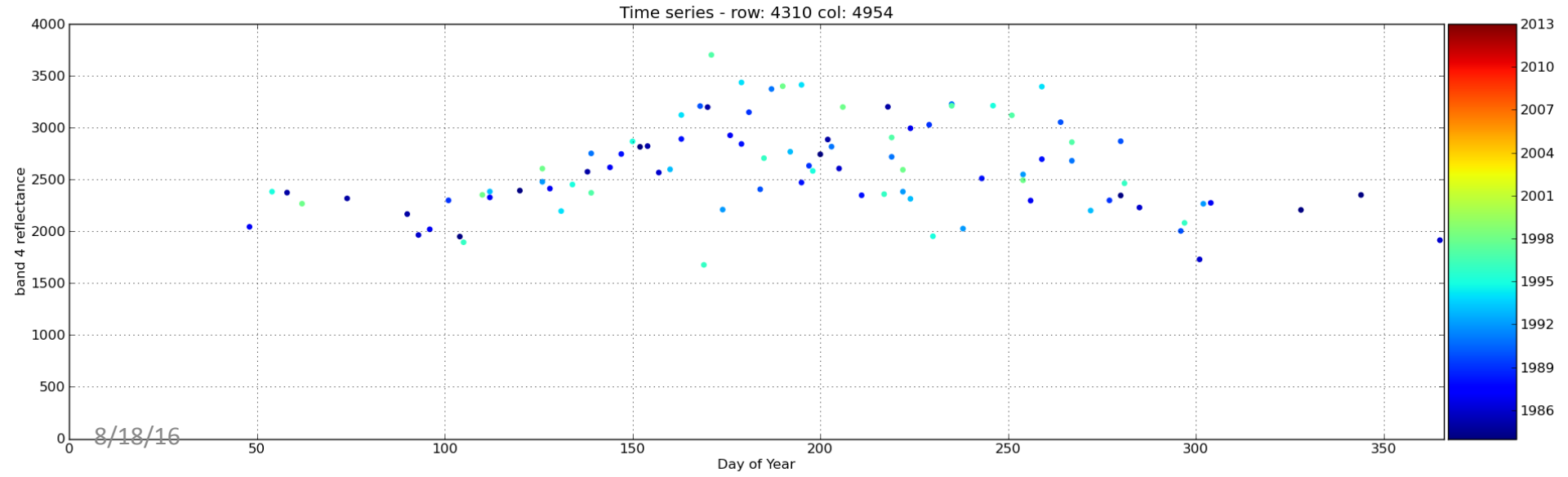




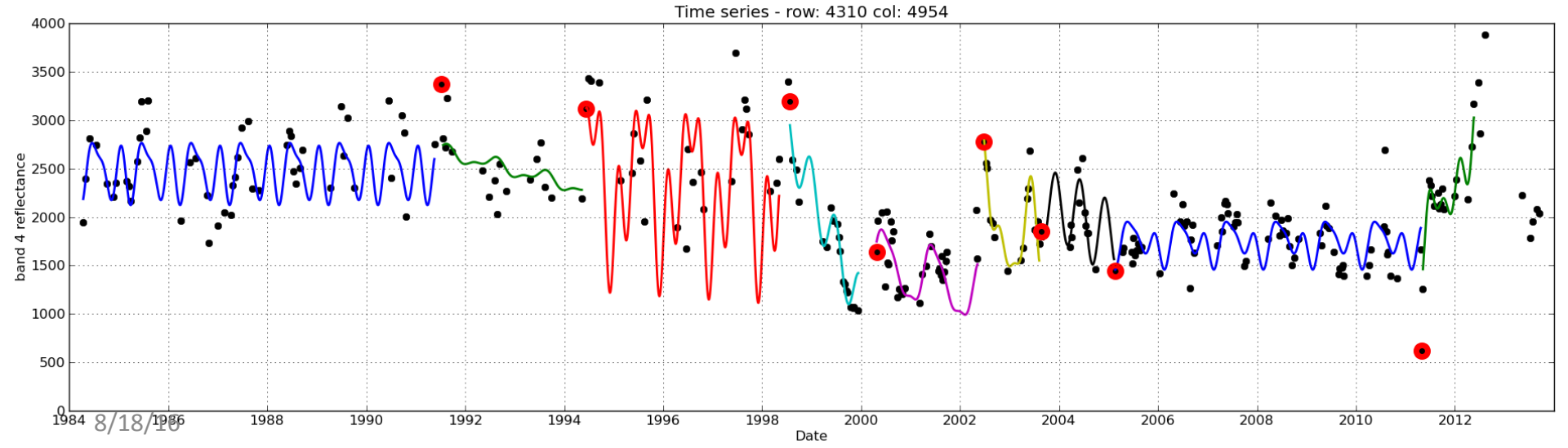
Google Earth – September 03, 1997



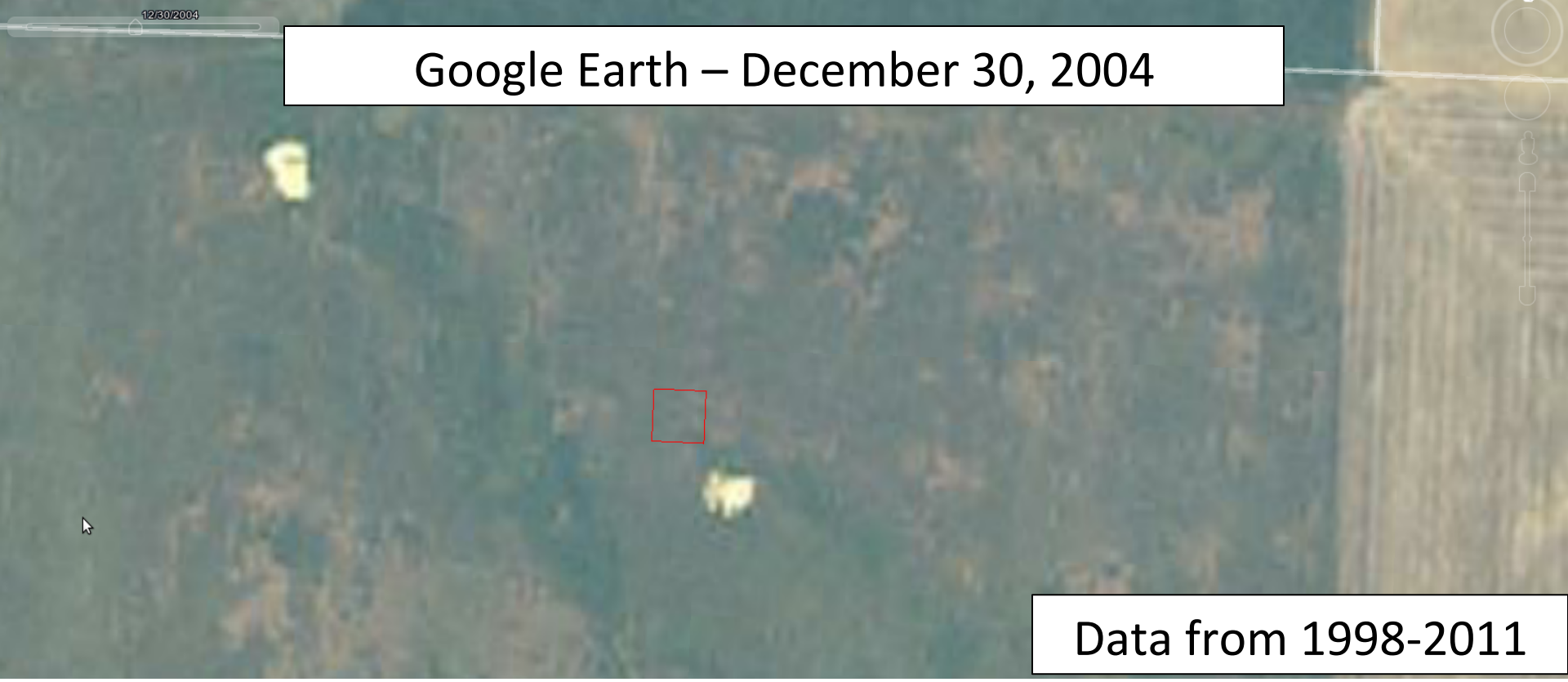
Data from 1984 - 1998



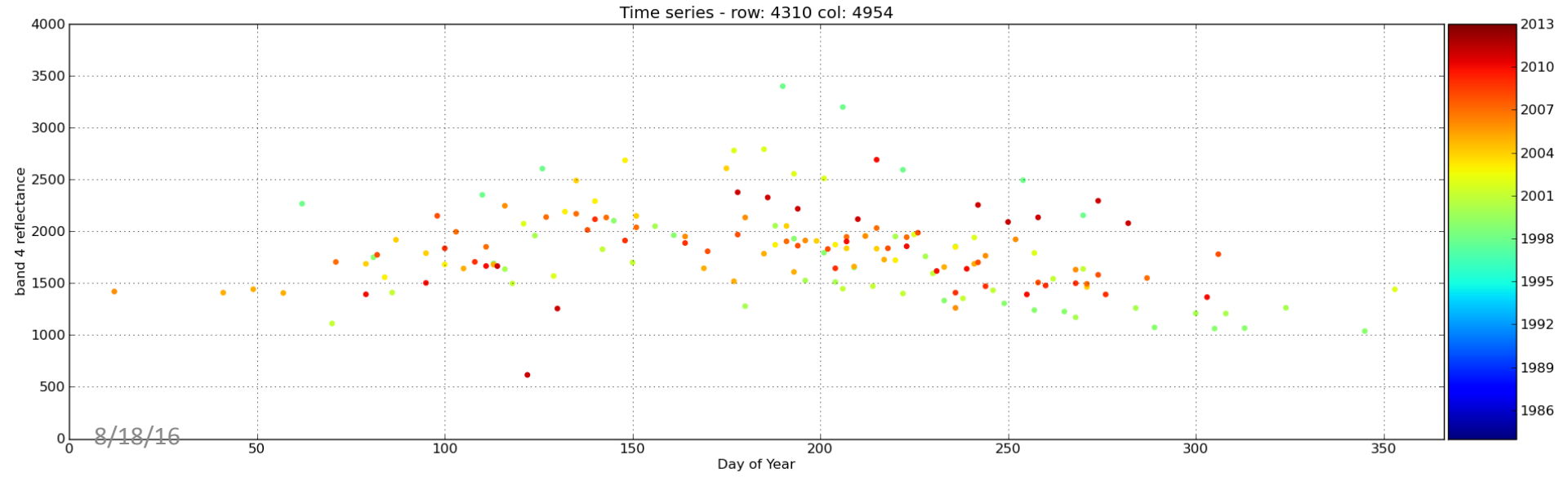
Google Earth – December 30, 2004



Google Earth – December 30, 2004



Data from 1998-2011



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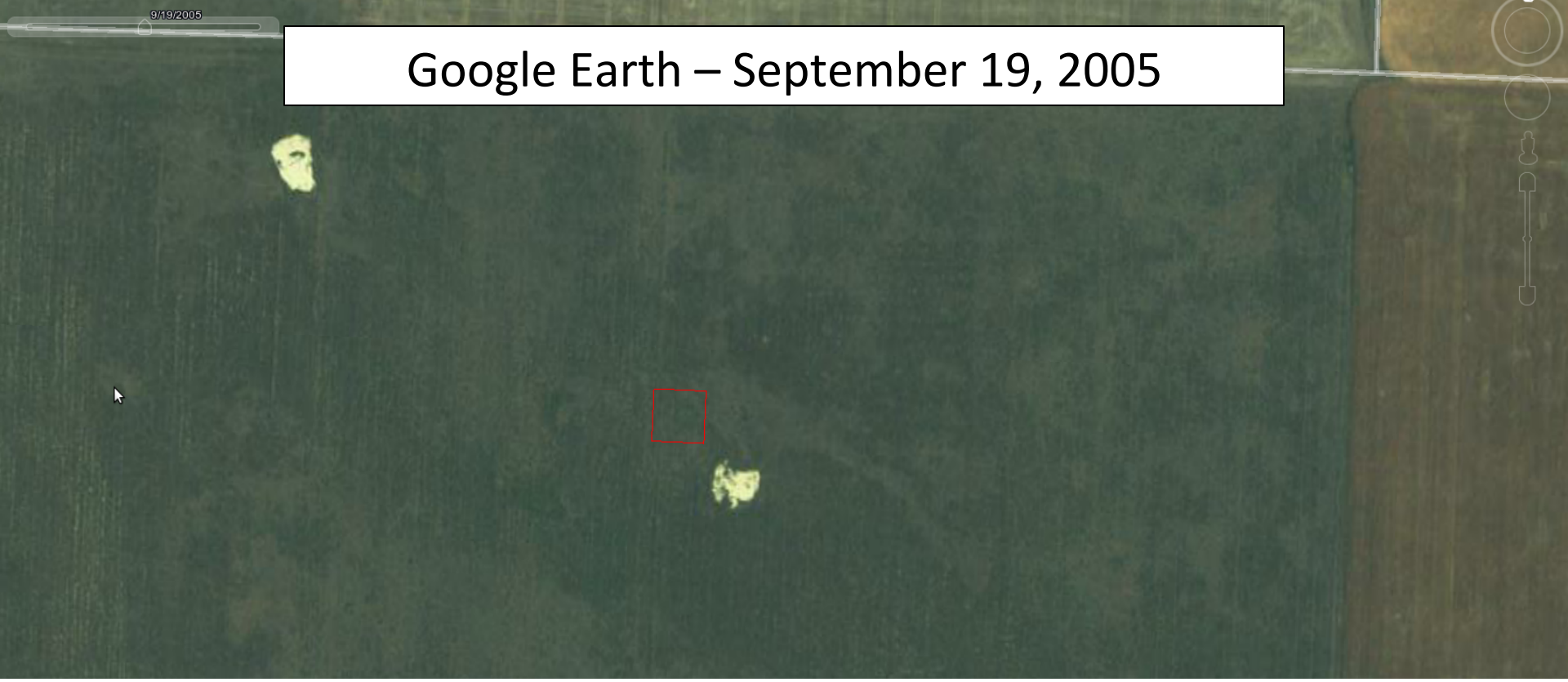
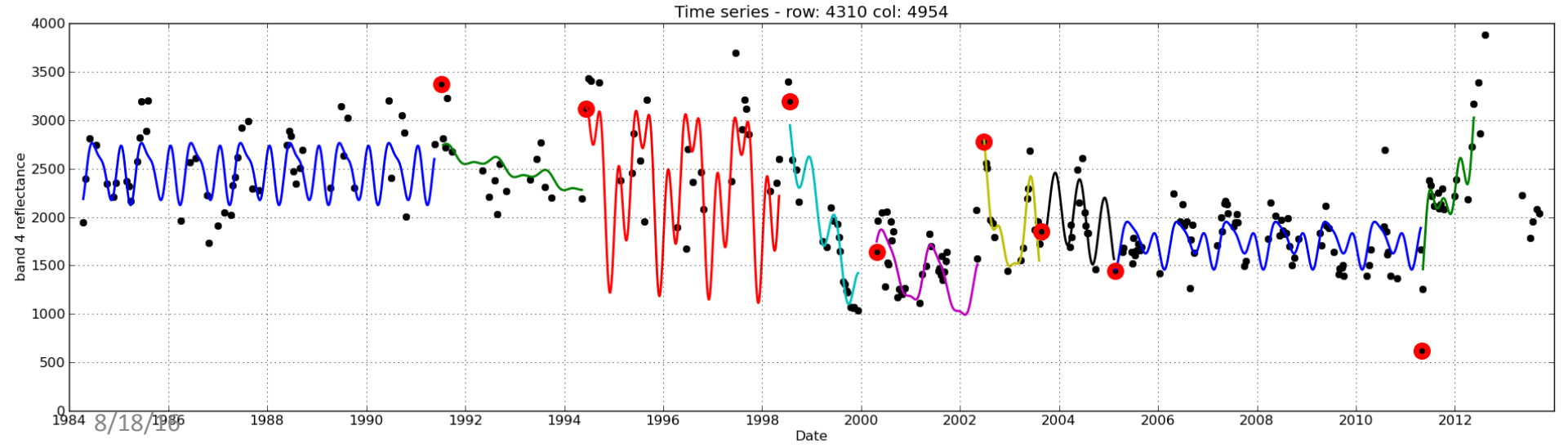
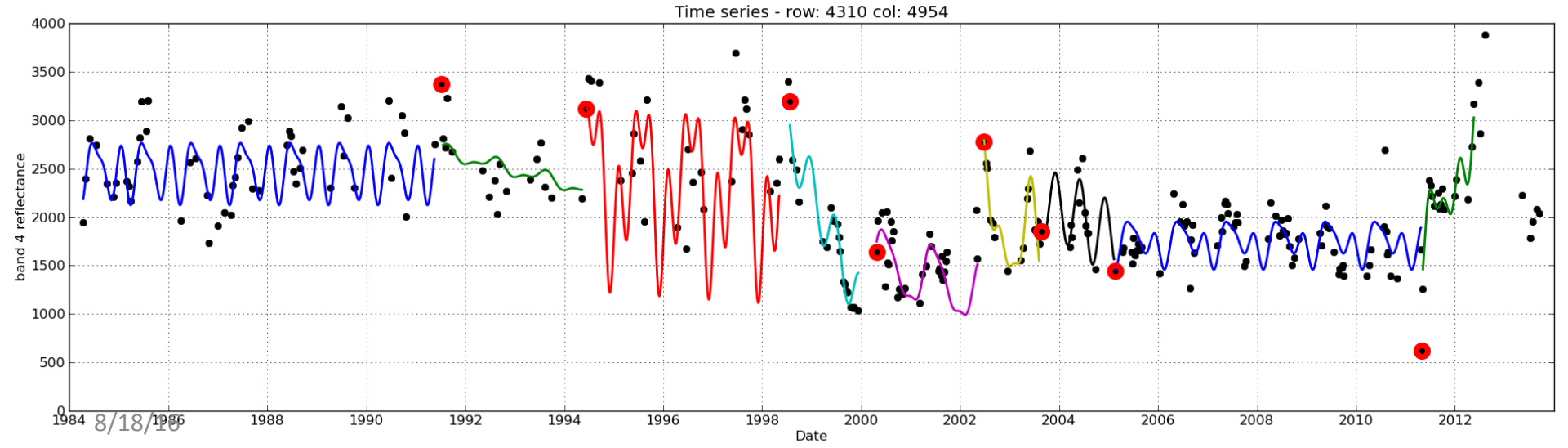
Google Earth – September 19, 2005

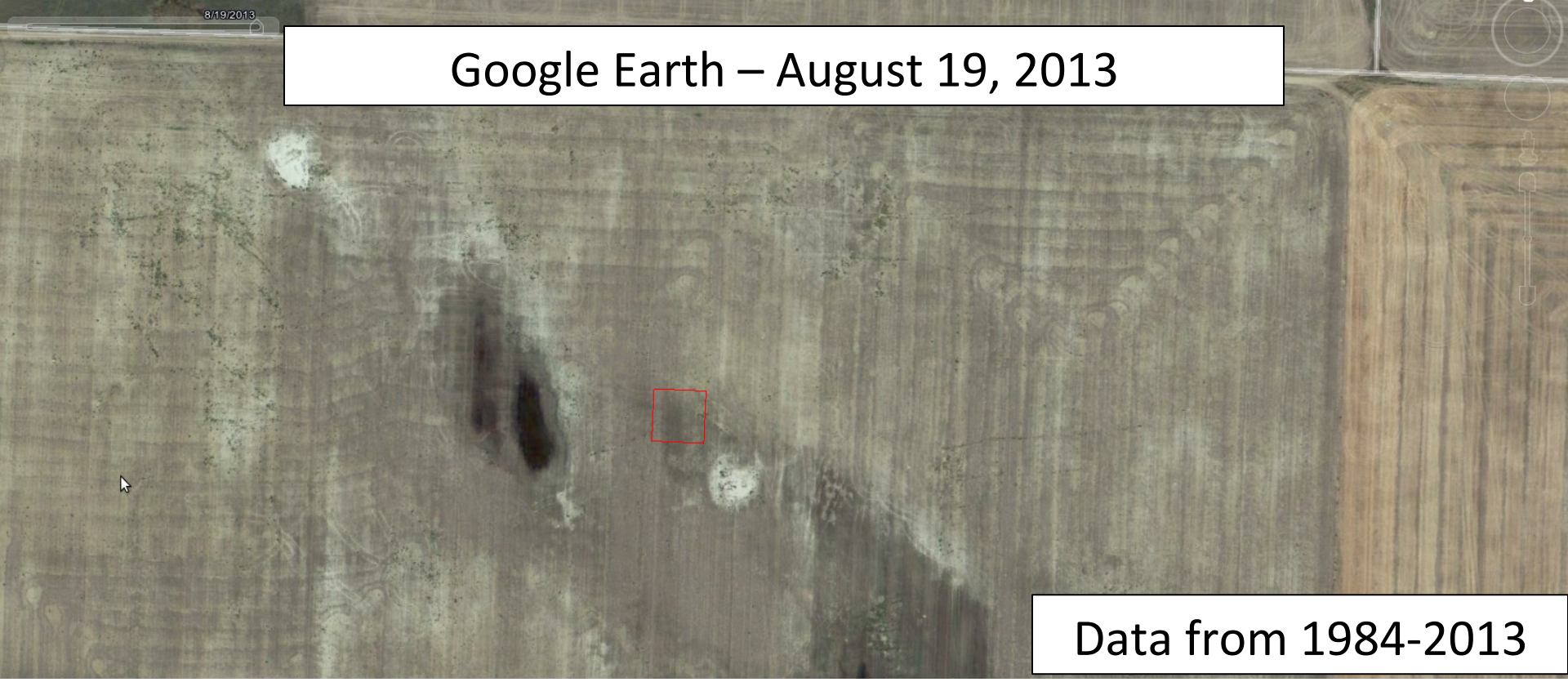




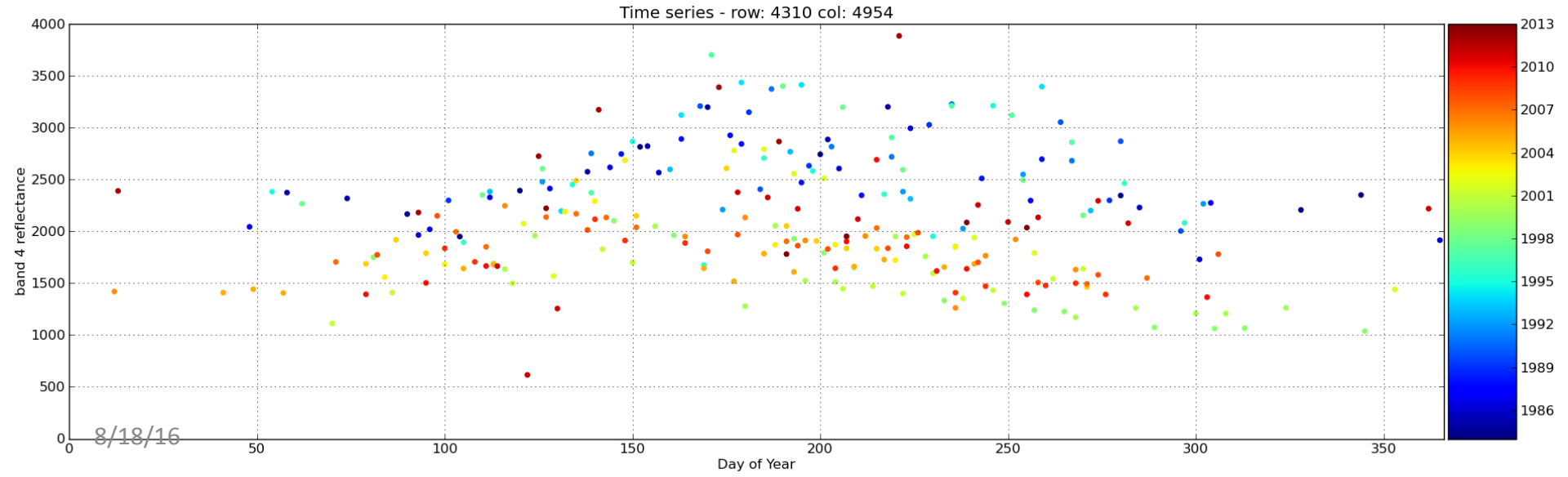
Google Earth – August 19, 2013



Google Earth – August 19, 2013



Data from 1984-2013



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Monitoring coastal salt marsh dynamics with Landsat time series:

A case study from Mass Audubon's Allens Pond Wildlife Sanctuary*

**This presentation includes slides from Robert Buchsbaum's talk "Death and Resurrection of Three Mass Audubon Salt Marshes" at the 2015 Mass Audubon Staff Natural History Conference*

