A statistical framework for the analysis of long image time series:

Examples and Applications

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Outline

- Background and research questions
- Theory and definitions
- Applications:
  - Trend analysis in the Pathfinder AVHRR Land (PAL) NDVI data for the deserts of Central Asia.
  - Institutional change in Kazakhstan.
  - Comparison of the Global Inventory Modeling and Mapping Studies (GIMMS) and PAL NDVI data.
- Conclusions
- Questions

“The earth is becoming a greener greenhouse” (2001)

“The greening of the north, real and caused by climate change” (2002)

“The greening of the North” (2002)

“World getting 'literally greener'“(2004)

TV (ABC, BBC, CNN, MSNBC etc.)
Broadsheets (Hundreds)
Radio (NPR, VOA, BBC, etc.)
Wires (AP, Reuters, etc.)
Internet News Magazines (about a hundred)
Magazines (Science, Sci. Am., Natl. Geog., Popular Science, etc.)
Countries: 20

From: Boston University: Climate and Vegetation Research Group

Background

- Significant global changes affect the carbon and water cycles as well as the biodiversity on earth.
- Increasing trends in the photosynthetic activity during the last two decades in North America and Northern Eurasia.
- Greening trends have generally been linked to increasing temperatures.

On a global scale anthropogenic changes are usually only inferred as indirect influences on land cover changes.

Central Hypothesis

- A period of great interest in global warming coincided with the period of one of the largest anthropogenic events in the Northern Hemisphere: the collapse of the Soviet Union.
- **The central hypothesis:** institutional changes significantly contributed to the observed increases in photosynthetic activity (or ”greening” trend) in Northern Eurasia.

Main Research Question

'Given abrupt, sweeping changes in political, social, and economic institutions and the subsequent redistribution of land use decisions, are the consequences of change observable in *land surface phenology* at spatial resolutions relevant to interactions with the atmospheric boundary layer?'

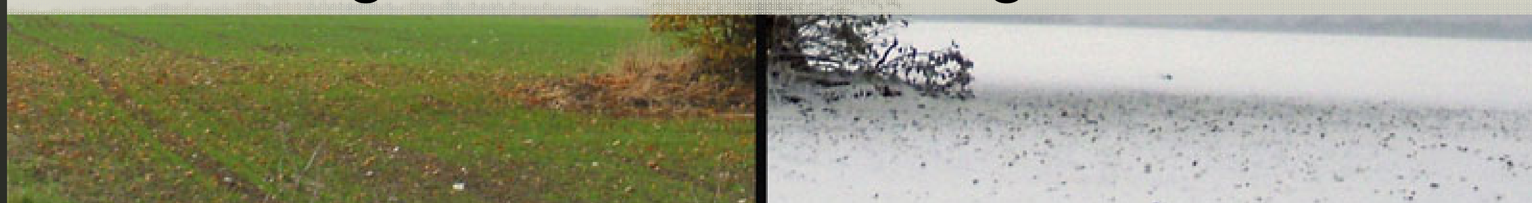
Vegetation Phenology

1 Beech four Seasons, Copyright: Heinz Koloska

Vegetation Phenology

the study of the timing of recurring biological phases, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species.

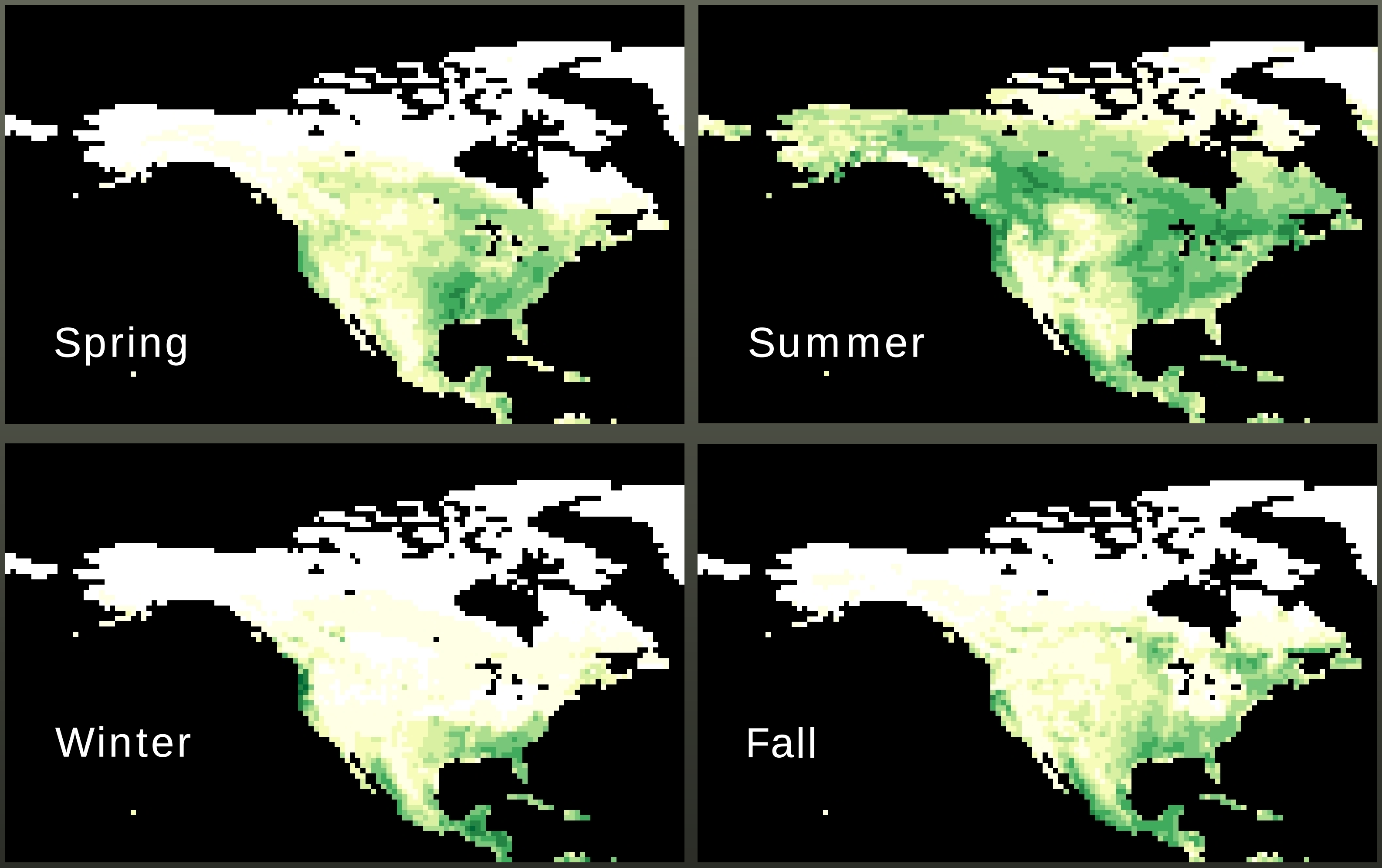
Phenological events, such as the first openings of leaf and flower buds, have been found to be good indicators of the impact of local and global climate change



(Menzel, 2003).

1 Beech four Seasons, Copyright: Heinz Koloska