Allens Pond Wildlife Sanctuary
Dartmouth, MA

Established Phragmites areas indicated in red

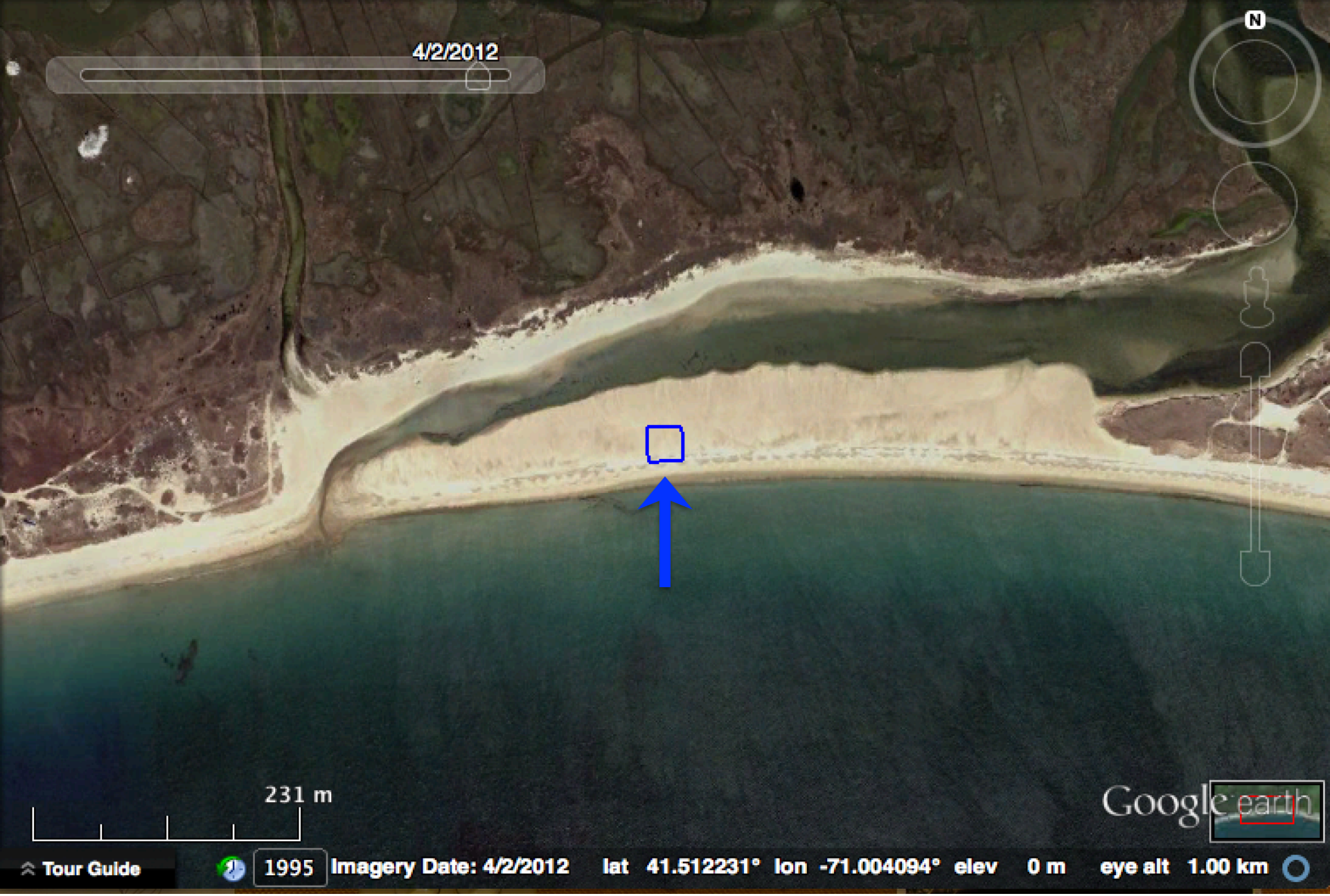
Mass Audubon

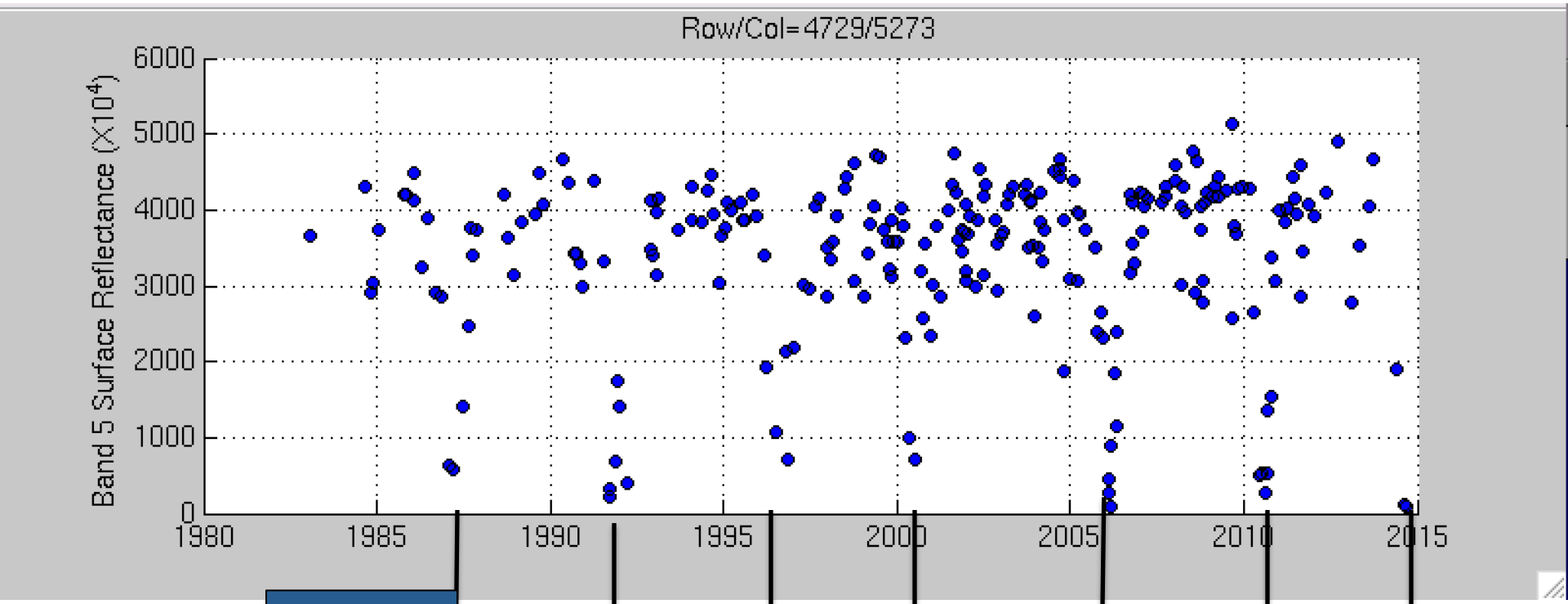
Slide from Dr. Robert Buchsbaum, Mass Audubon

Tidal Inlet movement

Inlet naturally shifts and closes, re-dig on a ~5 year cycle

Slide from Dr. Robert Buchsbaum, Mass Audubon


4/2/2012
N
231 m
Google earth
Tour Guide
1995
Imagery Date: 4/2/2012
lat 41.512231°
lon -71.004094°
elev 0 m
eye alt 1.00 km

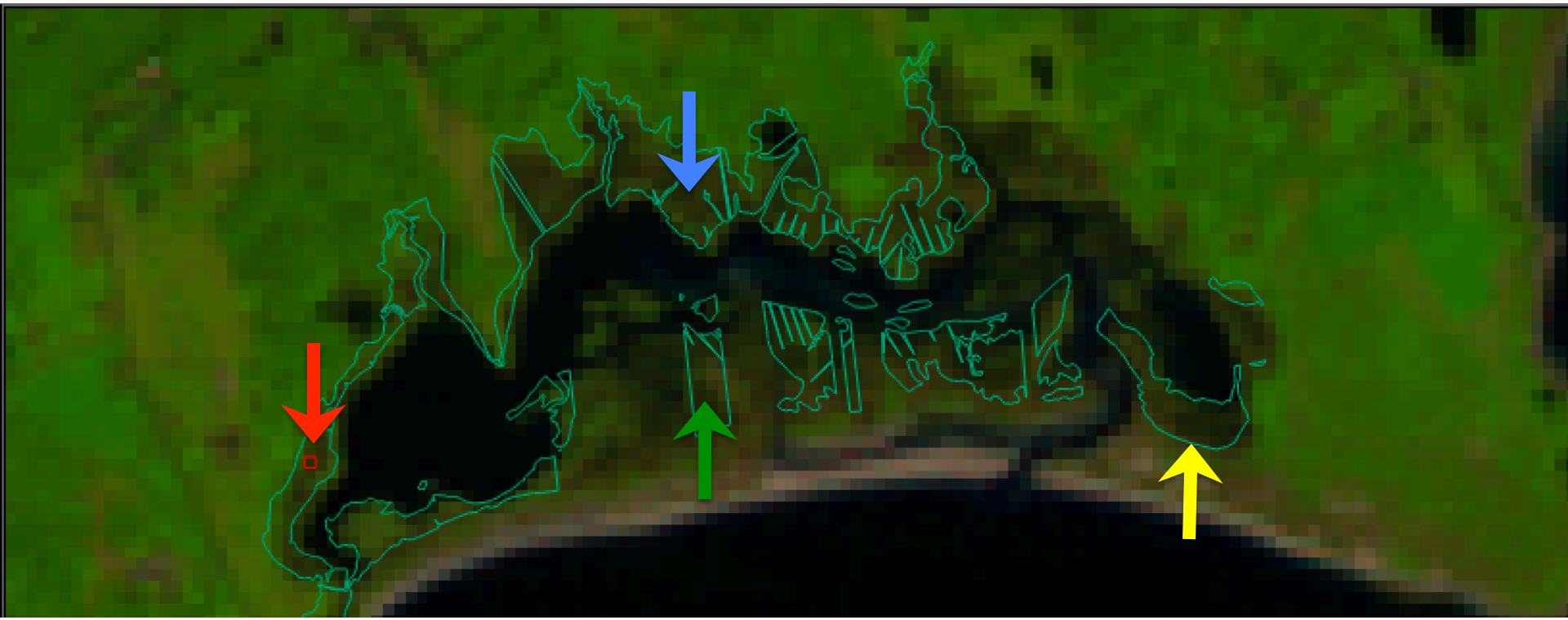


1987 — 5 yrs. — 1992 — 4 yrs. — 1996 — 4 yrs. — 2000 — 5 yrs. — 2005 — 5 yrs. — 2010 — 4 yrs. — 2014

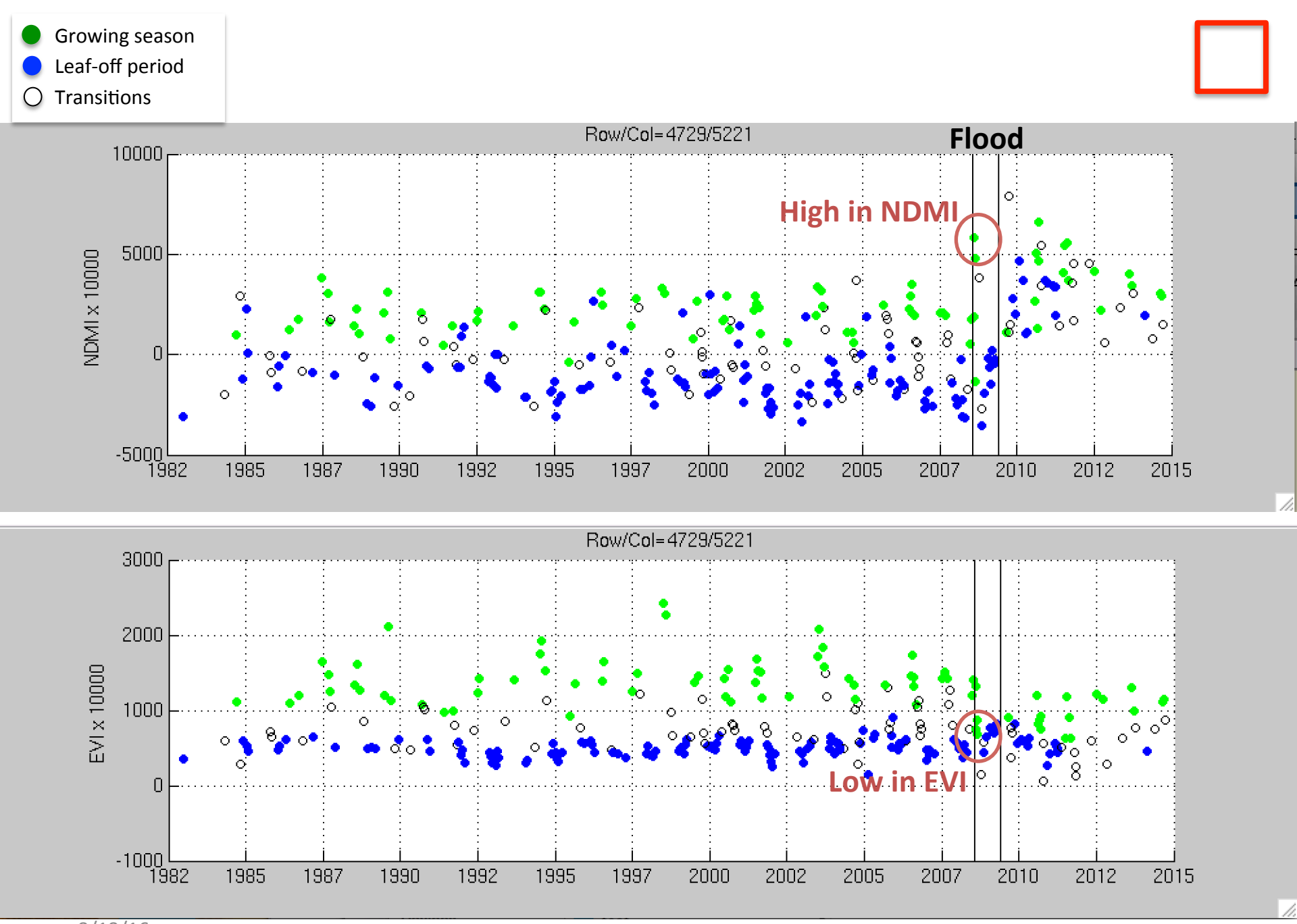
Summer of 2008: Inlet closed

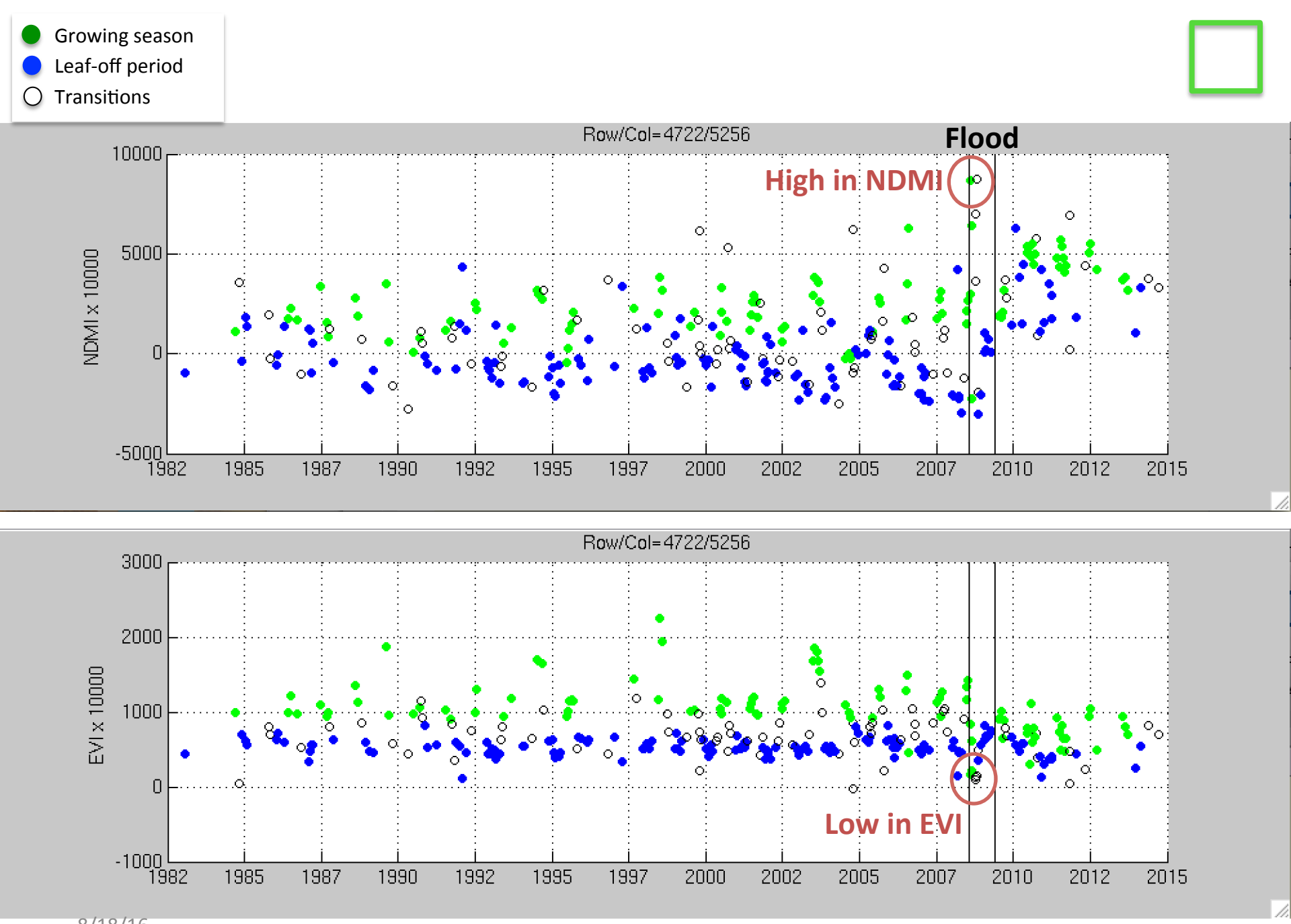
- Nesting Piping plovers (endangered species) prevent immediate re-digging of inlet
- Marsh submerged for about 5 months
- Inlet re-dug in Fall 2009 after end of the nesting season

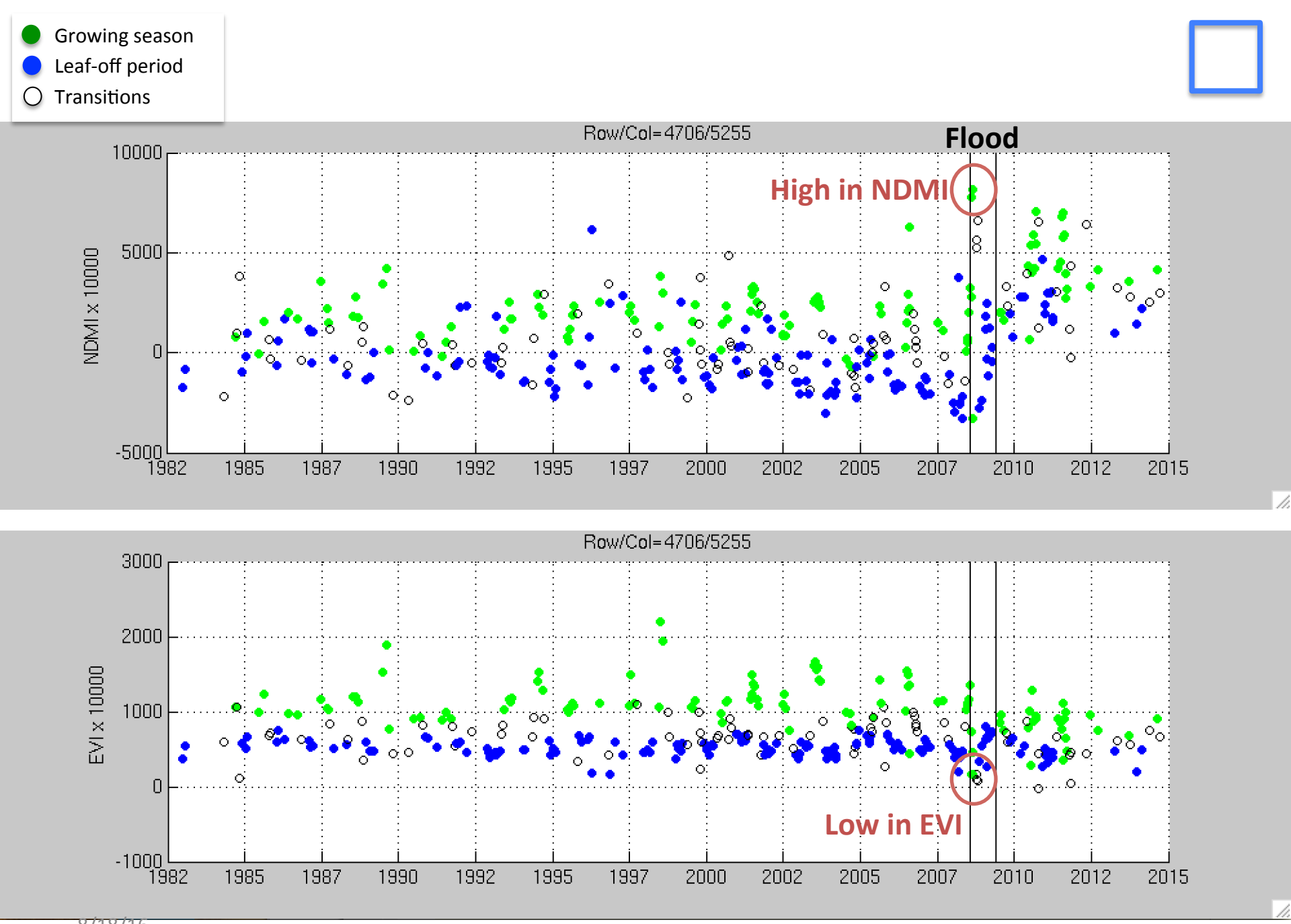
Photos from Dr. Robert Buchsbaum, Mass Audubon

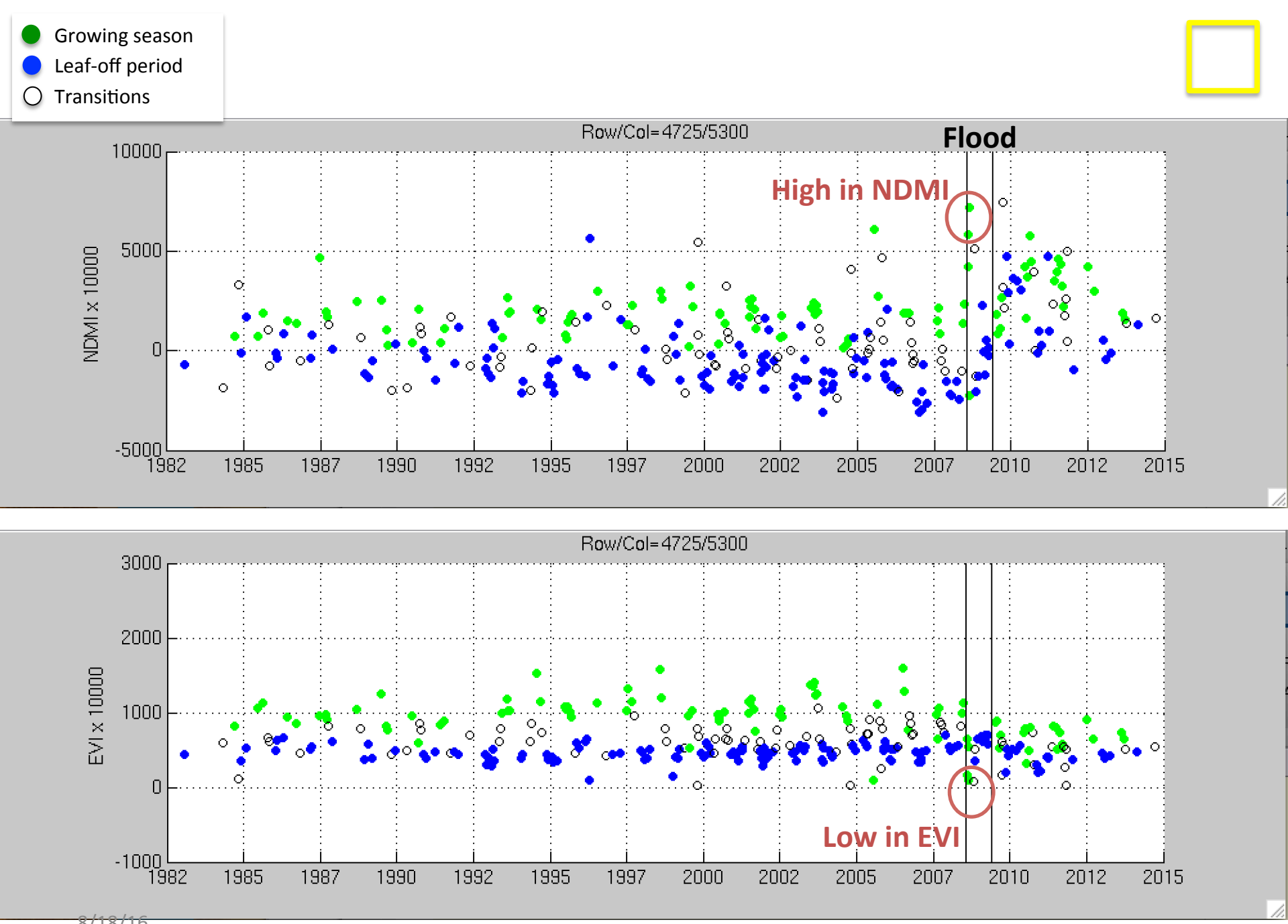


Pixels selected from various salt marsh areas

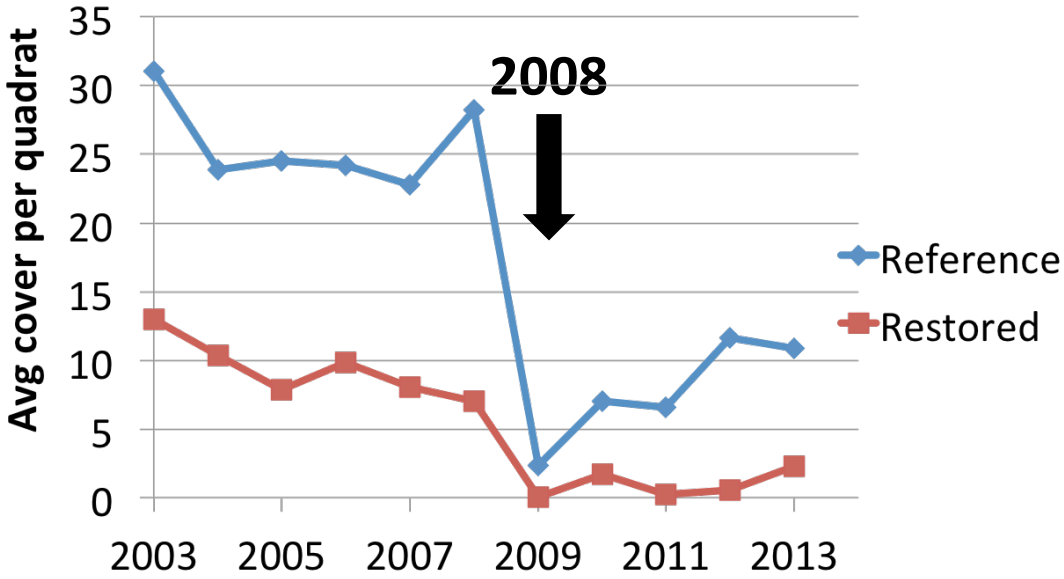

Growing season
Leaf-off period
Transitions
Row/Col=4729/5221
Flood
High in NDMI
NDMI x 10000
10000
5000
0
-5000
1982
1985
1987
1990
1992
1995
1997
2000
2002
2005
2007
2010
2012
2015
Row/Col=4729/5221
EVI x 10000
3000
2000
1000
0
-1000
Low in EVI

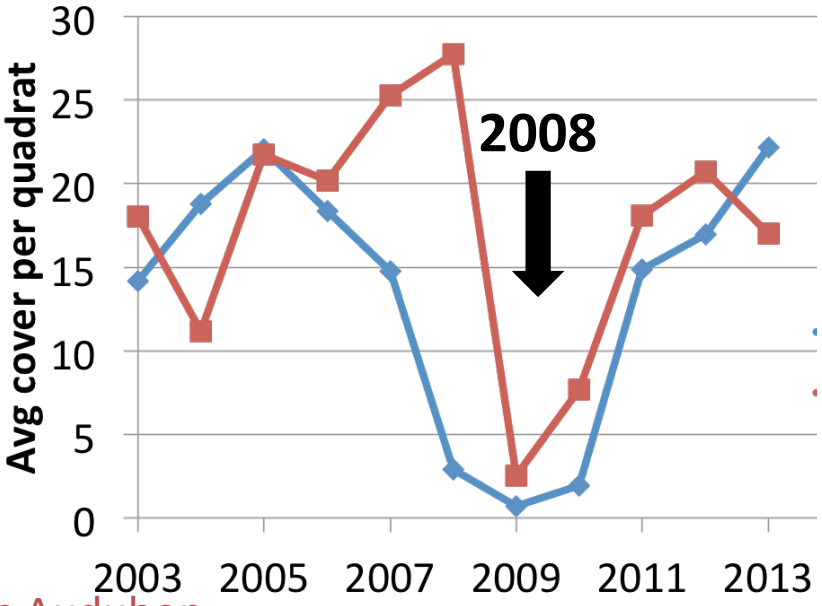

Growing season
Leaf-off period
Transitions
Row/Col=4722/5256
Flood
High in NDMI
NDMI x 10000
10000
5000
0
-5000
1982
1985
1987
1990
1992
1995
1997
2000
2002
2005
2007
2010
2012
2015
Row/Col=4722/5256
EVI x 10000
3000
2000
1000
0
-1000
Low in EVI


Growing season
Leaf-off period
Transitions
Row/Col=4706/5255
Flood
High in NDMI
NDMI x 10000
10000
5000
0
-5000
1982
1985
1987
1990
1992
1995
1997
2000
2002
2005
2007
2010
2012
2015
Row/Col=4706/5255
EVI x 10000
3000
2000
1000
0
-1000
Low in EVI


Growing season
Leaf-off period
Transitions
Row/Col=4725/5300
Flood
High in NDMI
NDMI x 10000
10000
5000
0
-5000
1982
1985
1987
1990
1992
1995
1997
2000
2002
2005
2007
2010
2012
2015
Row/Col=4725/5300
EVI x 10000
3000
2000
1000
0
-1000
Low in EVI

Monitoring Data: Vegetation Transects

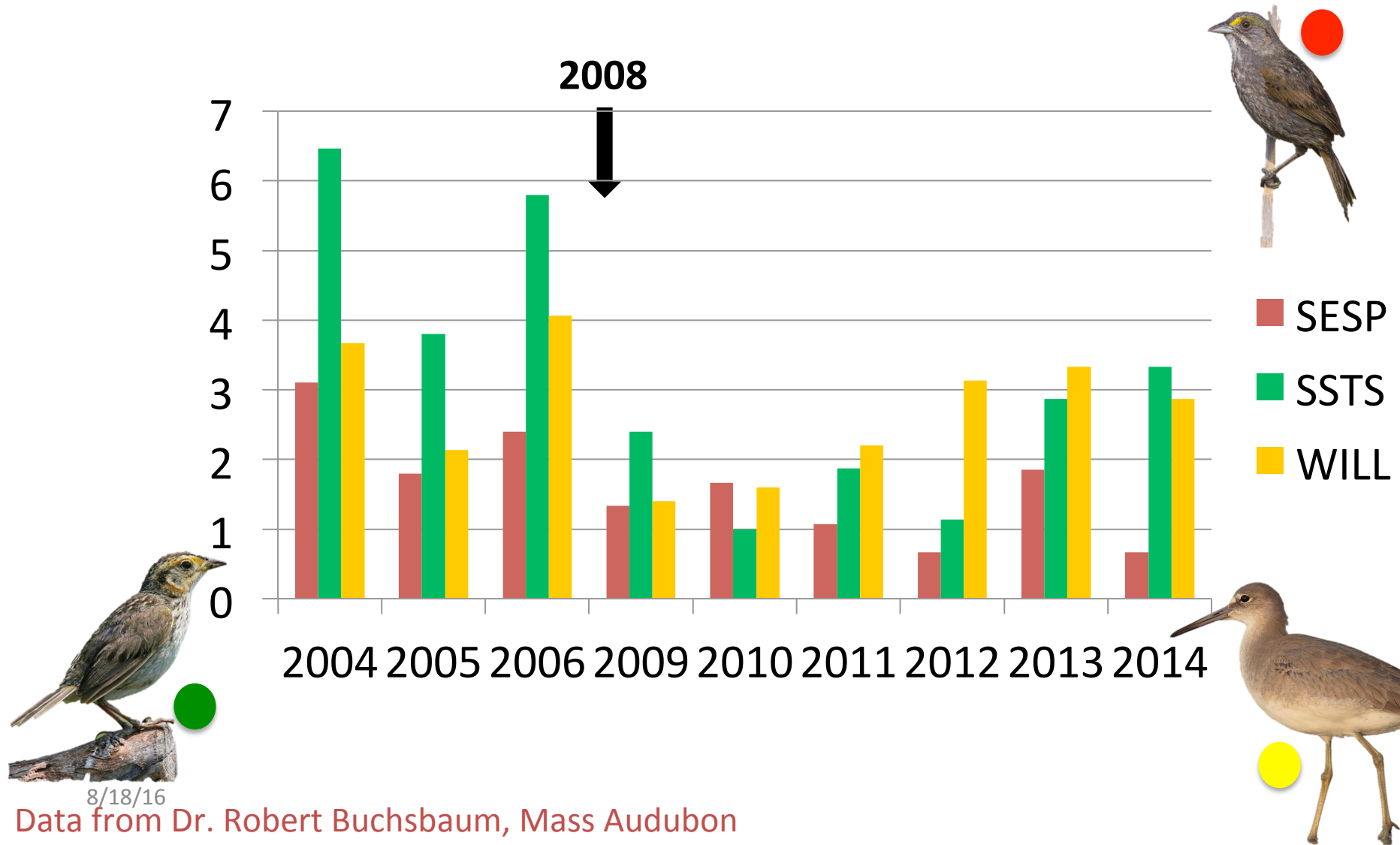




Data from Dr. Robert Buchsbaum, Mass Audubon

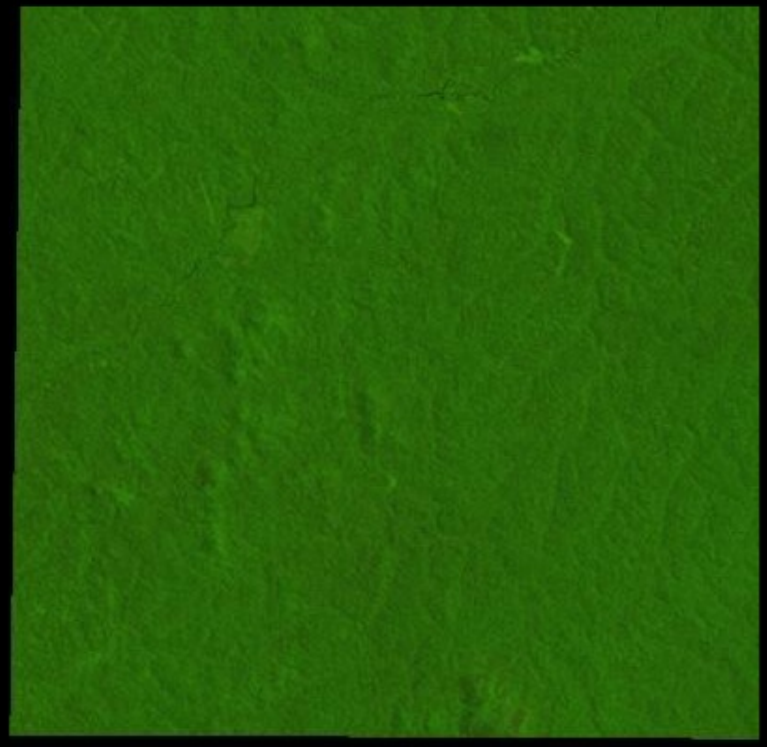
Monitoring Data: Impacts on Bird Species

Seaside Sparrow (SESP), Saltmarsh Sharp-tailed Sparrow (SSTS), Willet (WILL)

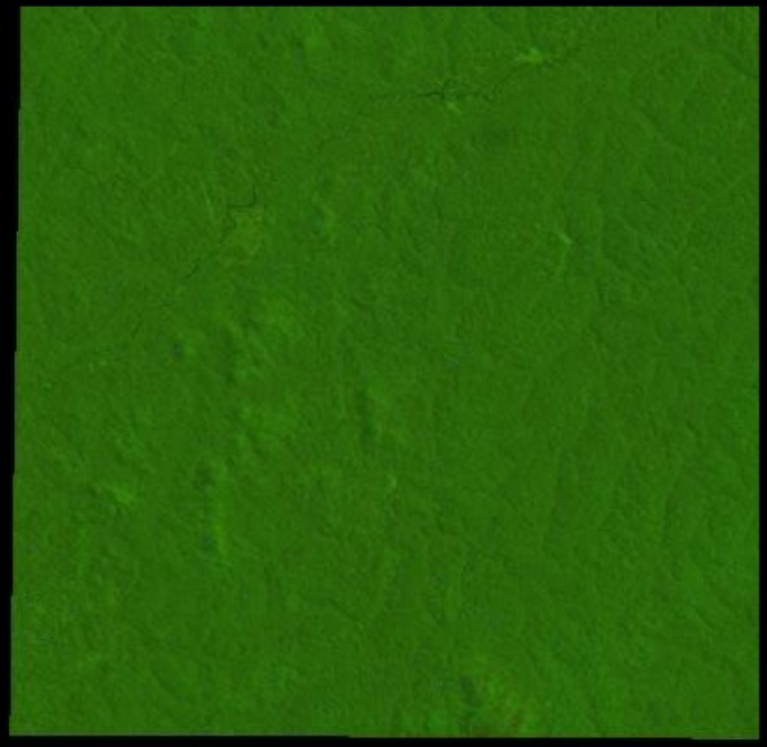


Data from Dr. Robert Buchsbaum, Mass Audubon

2000 - 249



Observed

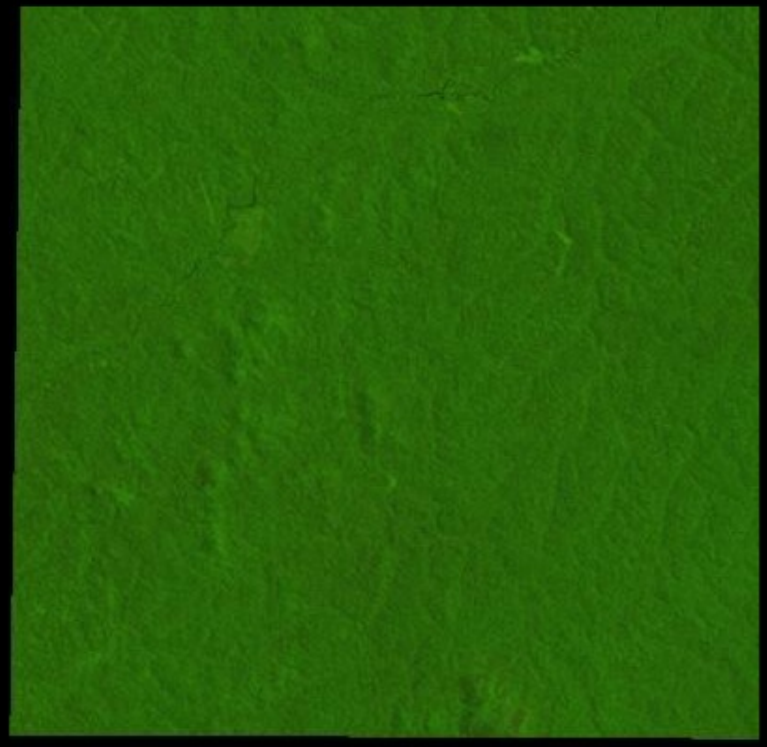


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 249



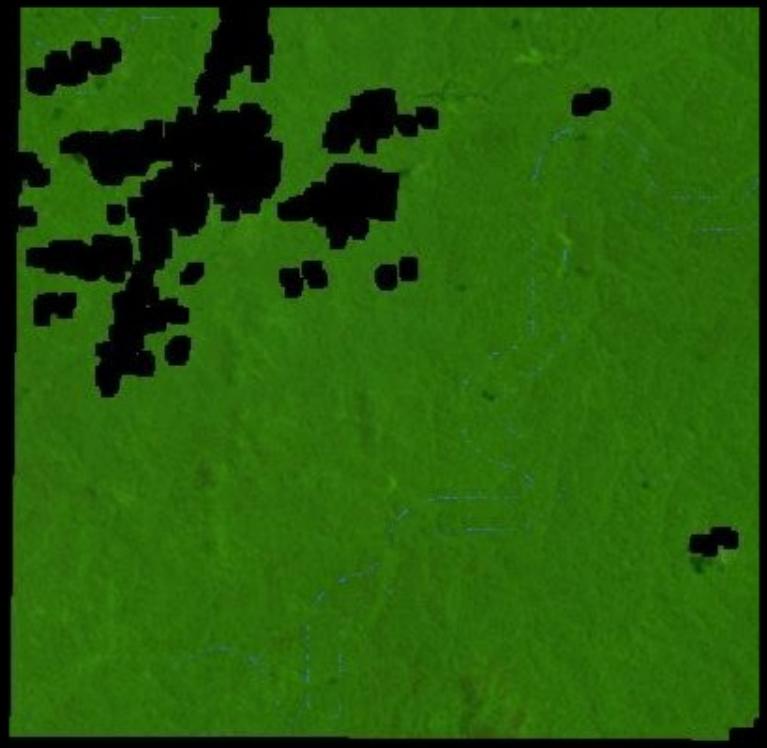
Observed

Predicted

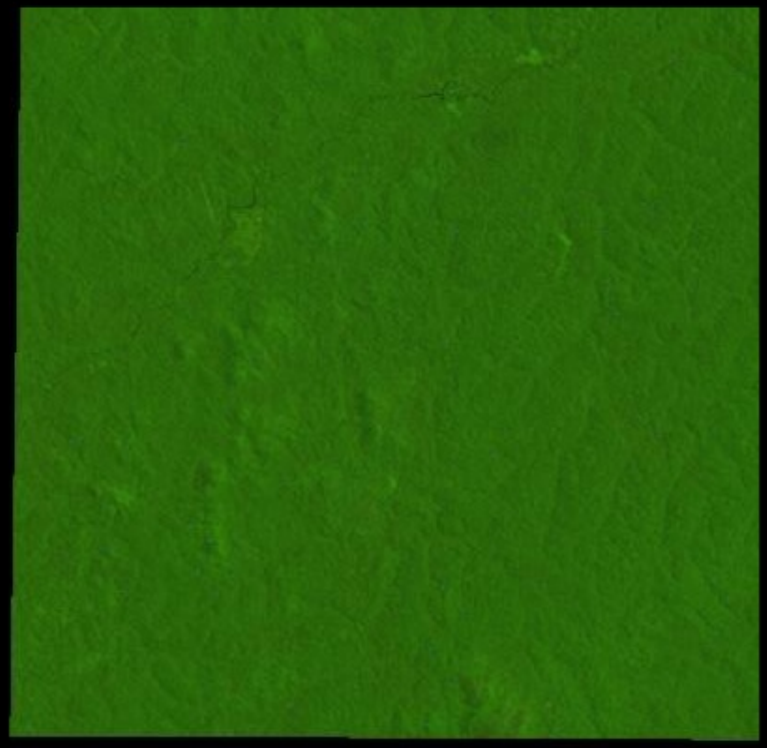
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 257



Observed

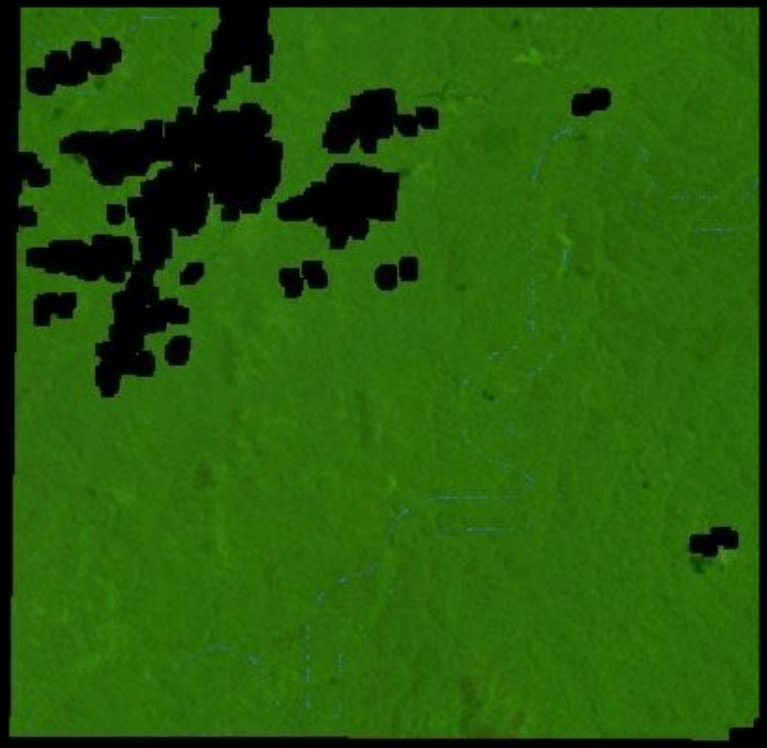


Predicted

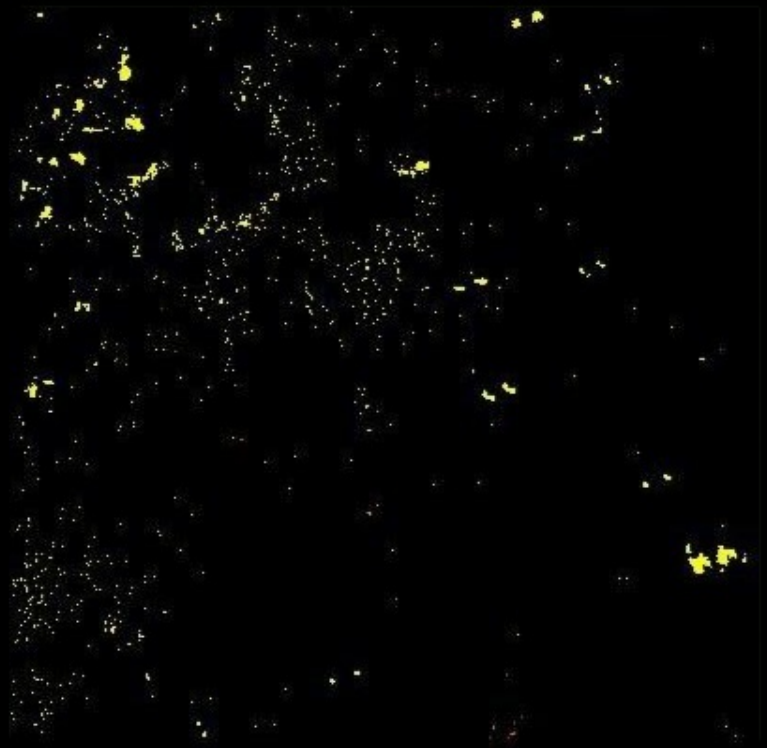
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 257



Observed

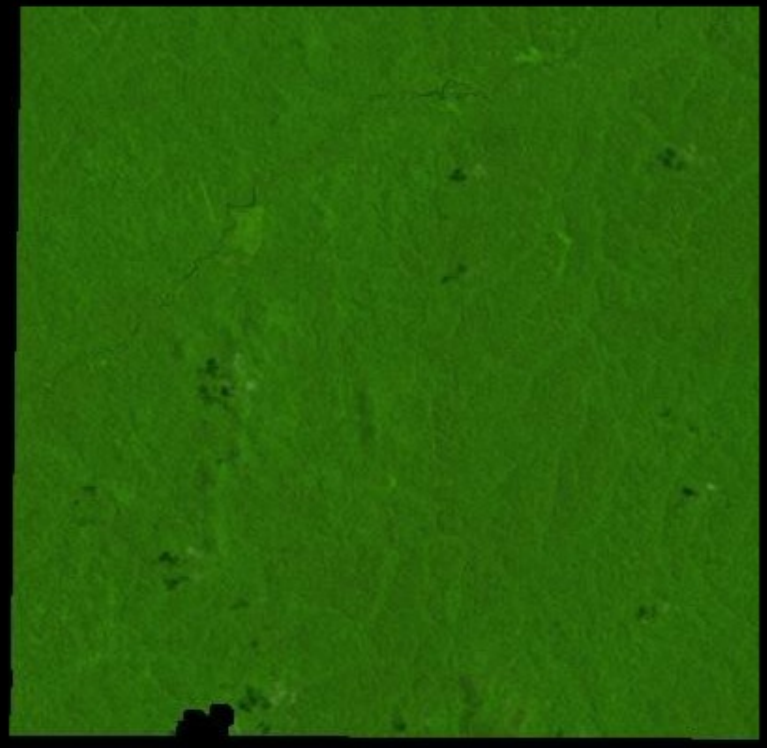


Predicted

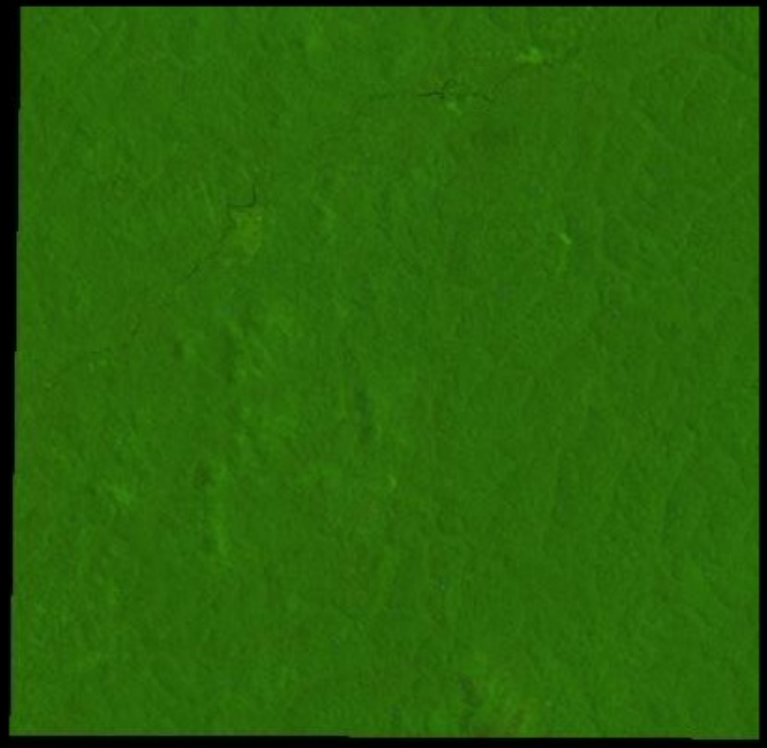
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 265



Observed

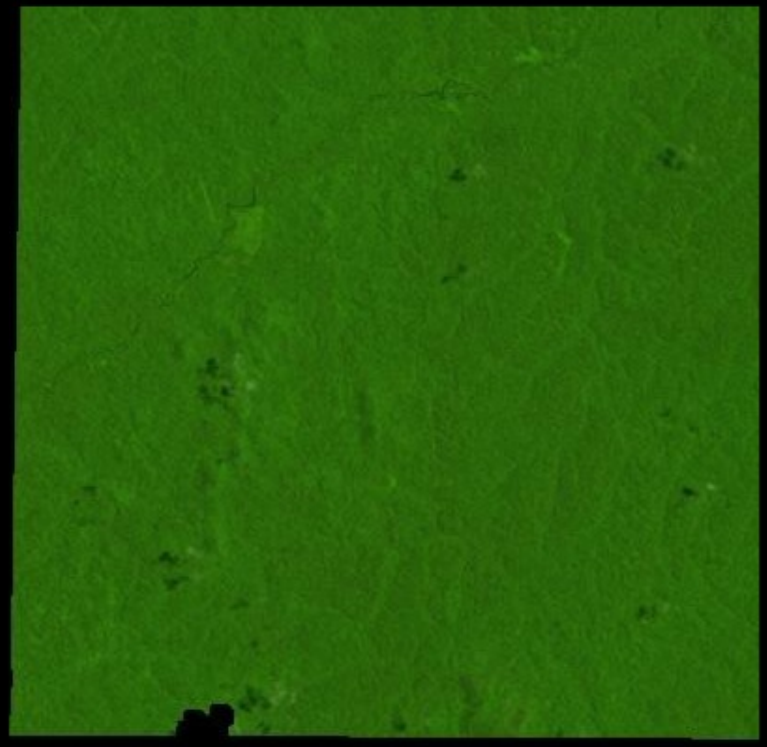


Predicted

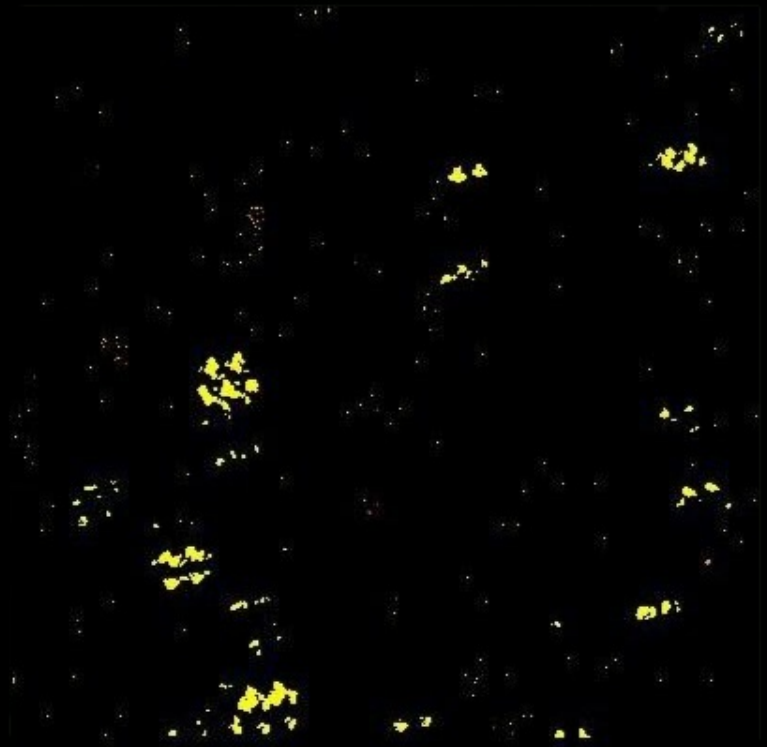
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 265



Observed

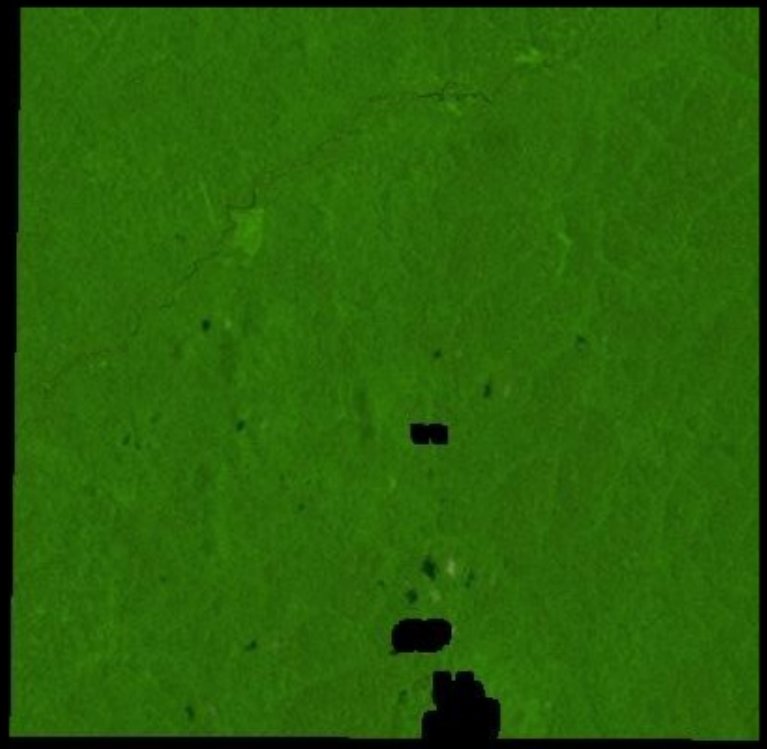


Predicted

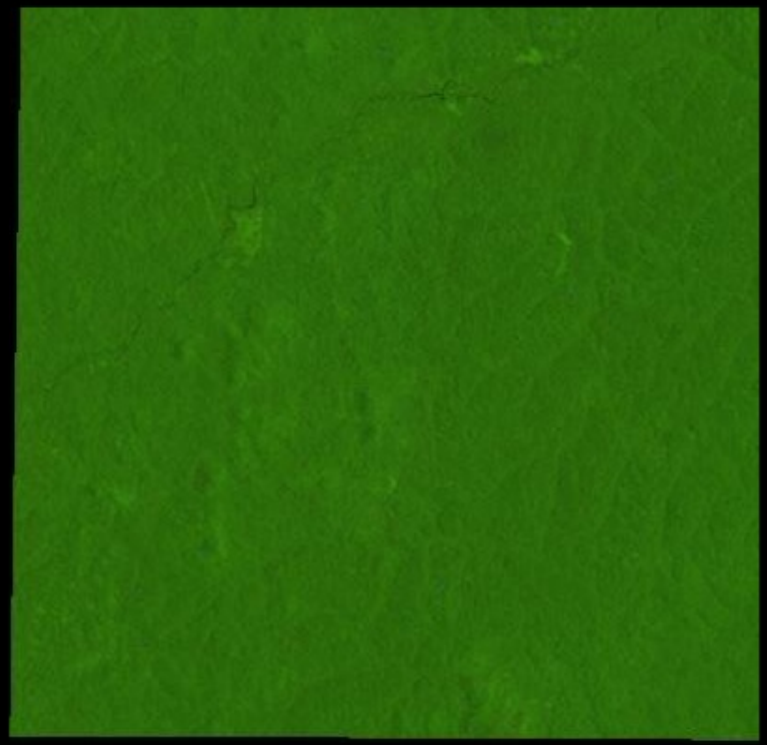
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 281



Observed

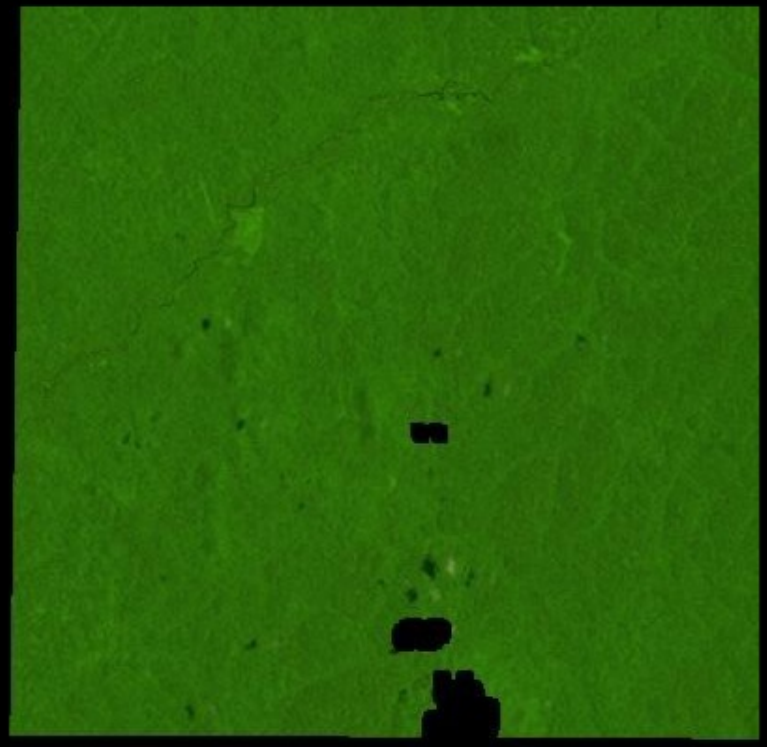


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 281



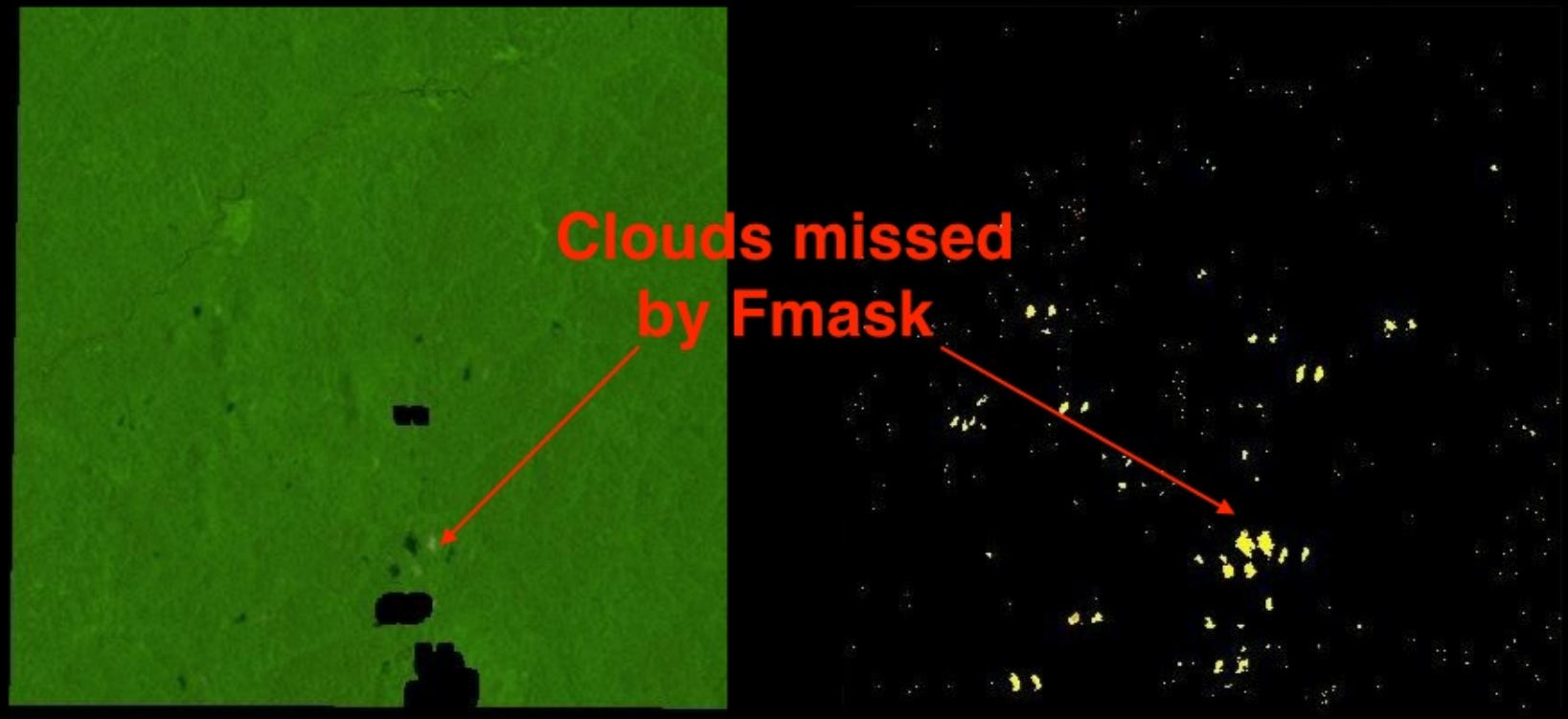
Observed

Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 281



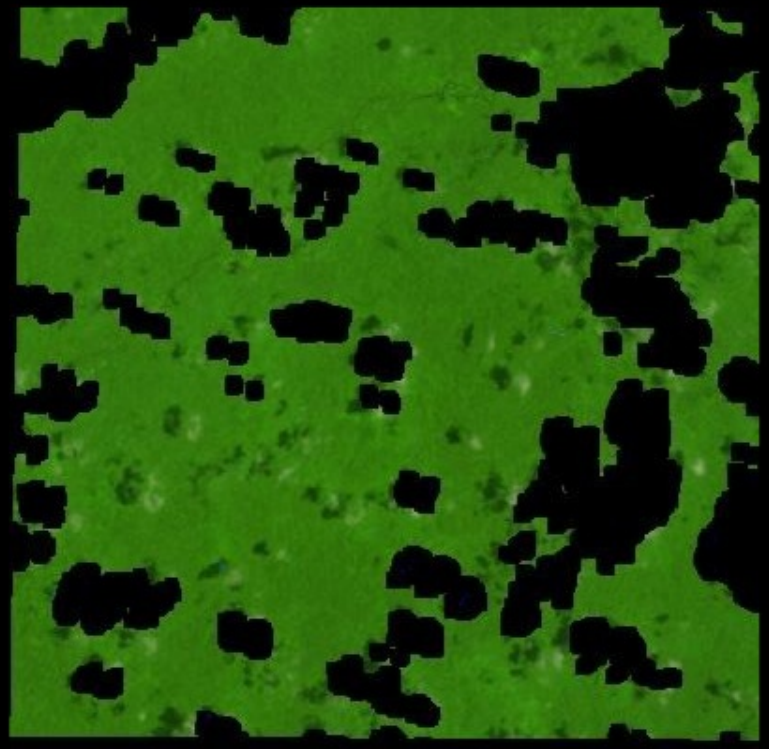
Observed

Predicted

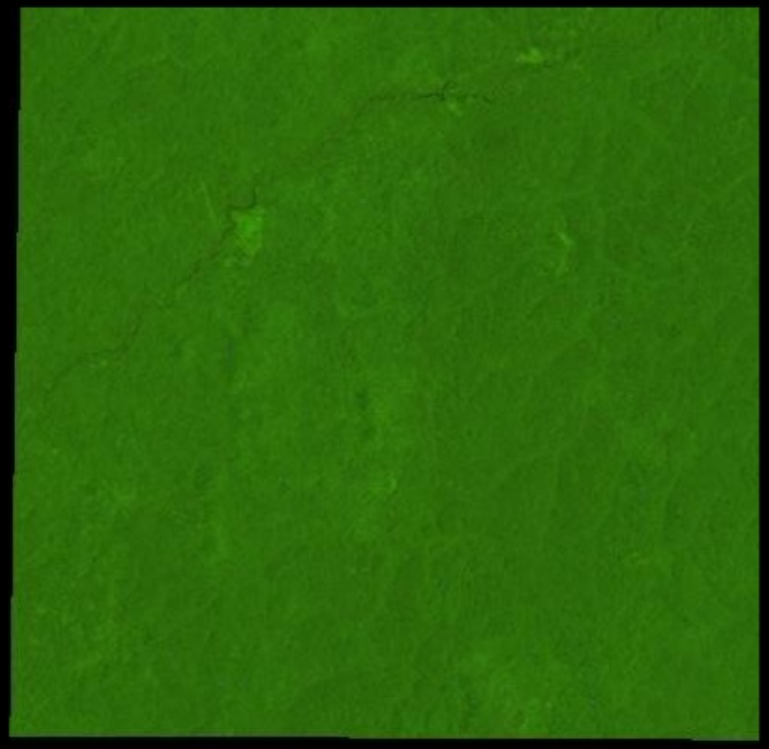
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 305



Observed

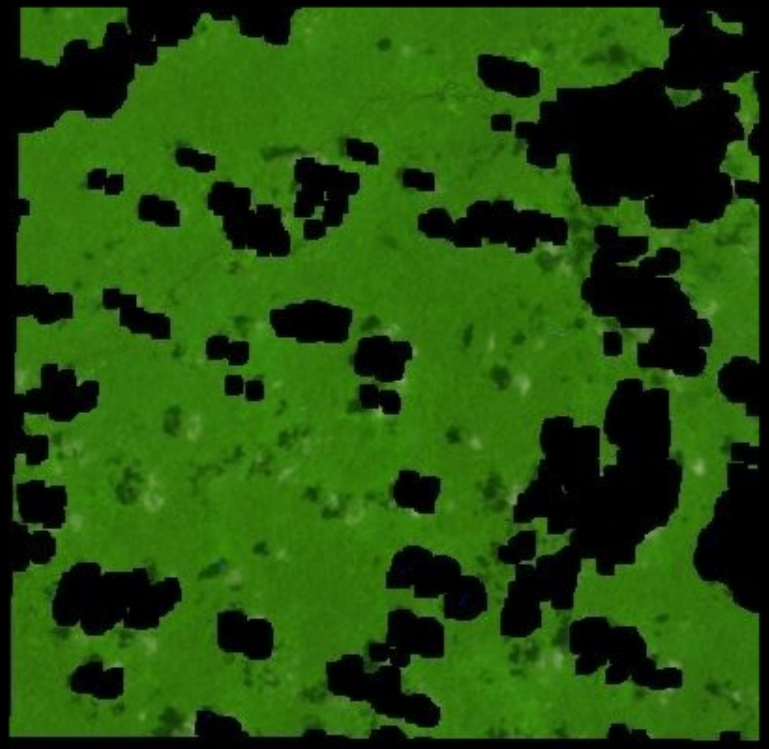


Predicted

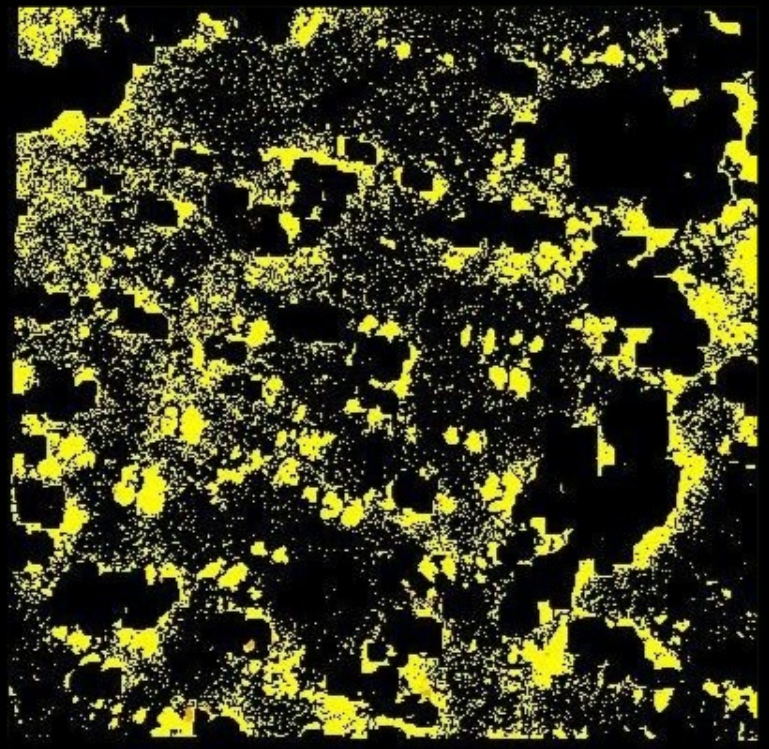
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 305



Observed

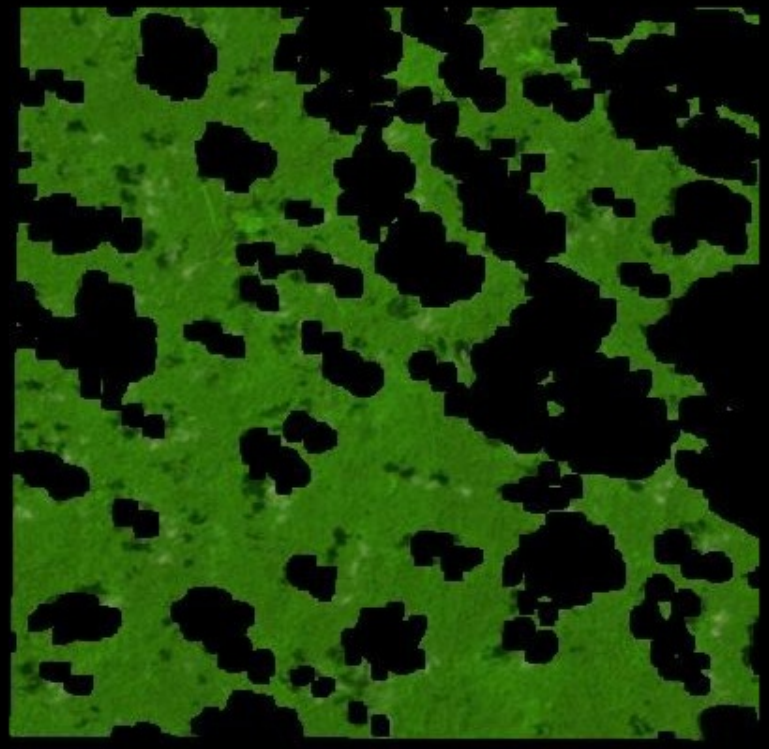


Predicted

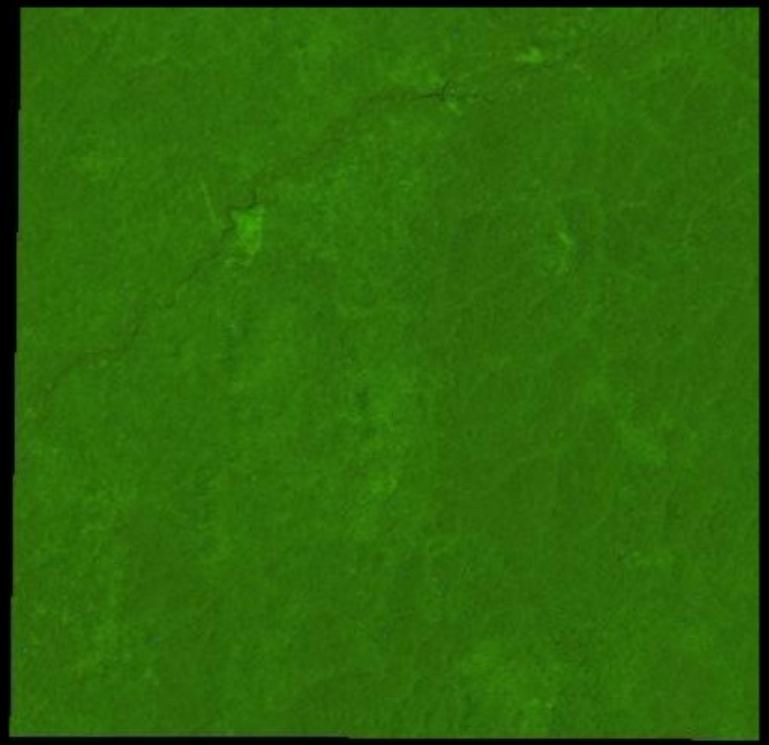
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 329



Observed

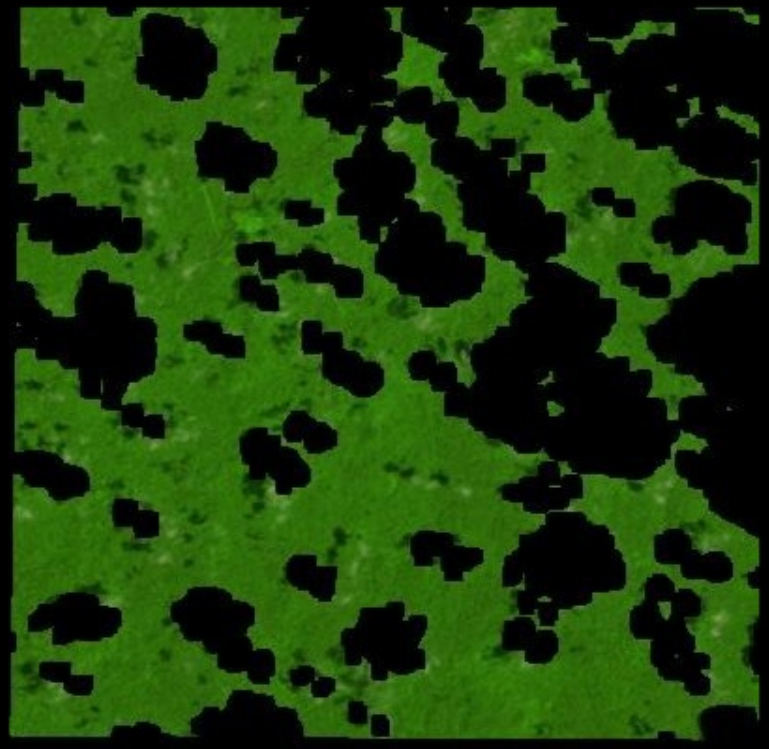


Predicted

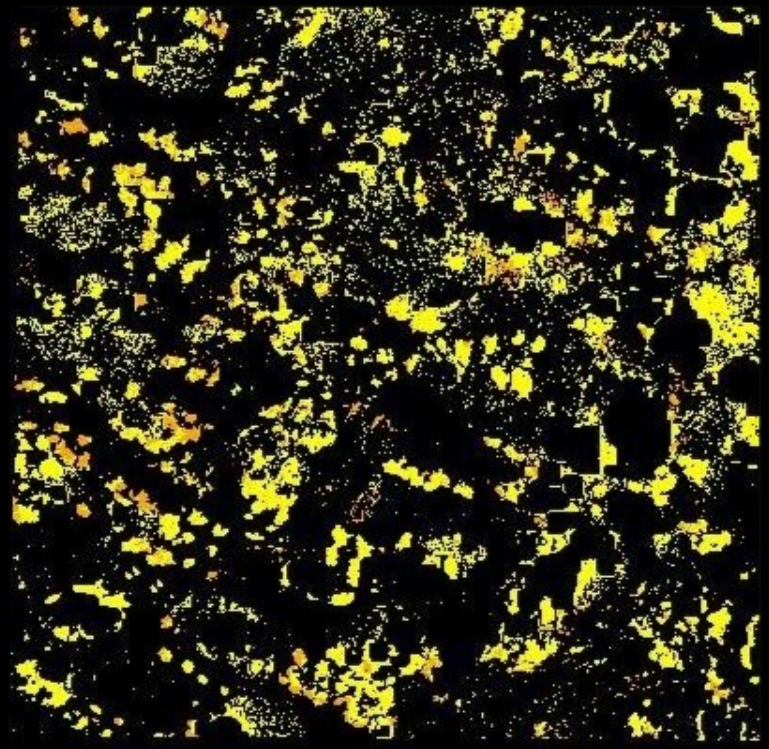
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2000 - 329



Observed

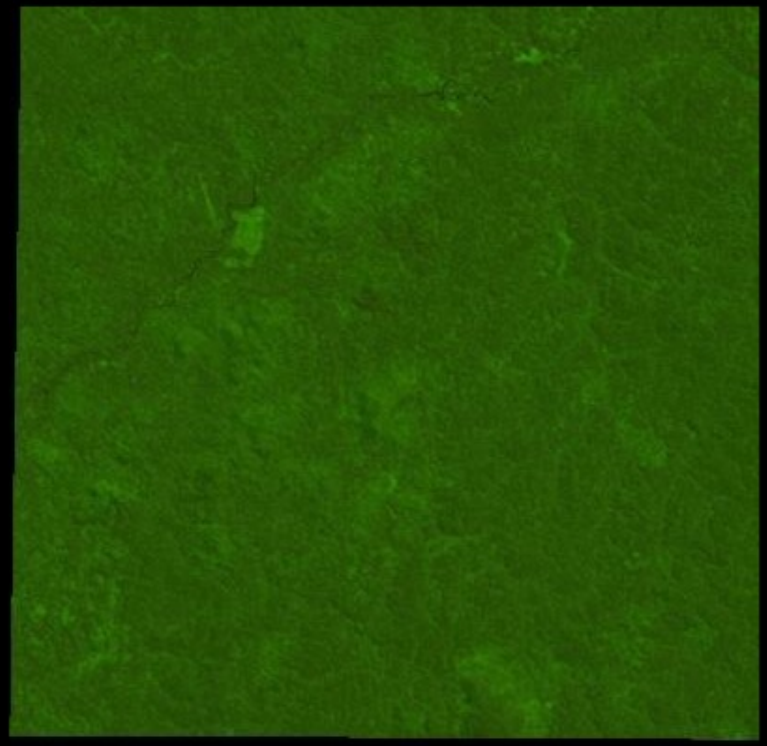


Predicted

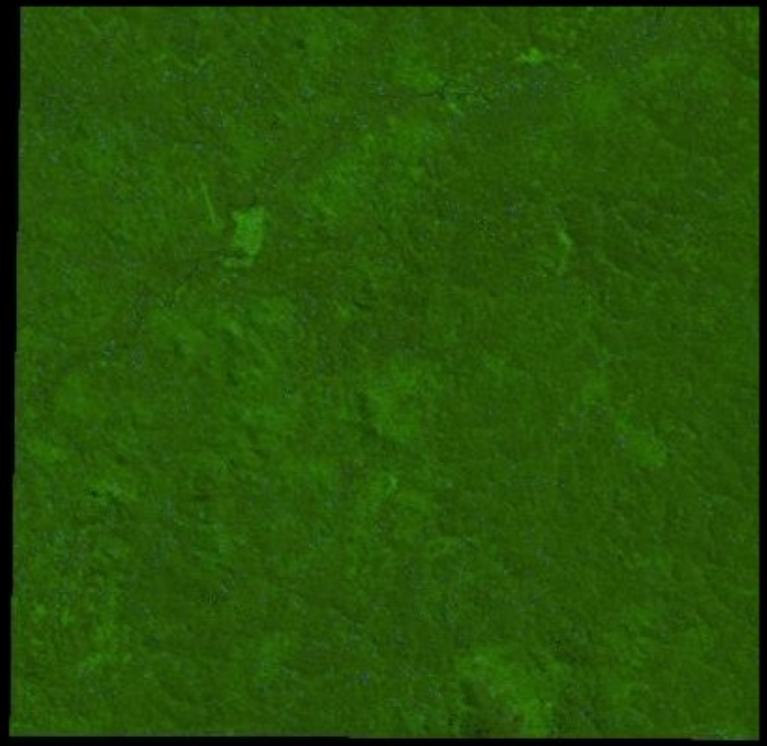
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 115



Observed

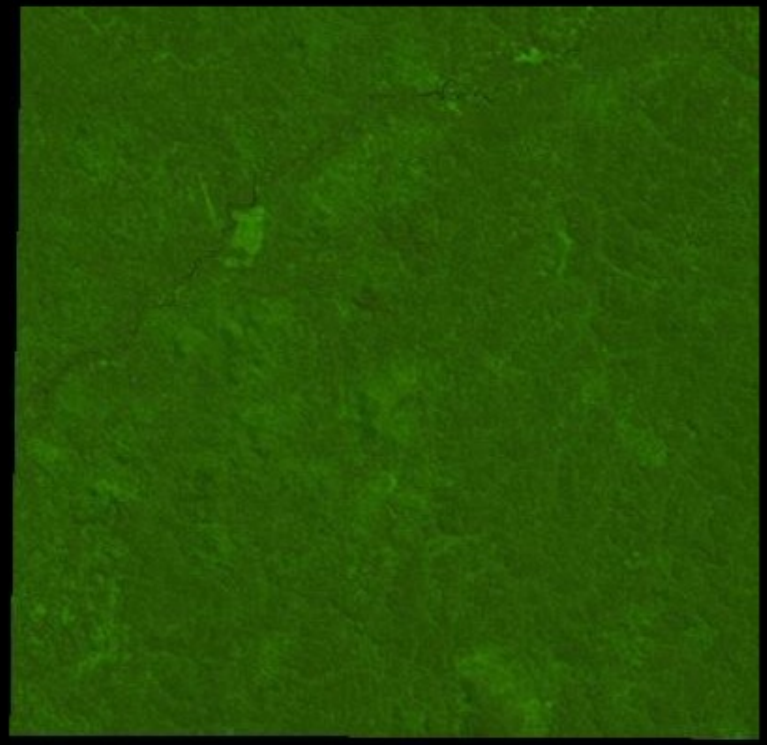


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 115



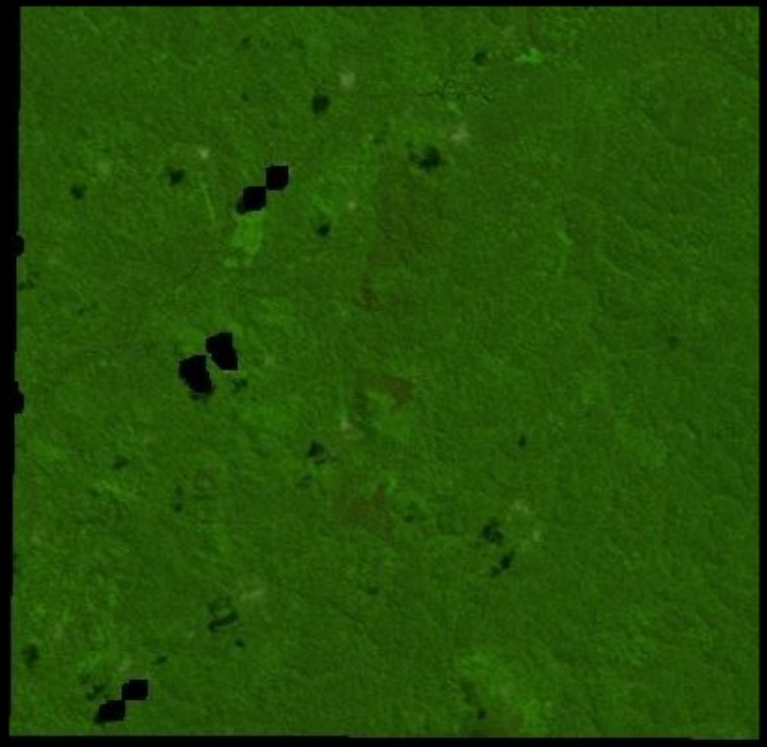
Observed

Predicted

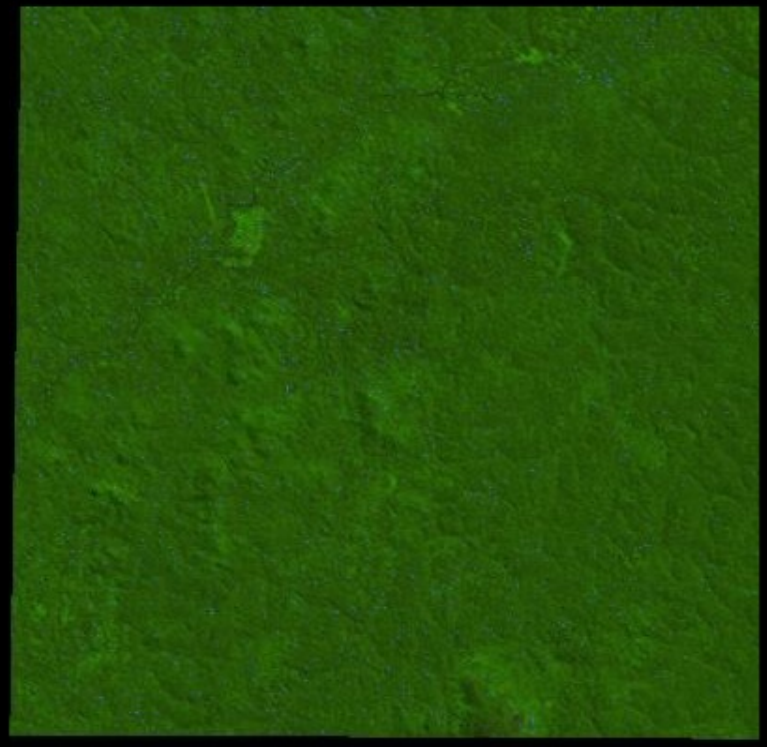
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 139



Observed

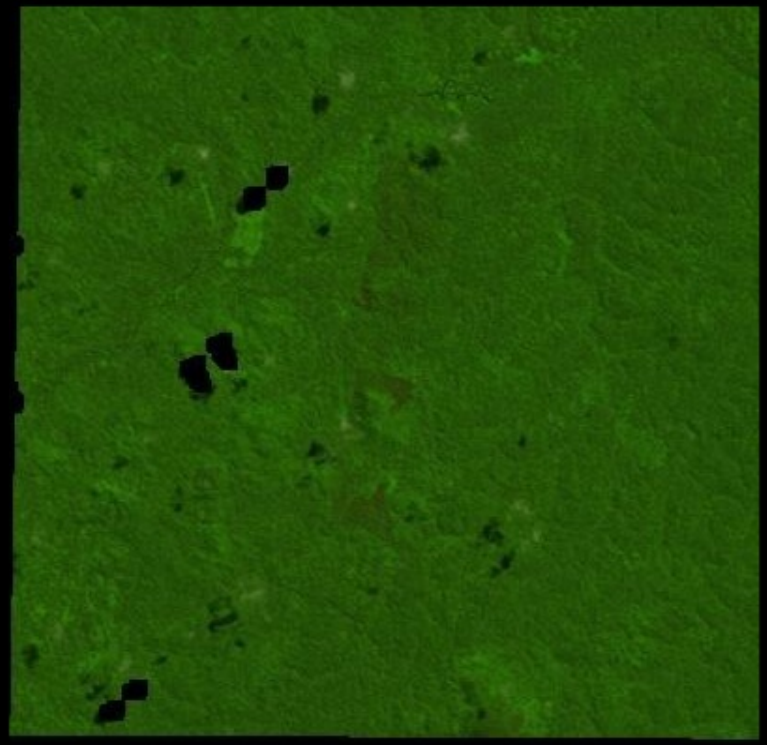


Predicted

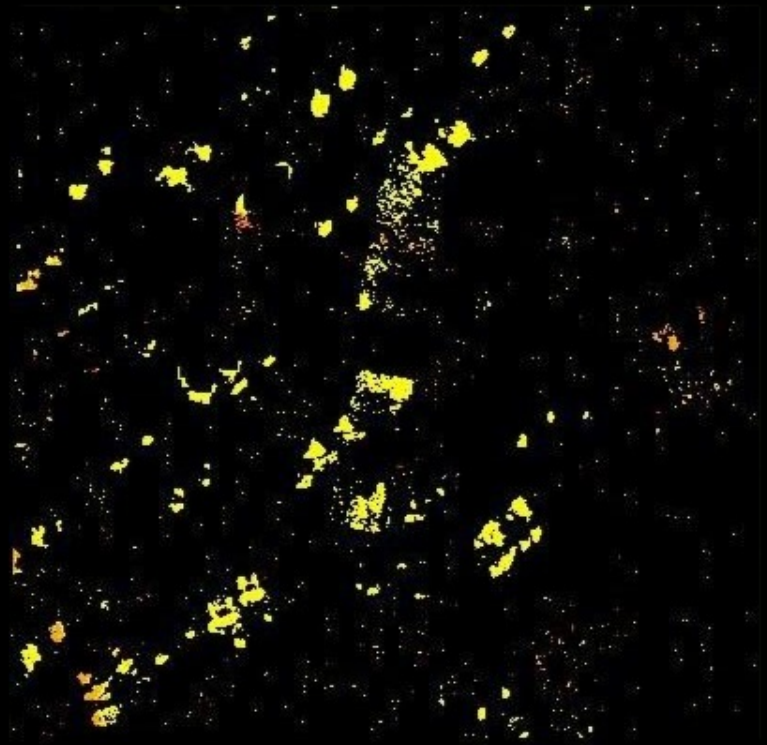
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 139



Observed

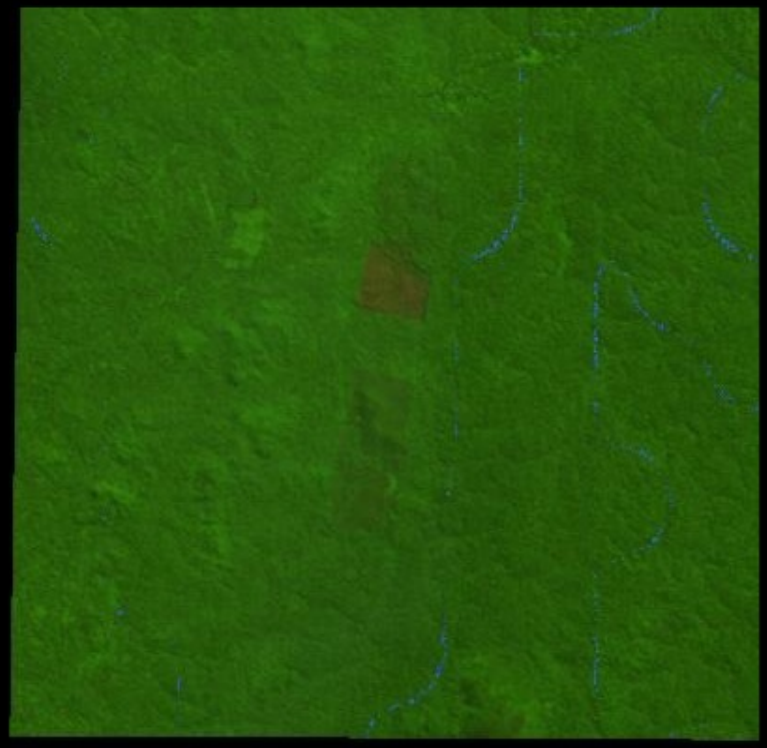


Predicted

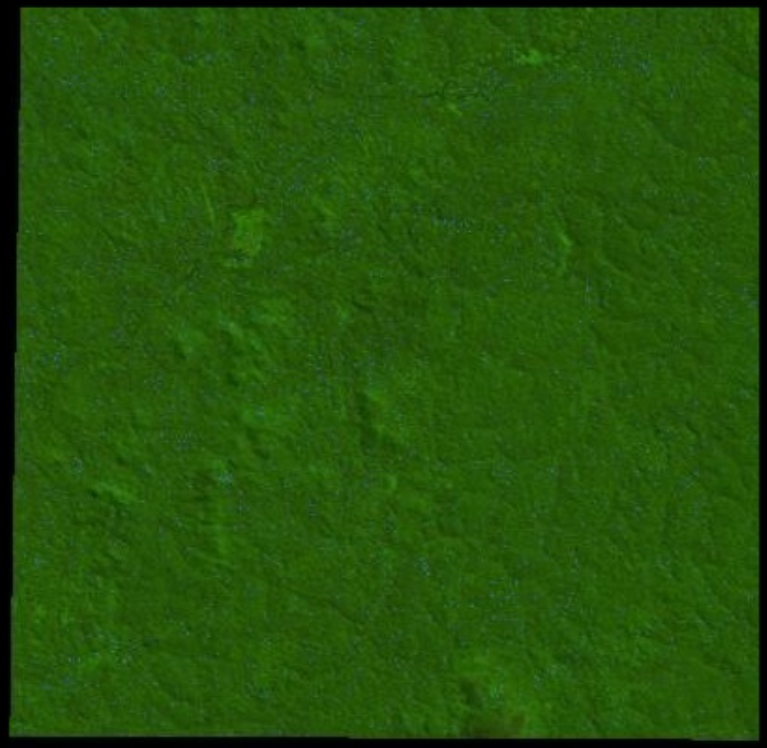
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 163



Observed

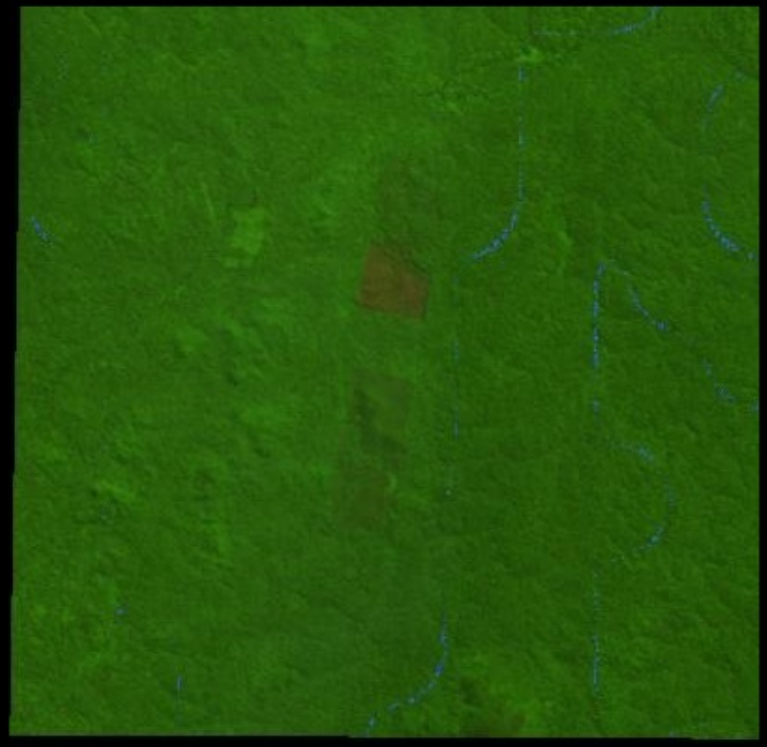


Predicted

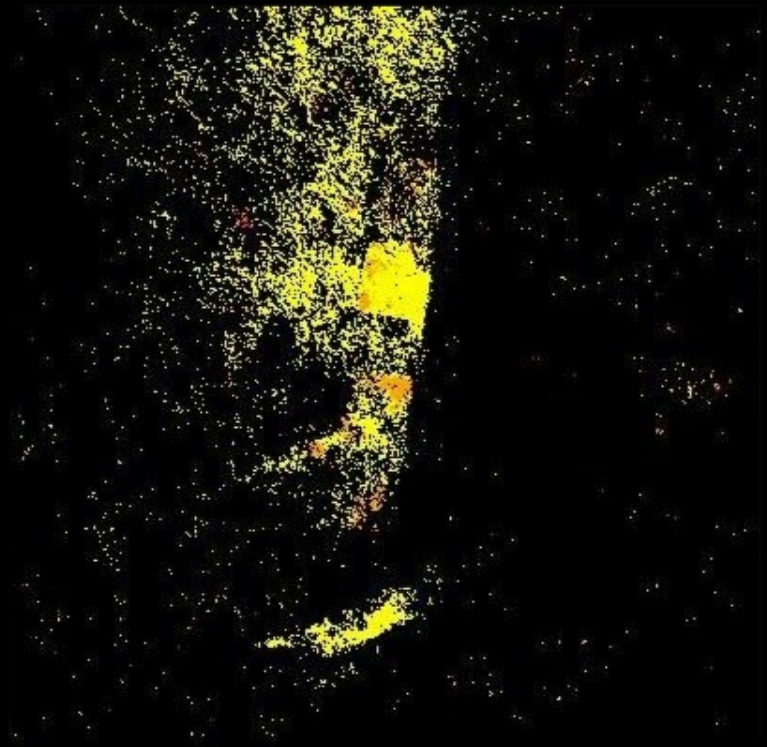
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 163



Observed

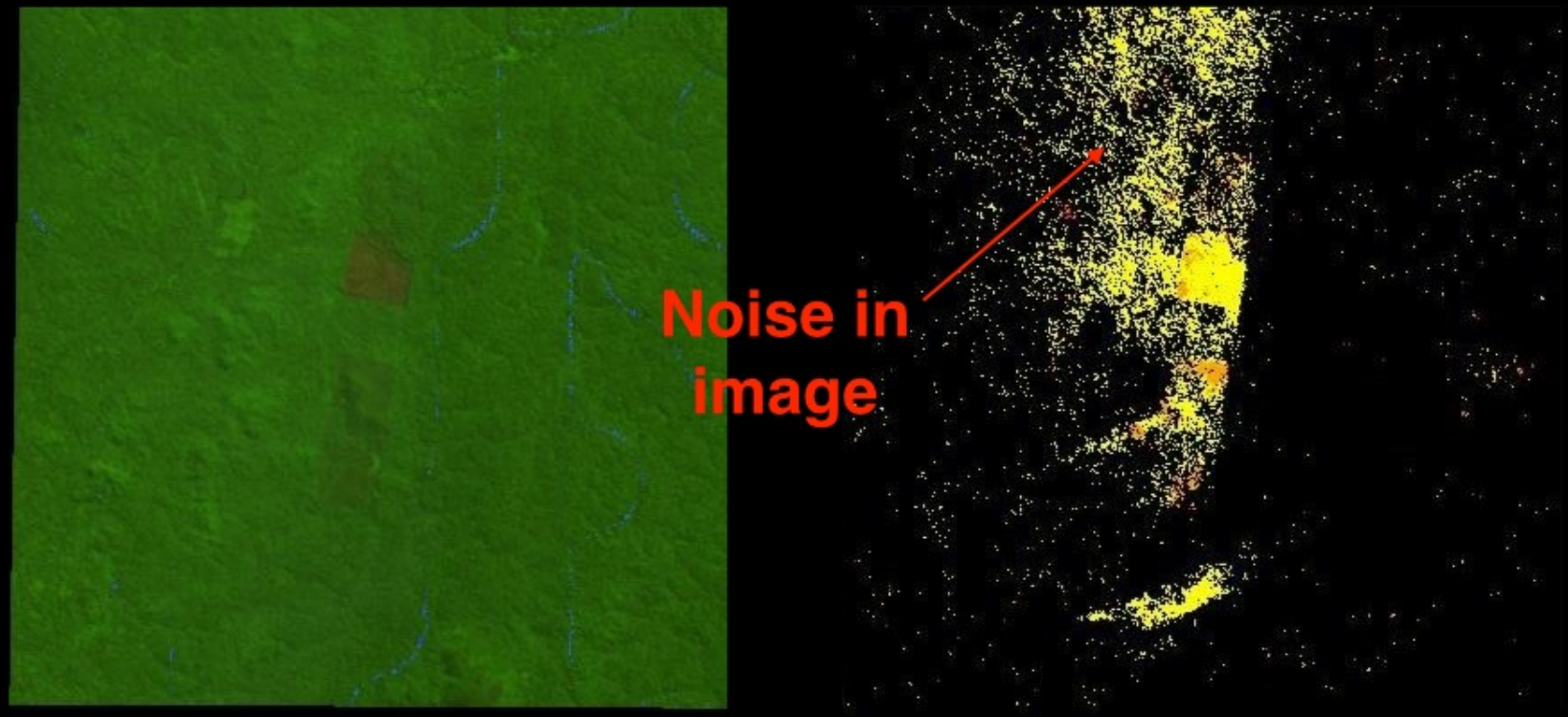


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 163



Observed

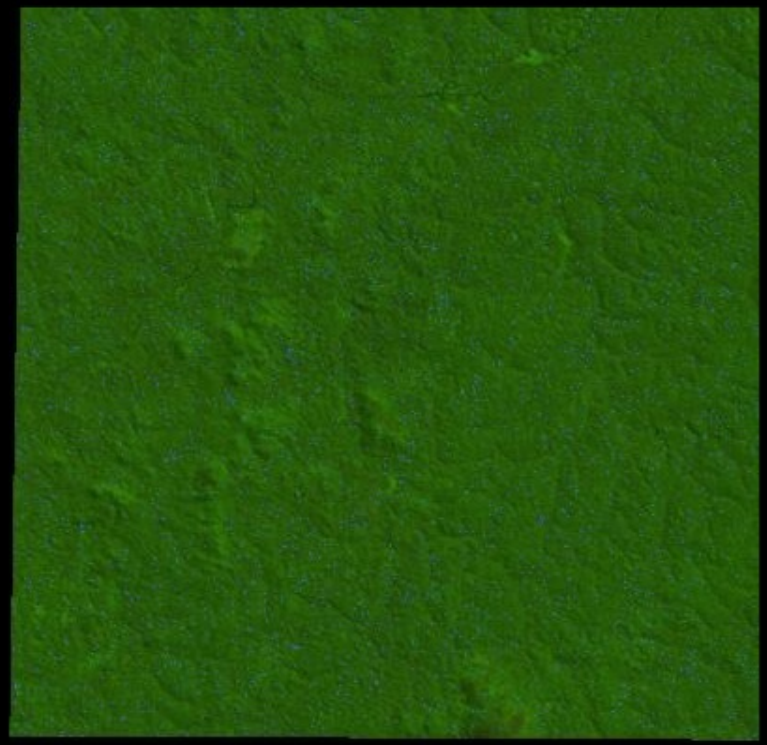
Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 179

Observed



Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 179

Observed

Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 195

Observed

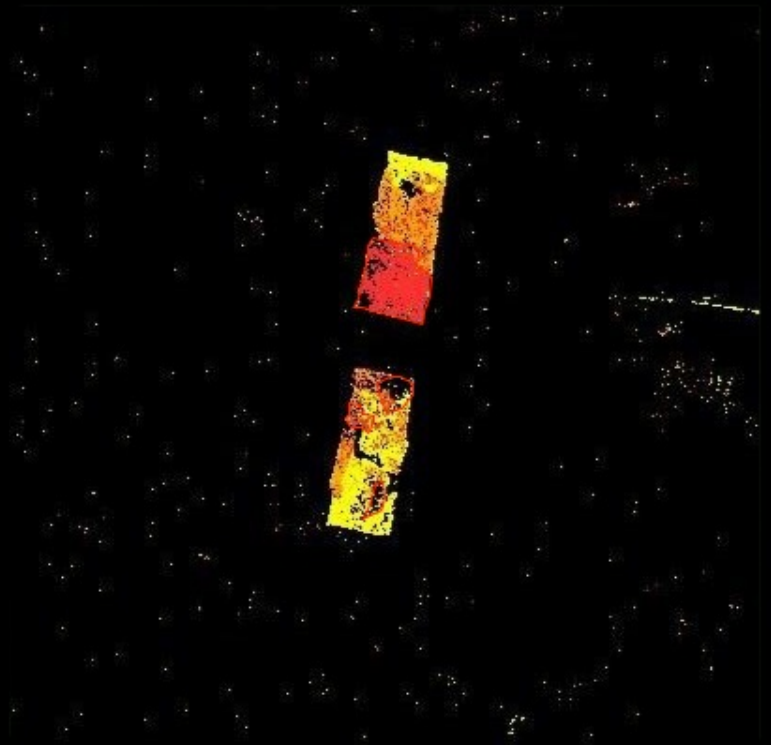
Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 195

Observed



Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 211

Observed

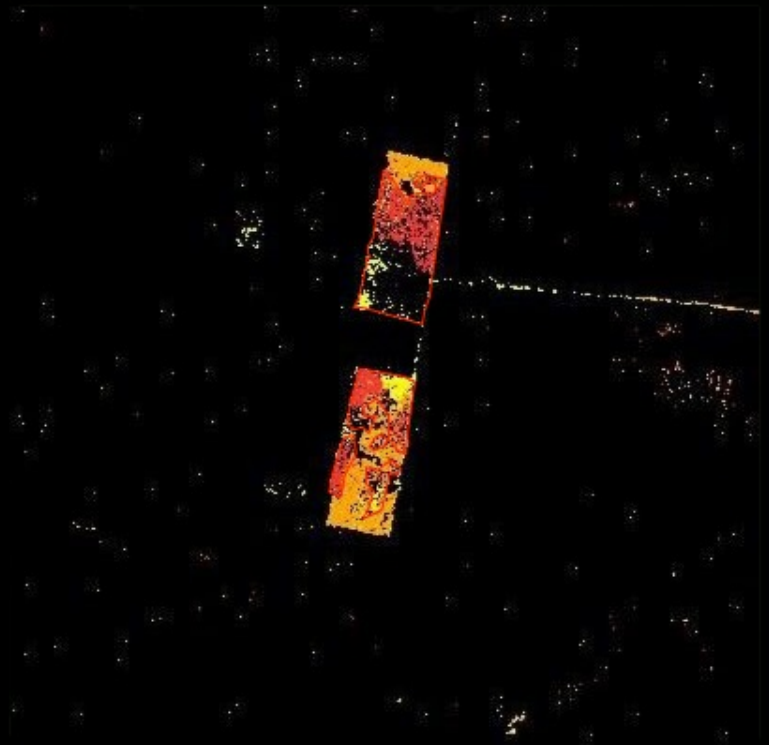
Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 211

Observed



Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 227

Observed

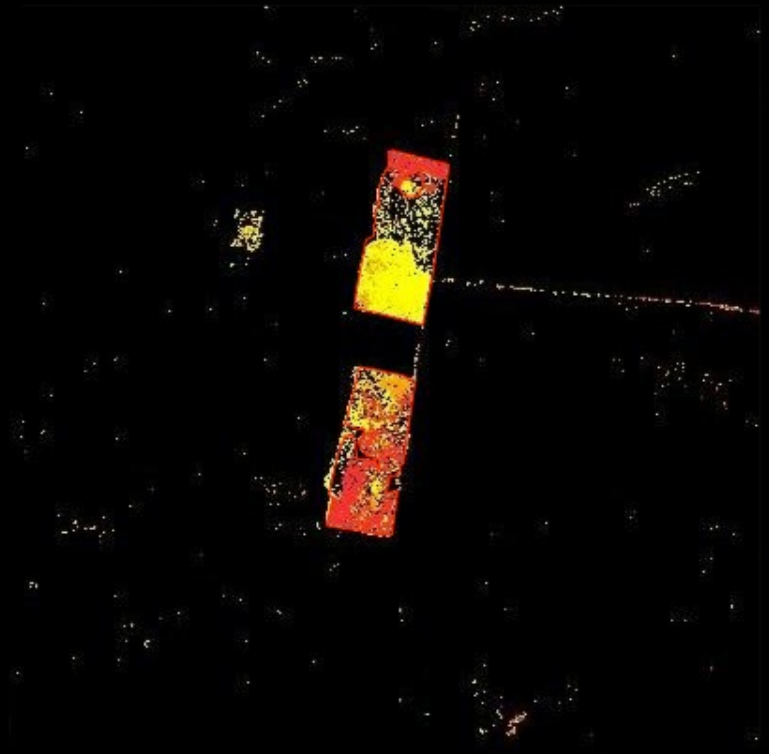
Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 227

Observed

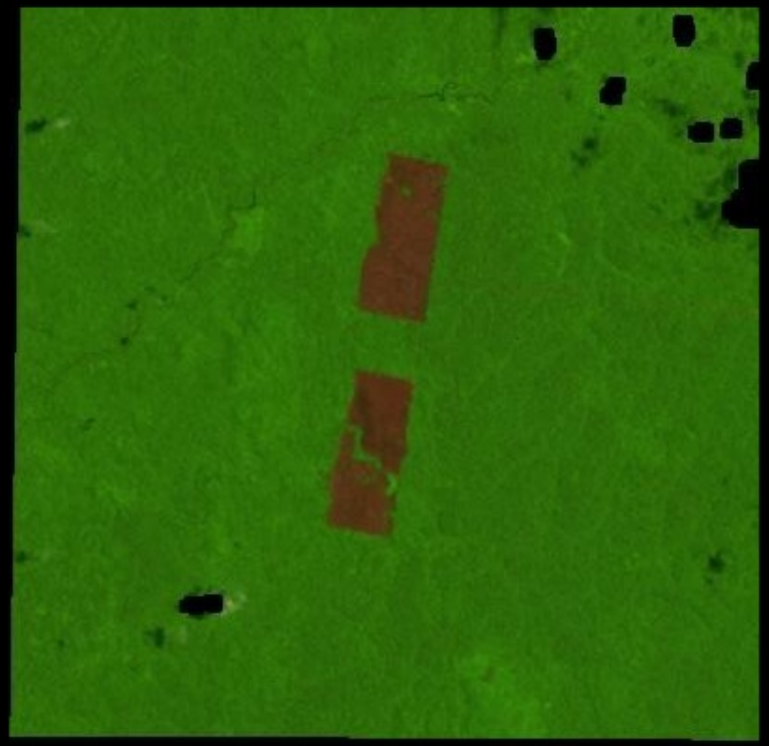


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 275



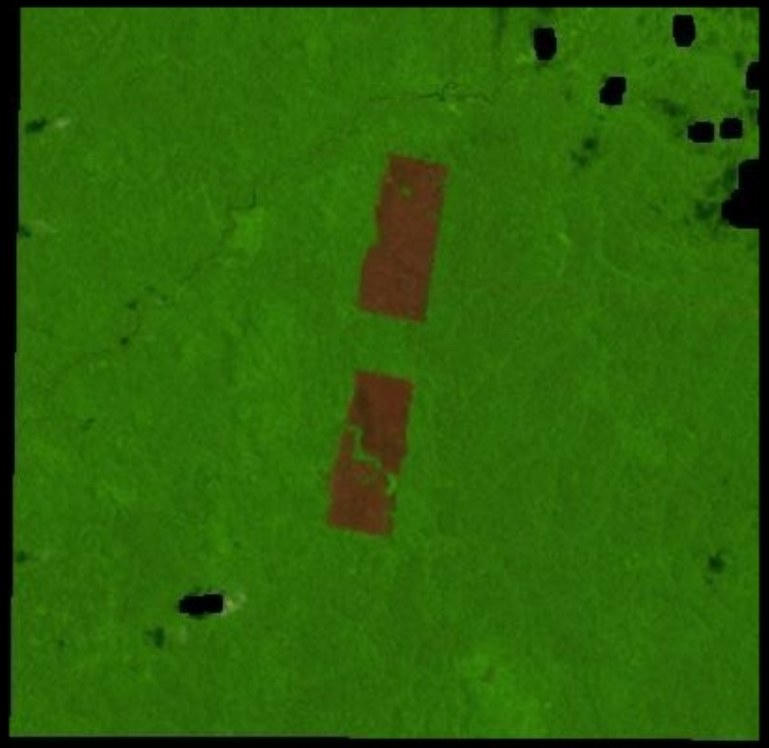
Observed

Predicted

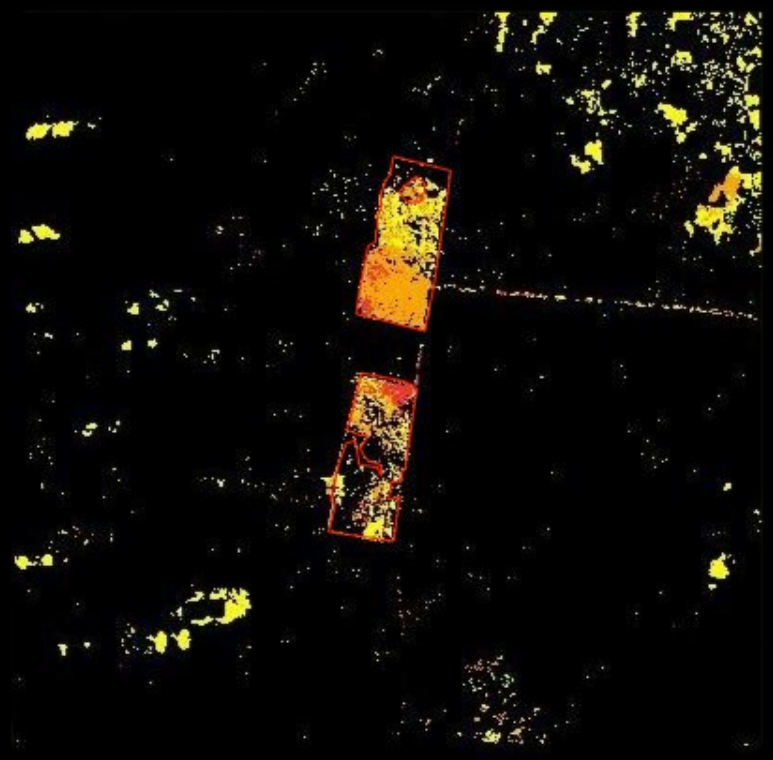
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 275



Observed

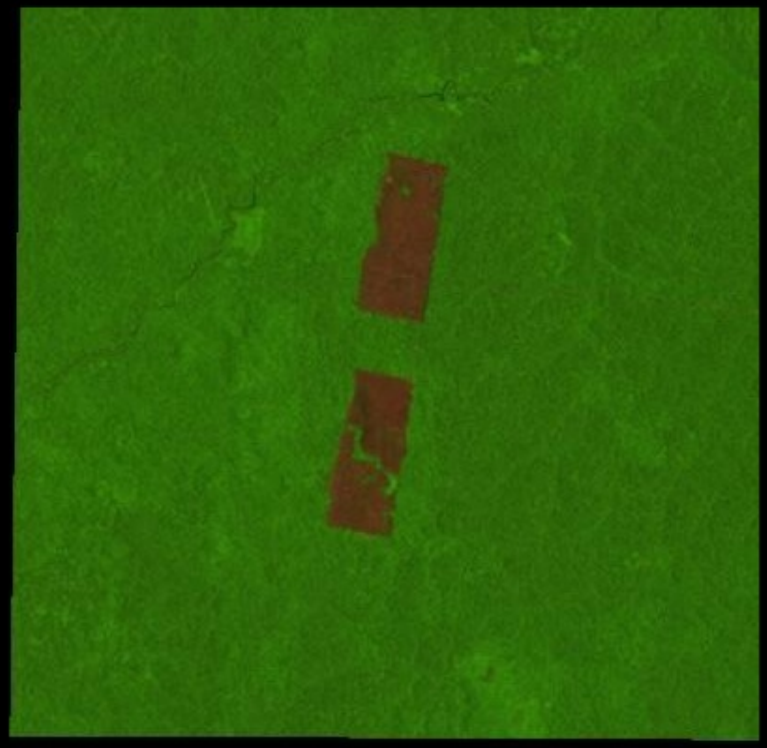


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 283



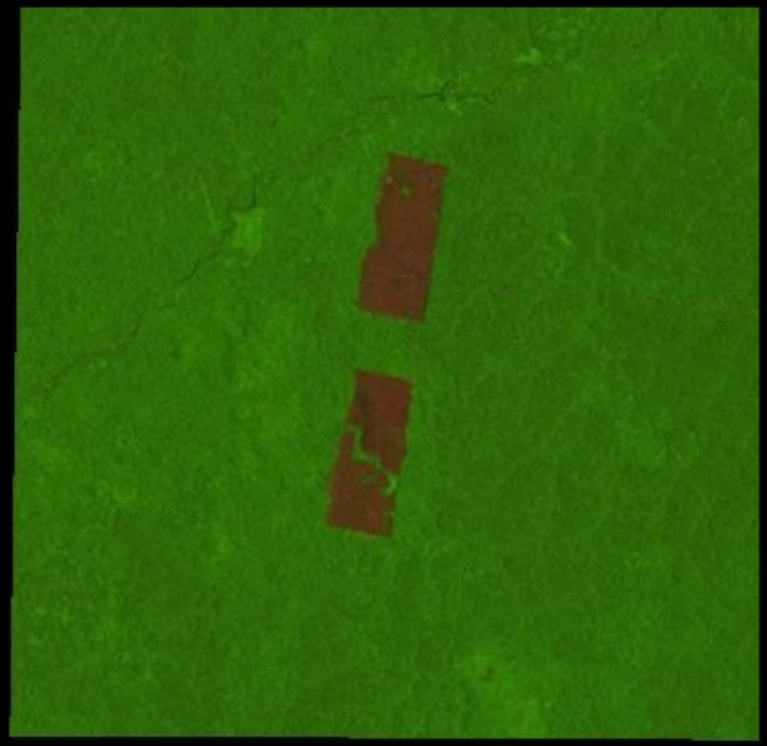
Observed

Predicted

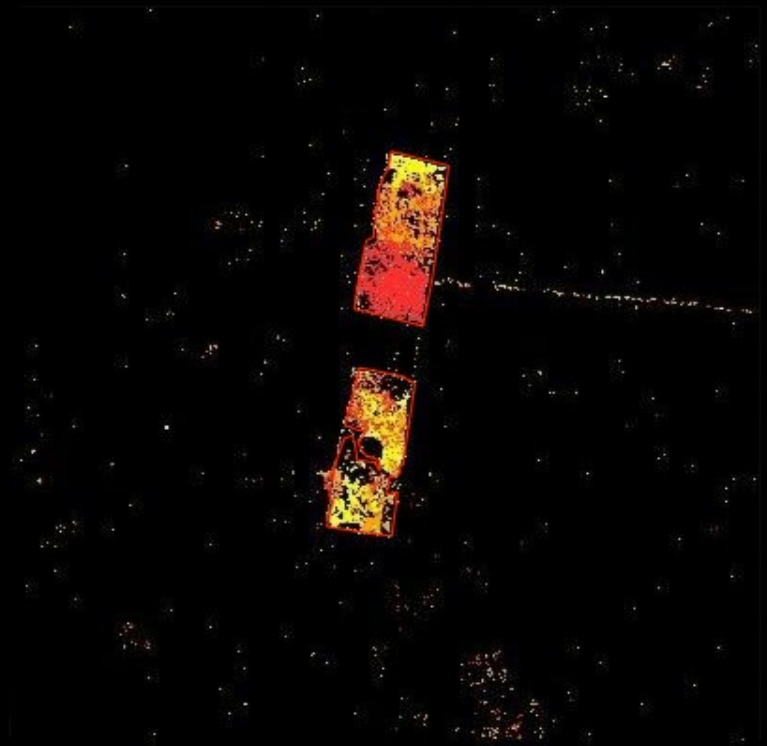
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 283



Observed

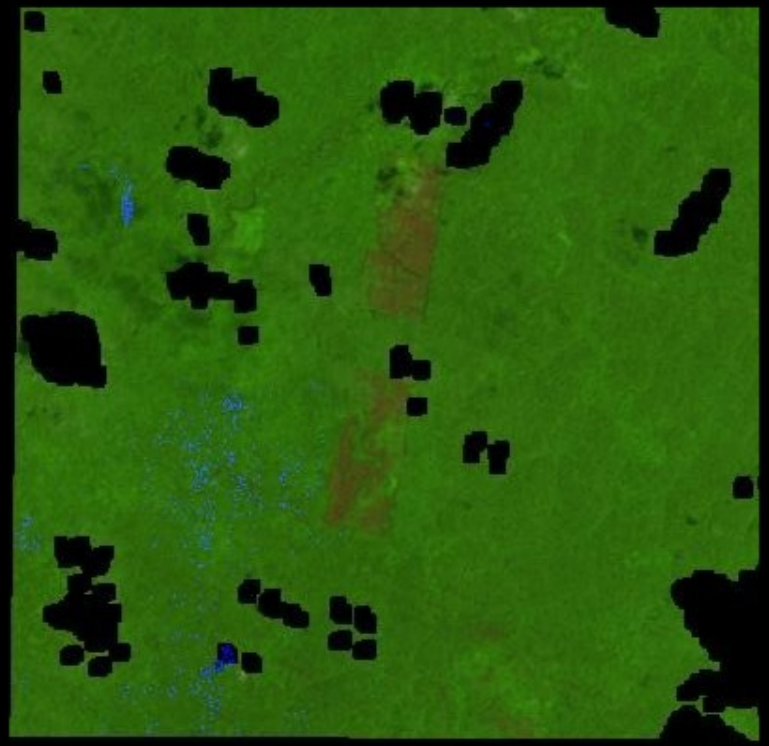


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 315



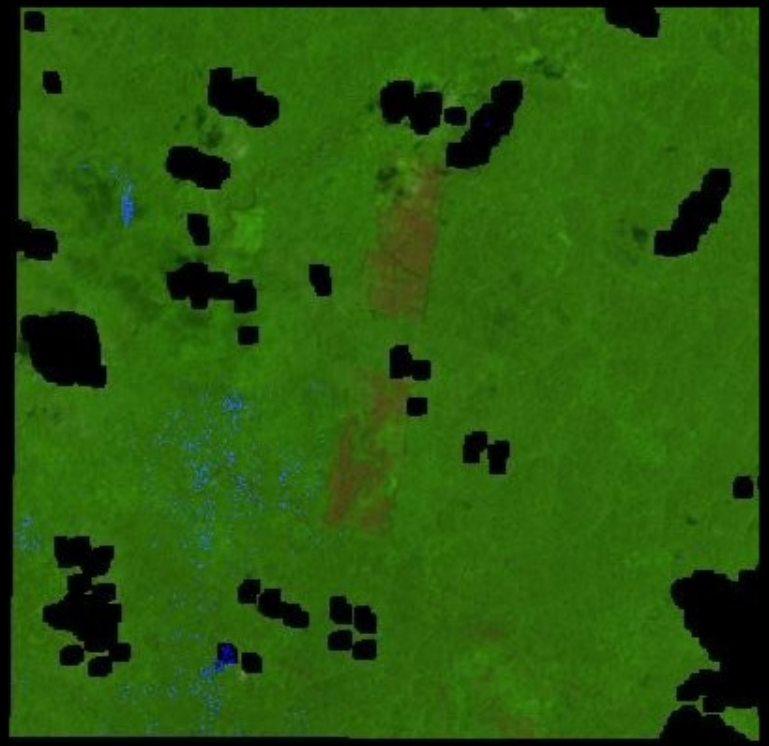
Observed

Predicted

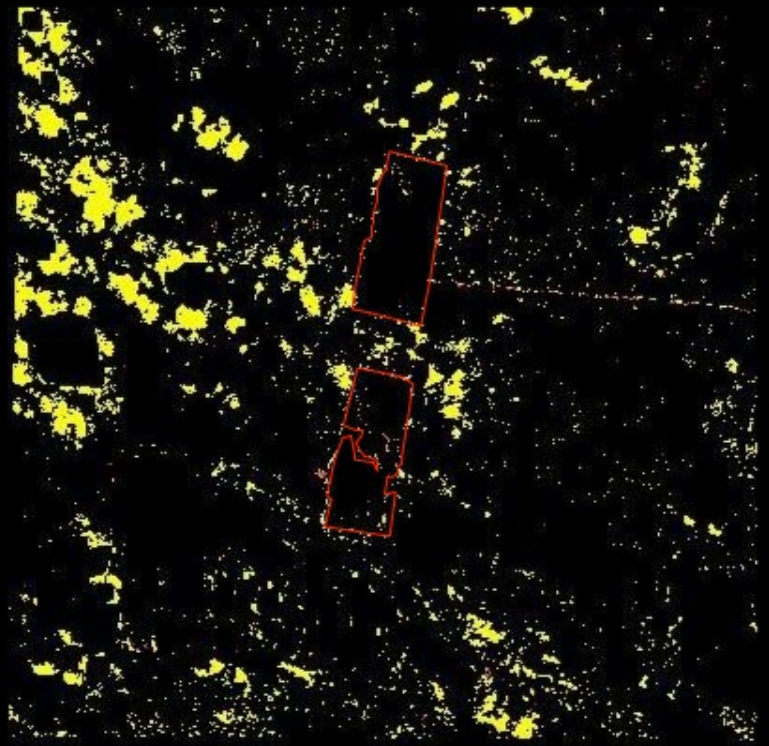
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2001 - 315



Observed

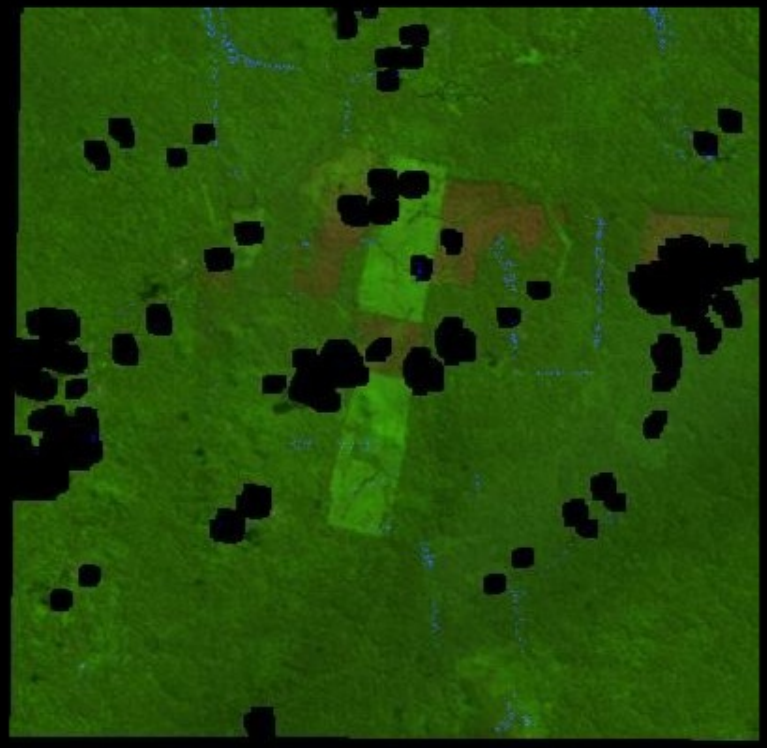


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 134



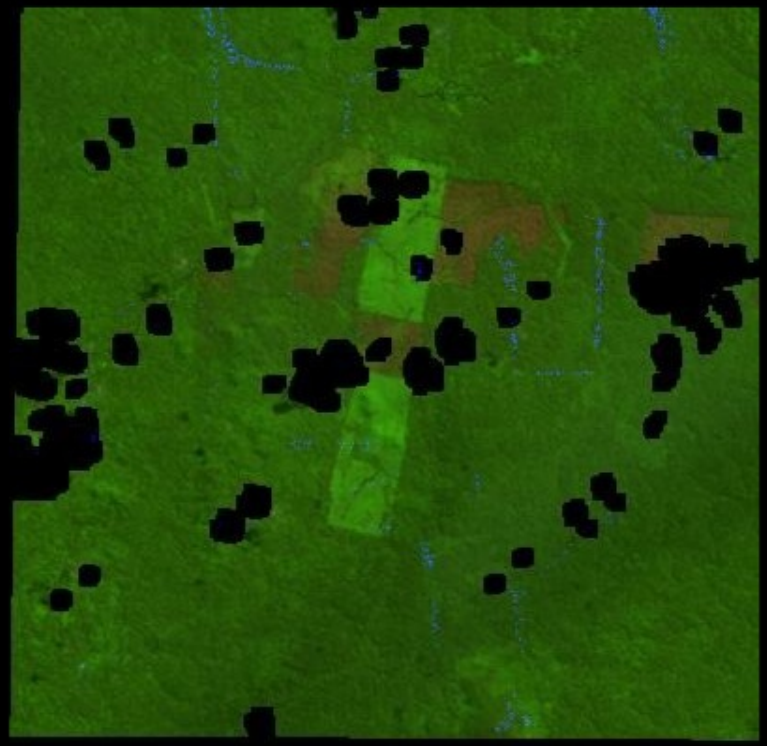
Observed

Predicted

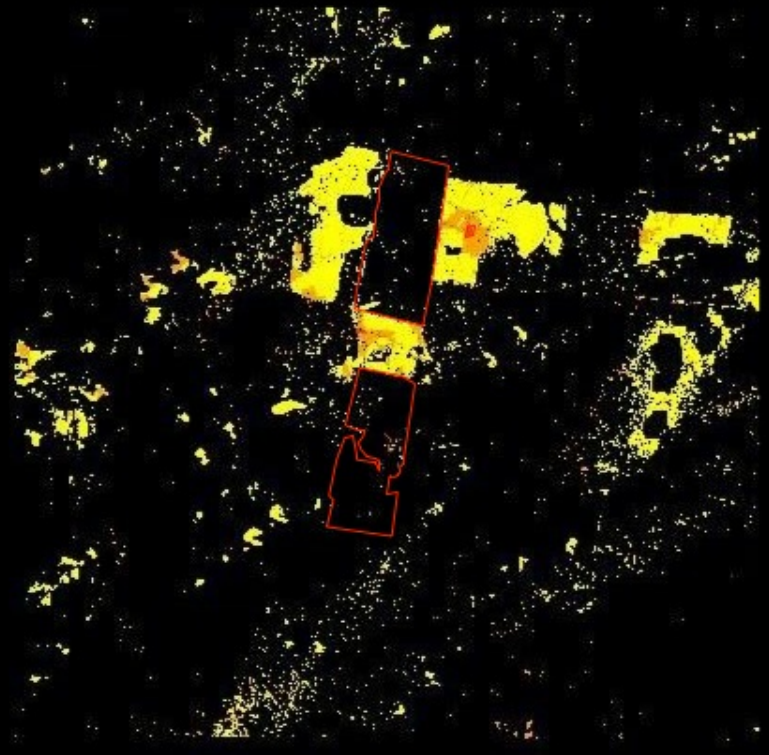
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 134



Observed



Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 150

Observed

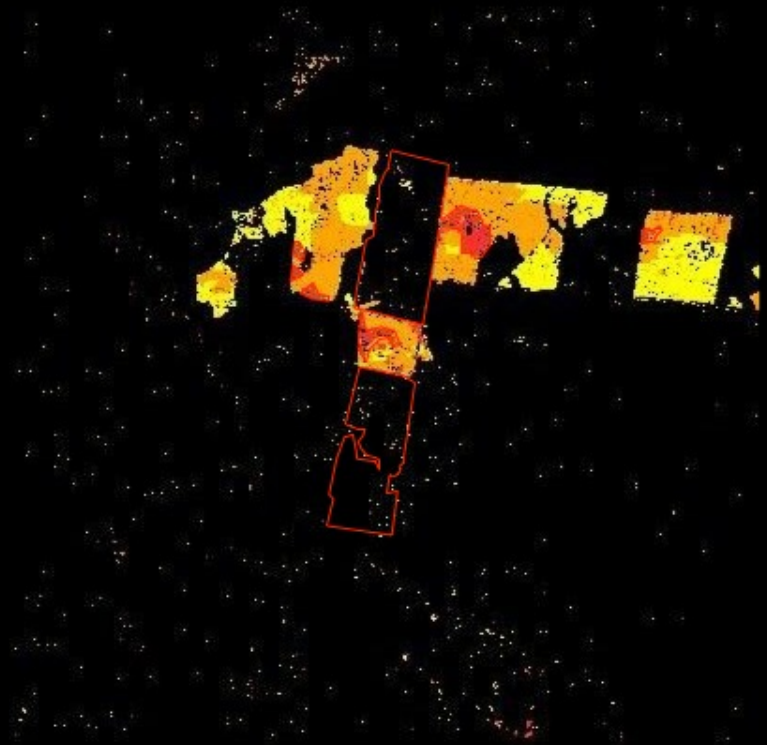
Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 150

Observed

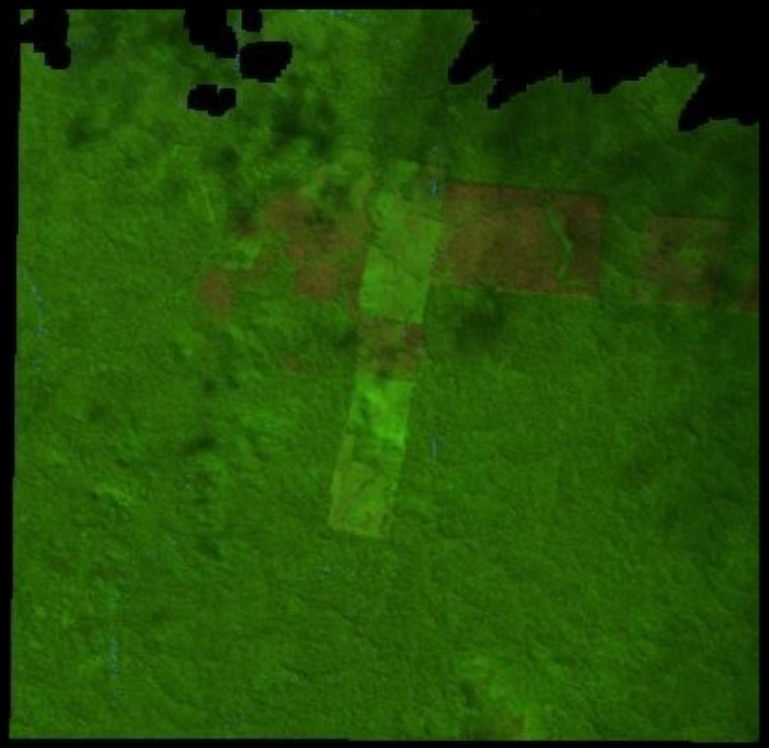


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 166



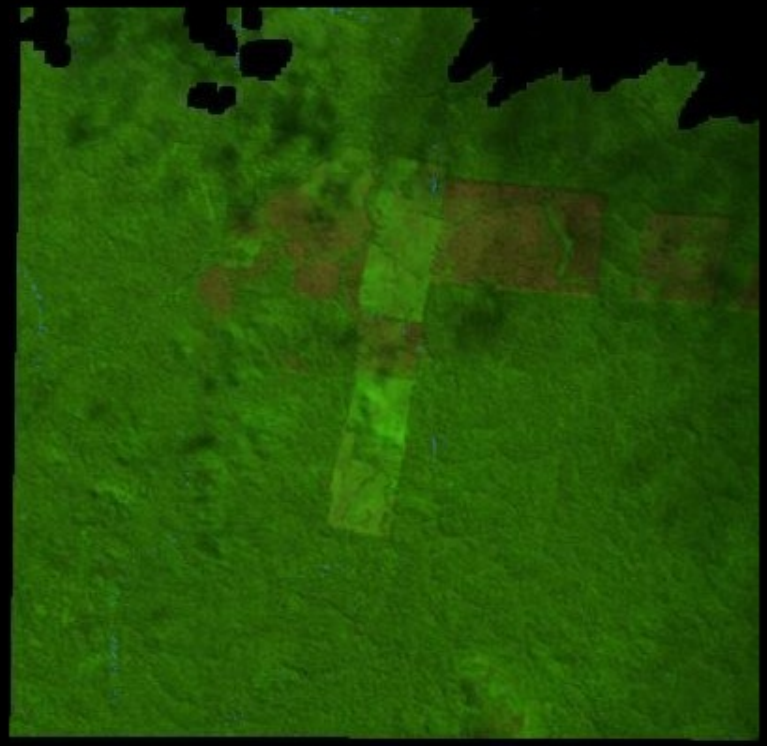
Observed

Predicted

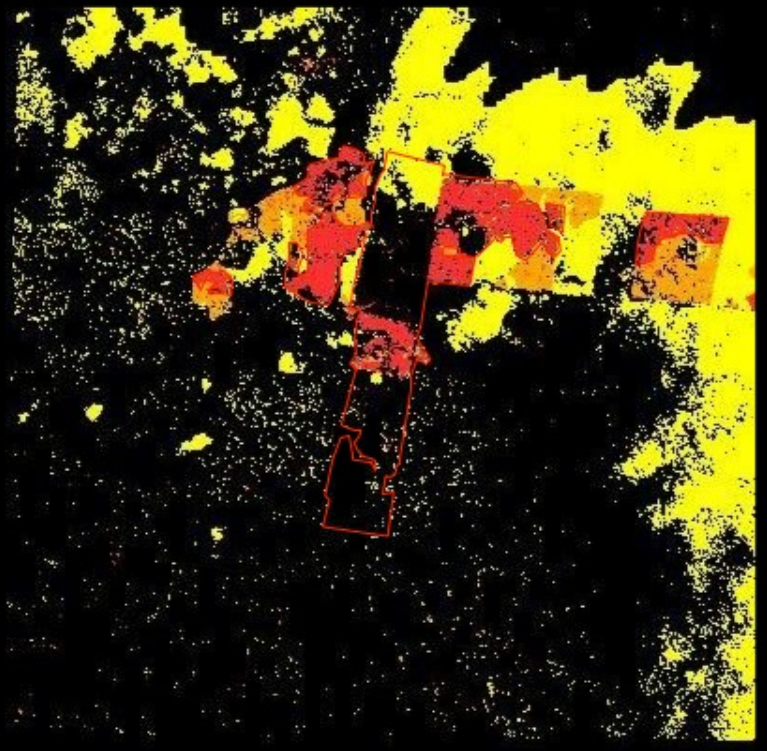
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 166



Observed

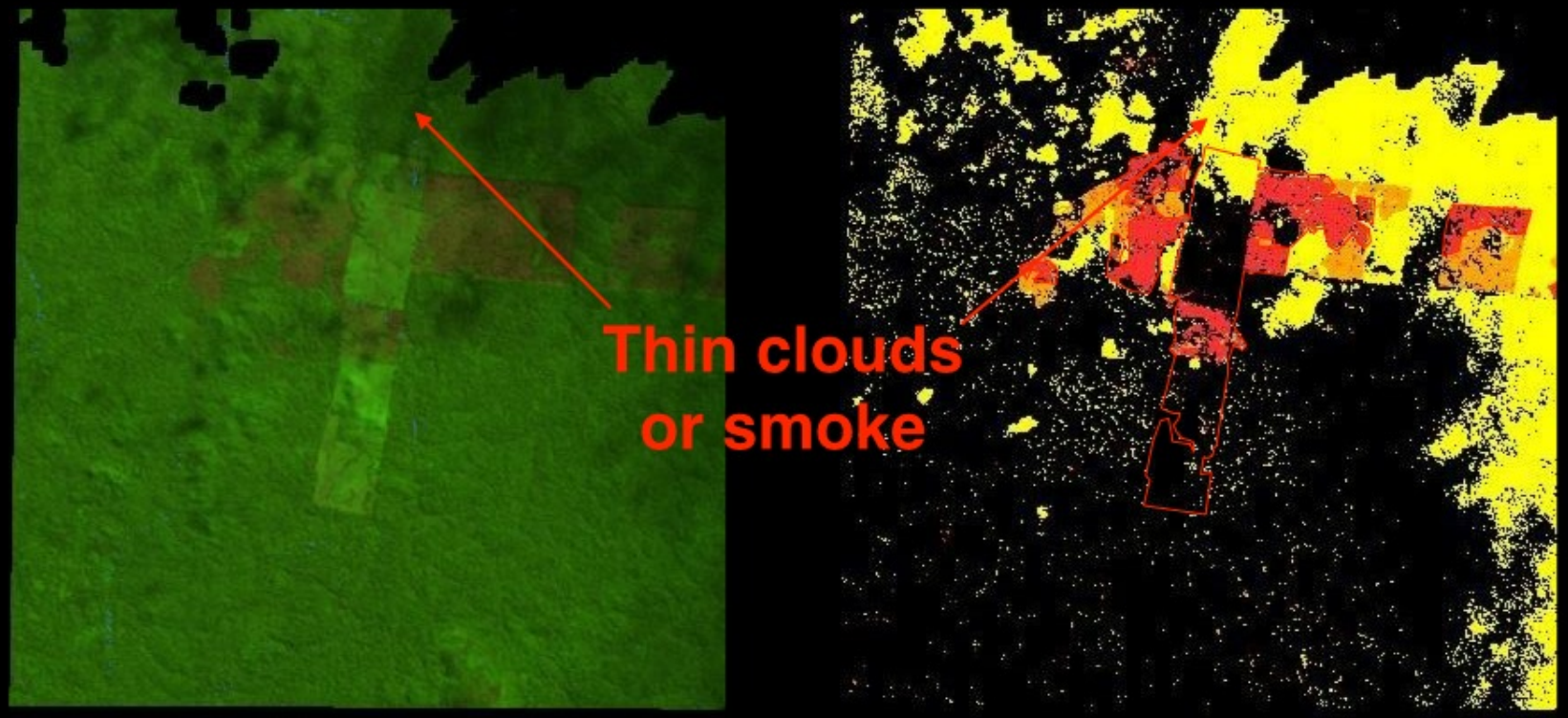


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 166



Observed

Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 182

Observed

Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 182

Observed

Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 214

Observed

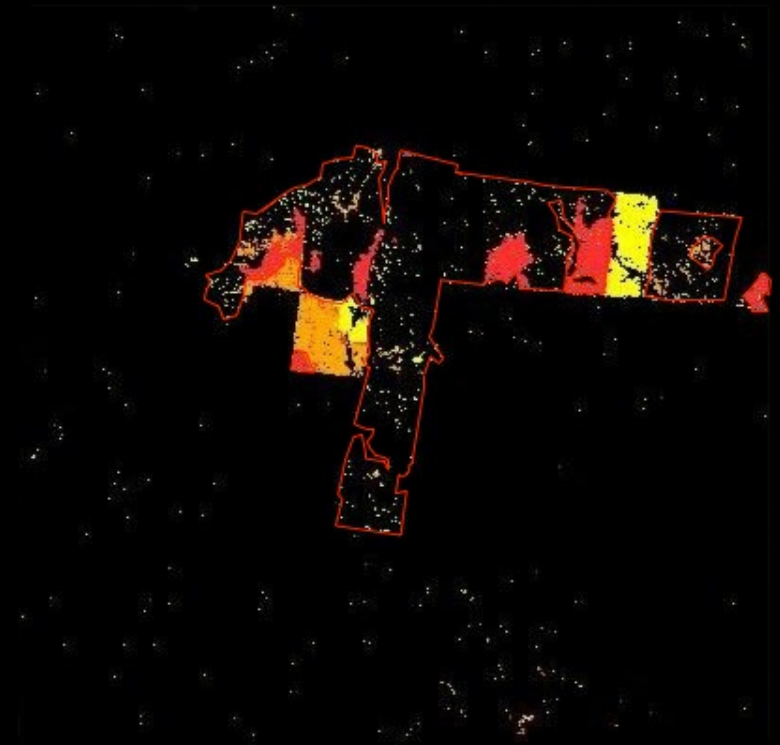
Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 214

Observed

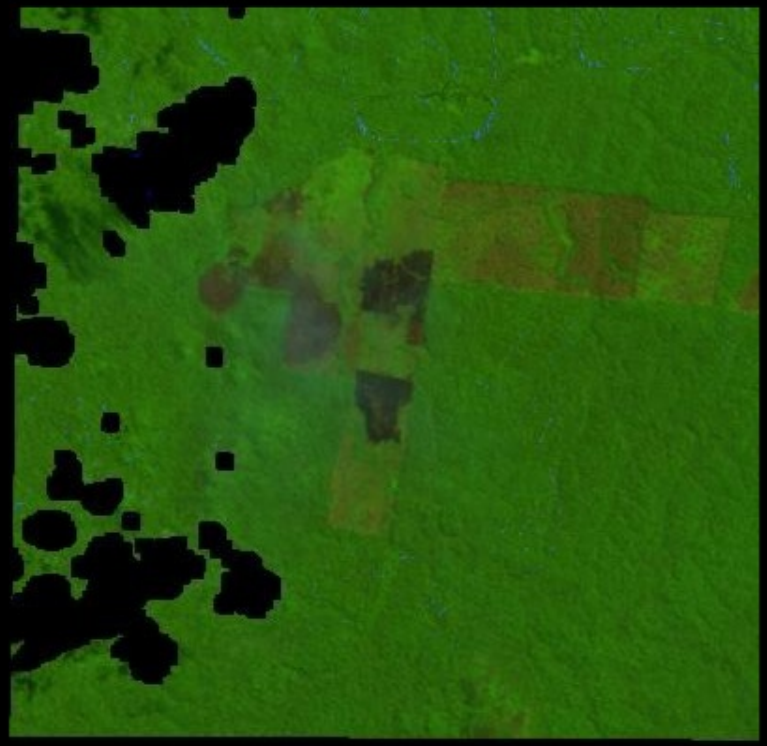


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 230



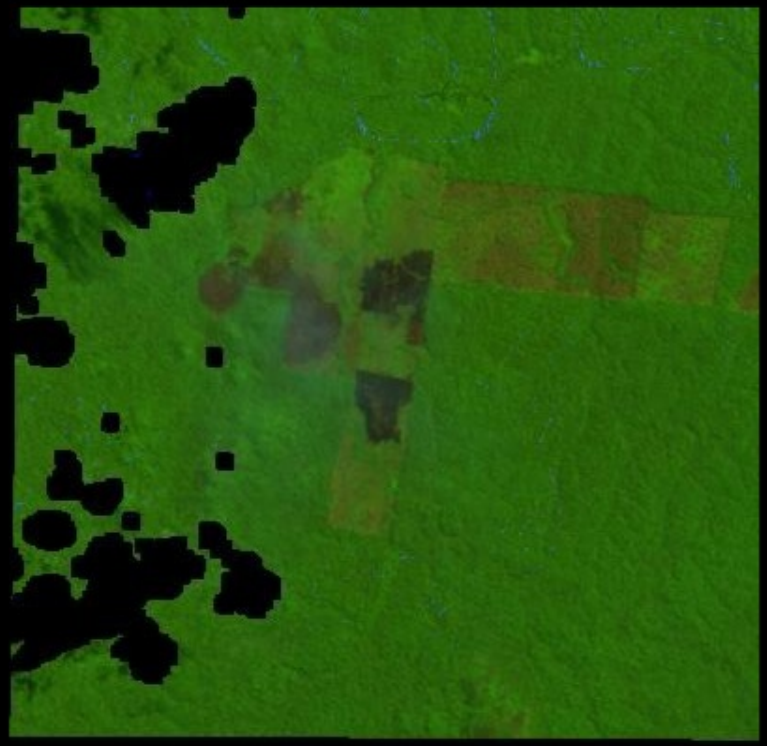
Observed

Predicted

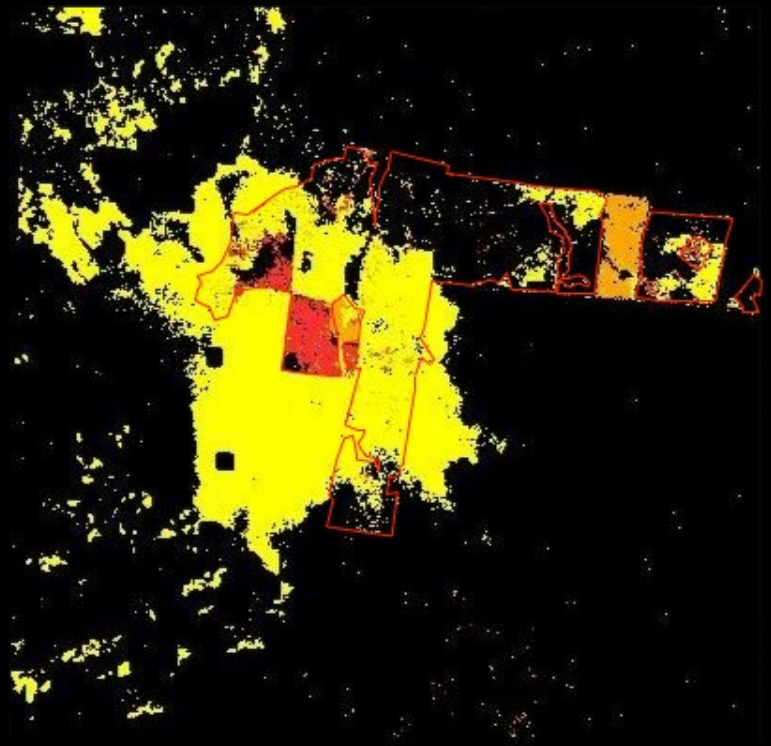
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 230



Observed



Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 246

Observed

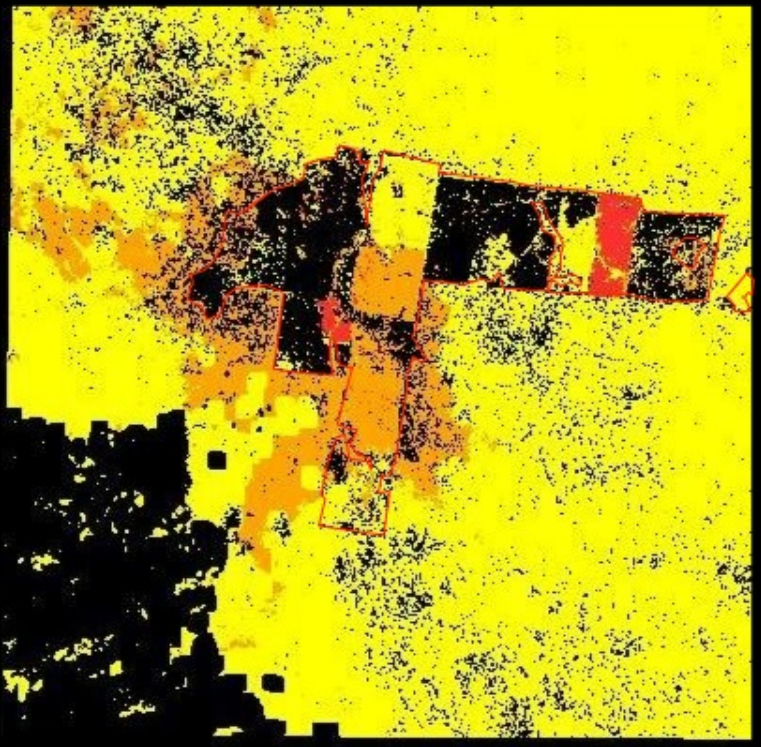
Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 246

Observed

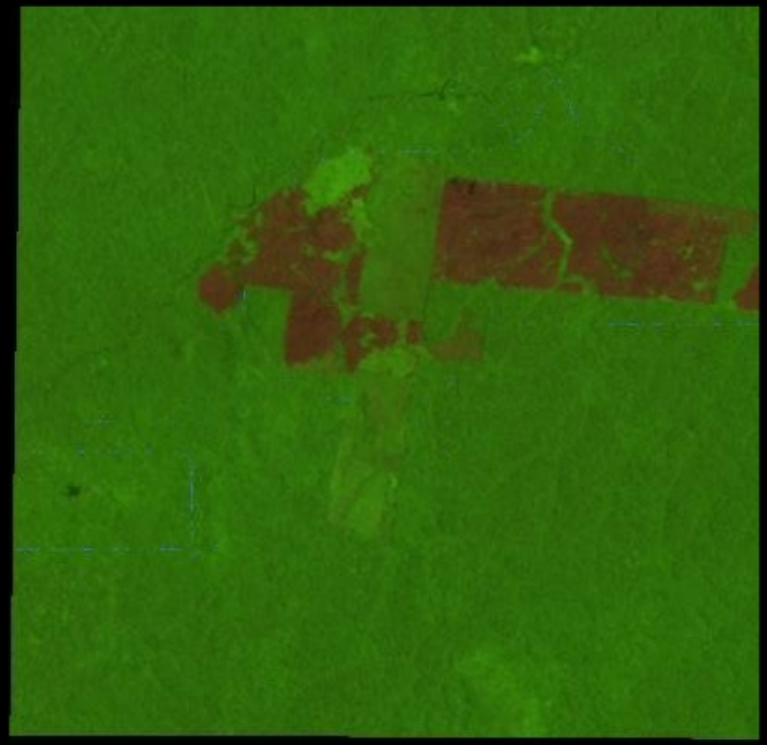


Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 262



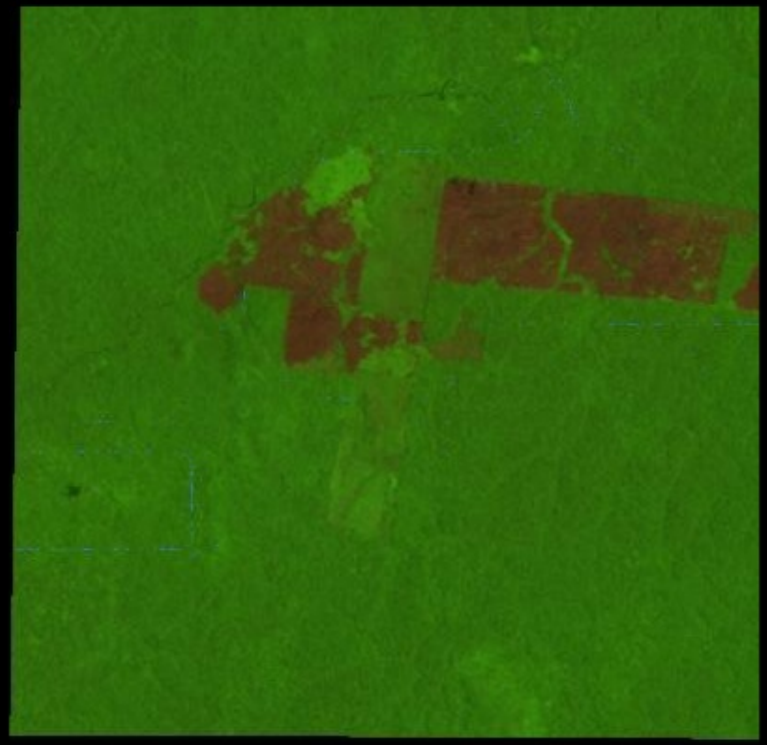
Observed

Predicted

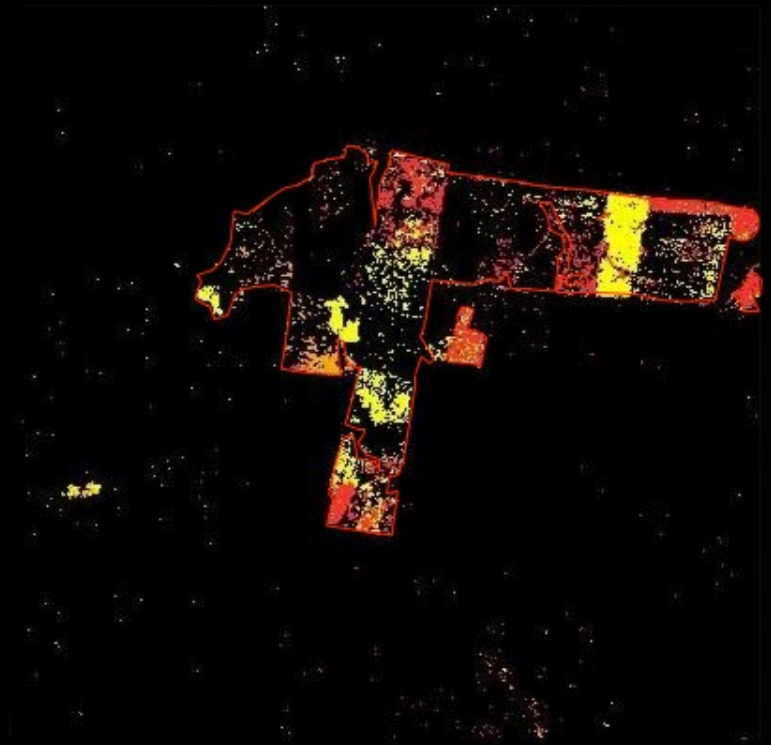
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2002 - 278



Observed



Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2003 - 137

Observed

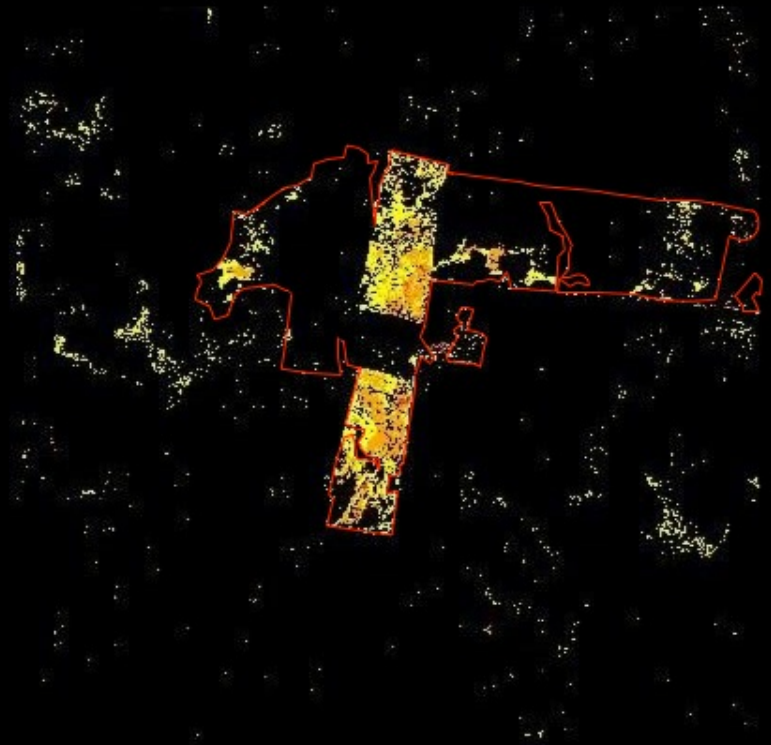
Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2003 - 137

Observed



Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2003 - 193

Observed

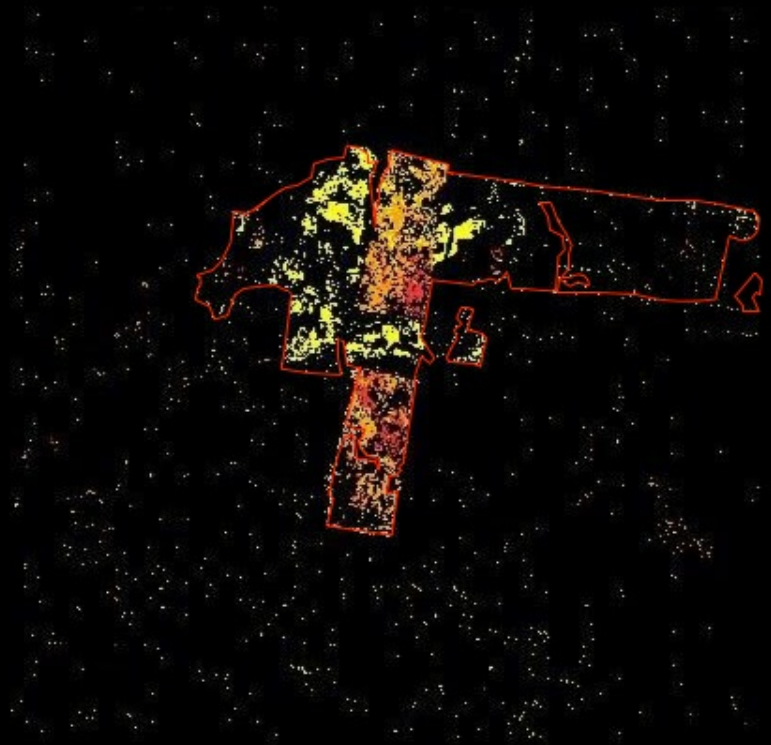
Predicted

Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

2003 - 193

Observed



Predicted

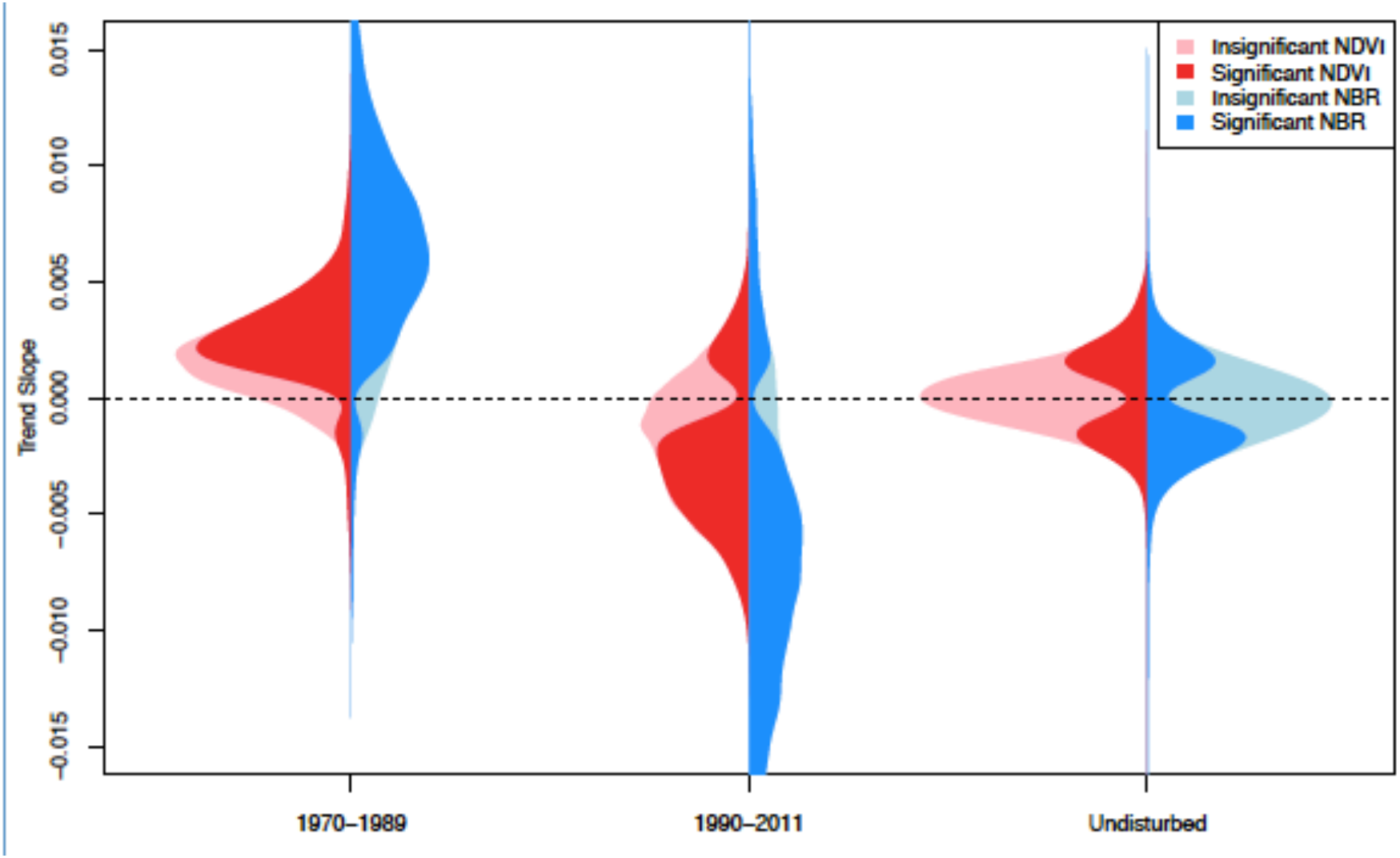
Threshold:

- 1 Day
- 2 Day
- 3 Day (Change)
- Detected Change Area

Couple of examples from Mark Friedl's students!

- Trends in peak greenness inforests in Canada (greening or browning) (Damien Sulla-Menashe)
- Forest Phenology (both average annual phenology and inter-annual variability) (Eli Meelas)

NDVI and NBR trends in Boreal Canada are primarily a function of disturbance history/timing (Slide from D. Sulla-Menashe)



Maps showing relationships between disturbance history and trends in NBR (slide from D. Sulla-Menashe)

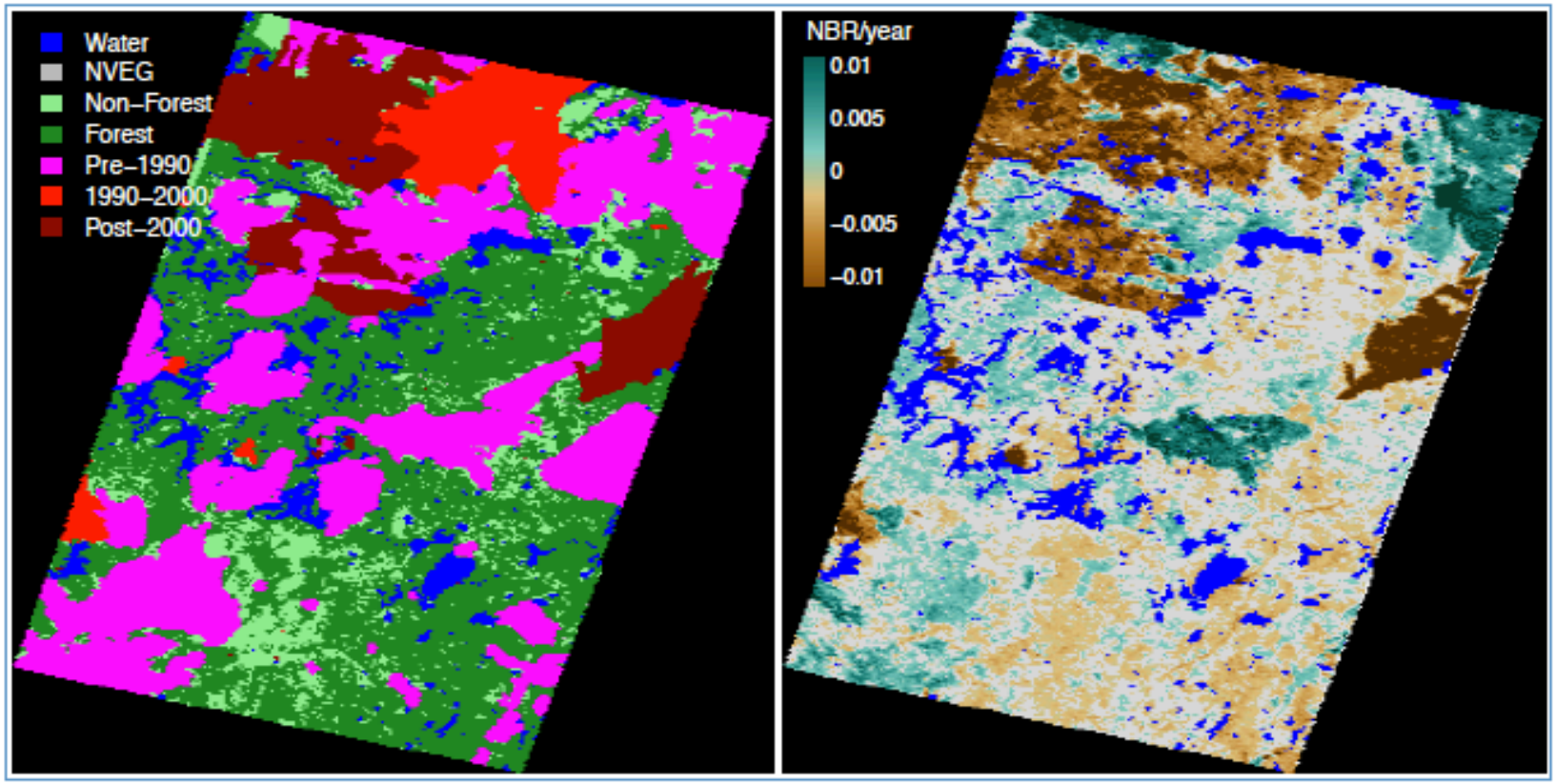
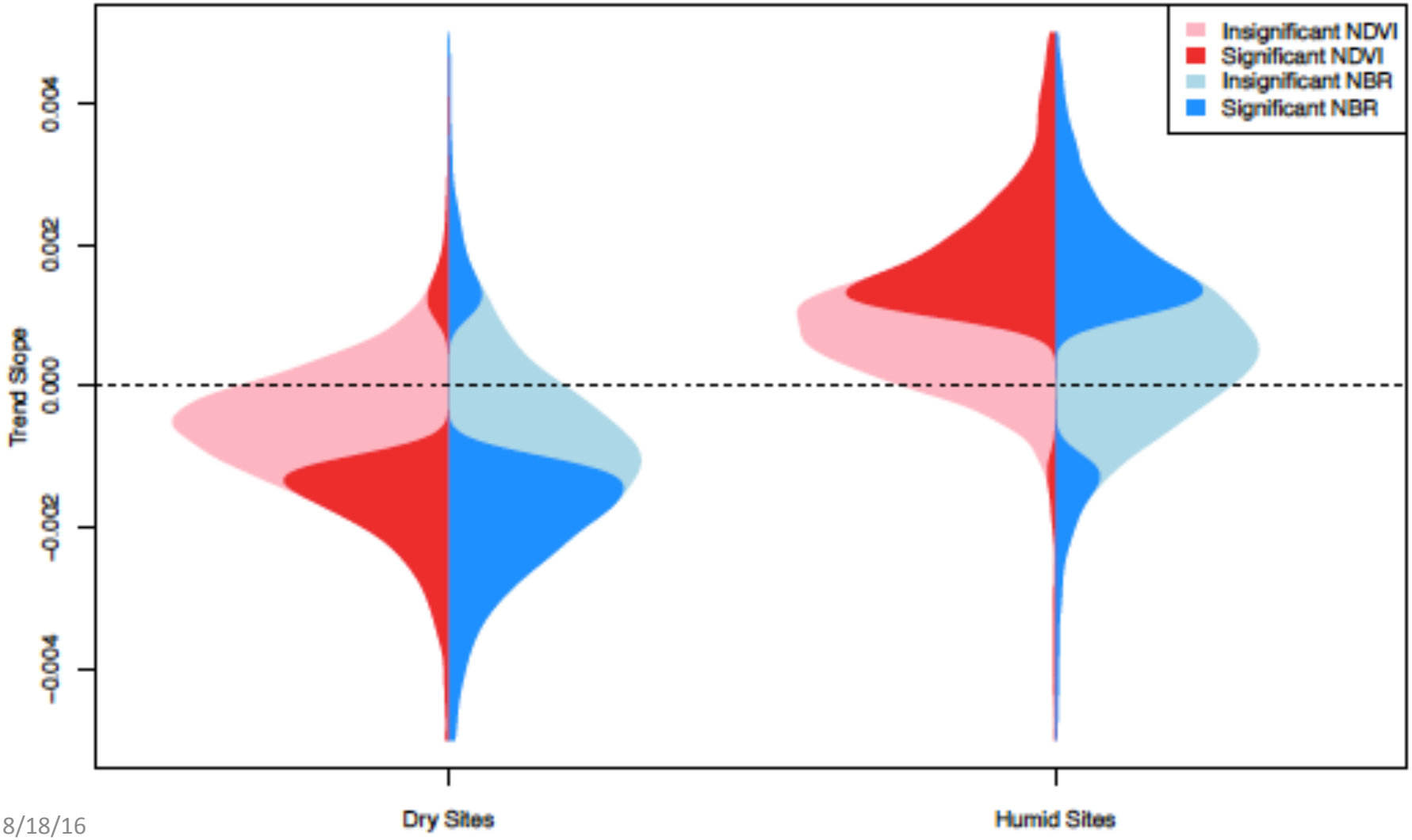


Figure 9. An example of land cover, disturbance information, and panel regression results for Landsat 5 TM NBR data centered on the Northern Old Black Spruce BOREAS site.

Geographic Variability in trends in NDVI and NBR is climate related (Slide from D. Sulla-Menashe)



Average annual phenology and inter-annual phenology for a deciduous forest from Landsat (slide from E. Meelas)

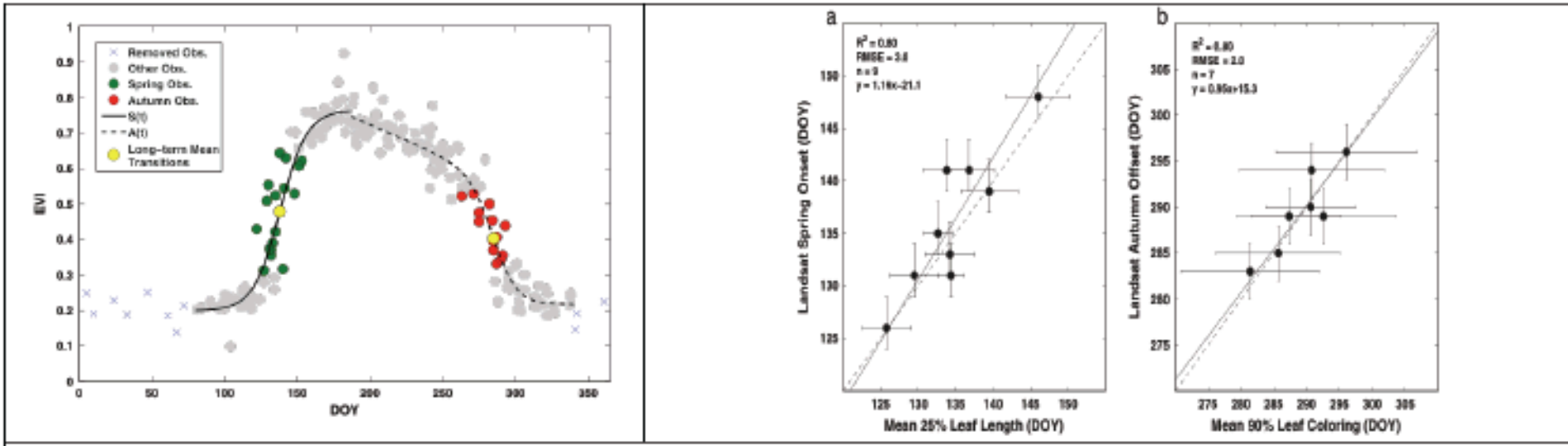
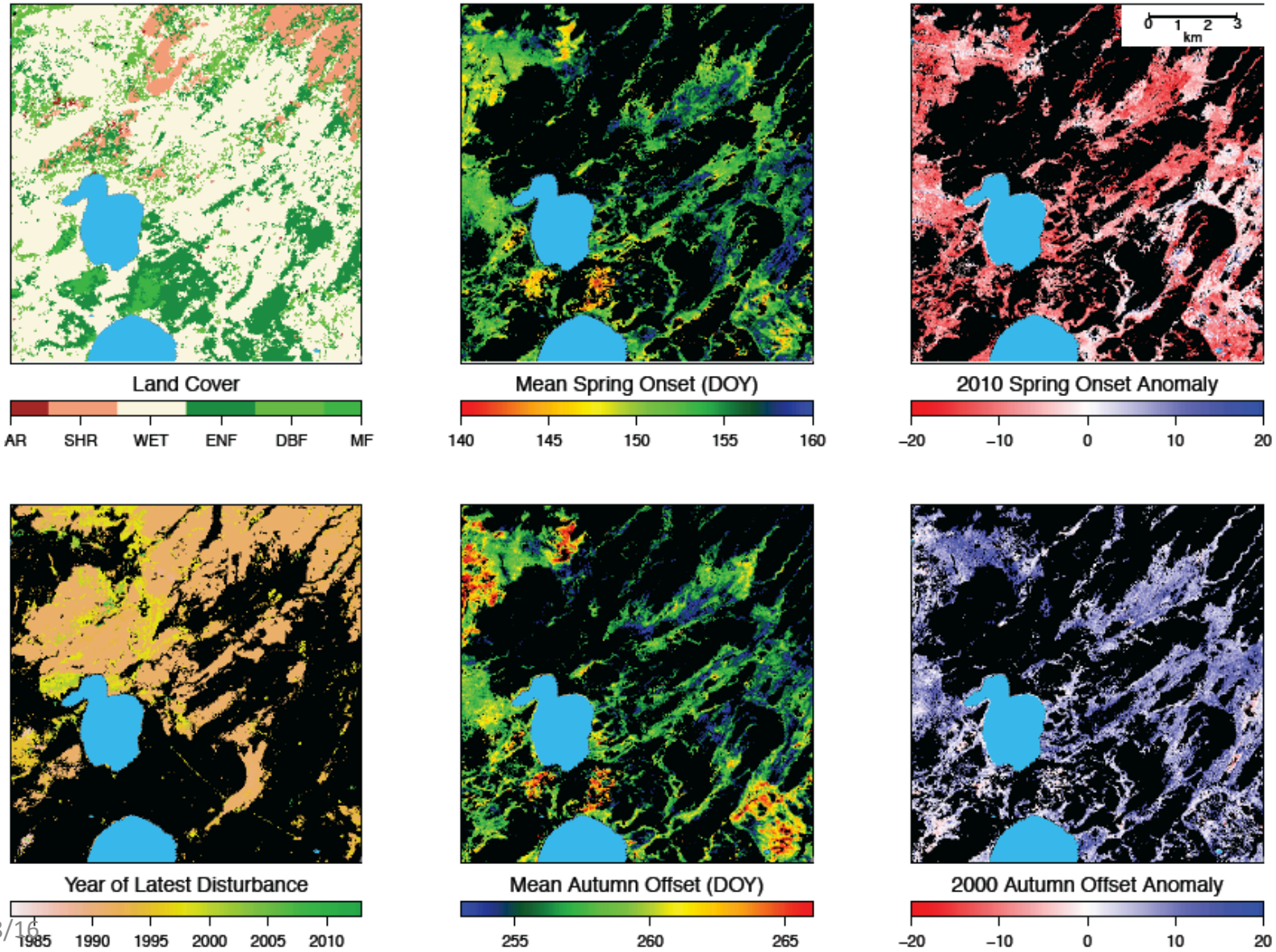


Figure 3. *Left panel: schematic illustrating the basic algorithm described in Melaas et al. (2013). EVI values correspond to ~250 observations between 1982-2012 for a single pixel at Harvard forest. Yellow dots indicate long-term average start and end of season; green and red points indicate values used to estimate interannual variation. Right panel: comparison of SOS and EOS from Landsat against field data from Harvard Forest.*

Landscape patterns of inter-annual phenology – at the patch scale from Landsat (slide from E. Meelas)



What are we finding?

- Time series of Landsat have incredible advantages – more observations reduces the dependence on noisy single observations
- Time series reveal a complicated and rich history to places
- Time series allow characterization of condition and trends (phenology, growth, stress)
- Agricultural landscapes are by far the most dynamic and challenging (to the point of being diagnostic), and we need new ways to think about what constitutes change in these areas

Where and how are we applying these new time series models?

- Developing a prototype for the activity data for REDD+ reporting in the Colombian Amazon
- LCMAP – a new national initiative on Land Change Monitoring, Assessment and Projection (USGS)
- Near real-time monitoring of forest change in the tropics by fusion of MODIS and Landsat
- Fusion of Landsat and radar data for improved monitoring of change in the cloudy tropics
- Improved mapping of species composition in New England forests
- Monitoring forest degradation
- Improving models of terrestrial carbon dynamics by integration of time series models

Sentinel 2A and 2B

- Sentinel 2A has been successfully launched!!!
- Sentinel 2A makes observations more frequently than a single Landsat satellite!!

- *Combining Sentinel 2A, 2B and Landsat 8, we will be getting at least 8 observations a month globally!*
- *Thanks to Europe for a free access data policy for Sentinel 2!! Will multiply the benefits of your investment many times over.*

Thoughts going forward

- While we are currently using primarily Landsat data, it will be exciting to include:
  - Sentinel 2
  - Sentinel 1
  - ALOS PALSAR
  - Chinese data???
  - Others???
- Initial attention has been on monitoring abrupt change, but with time we will focus on more subtle kinds of change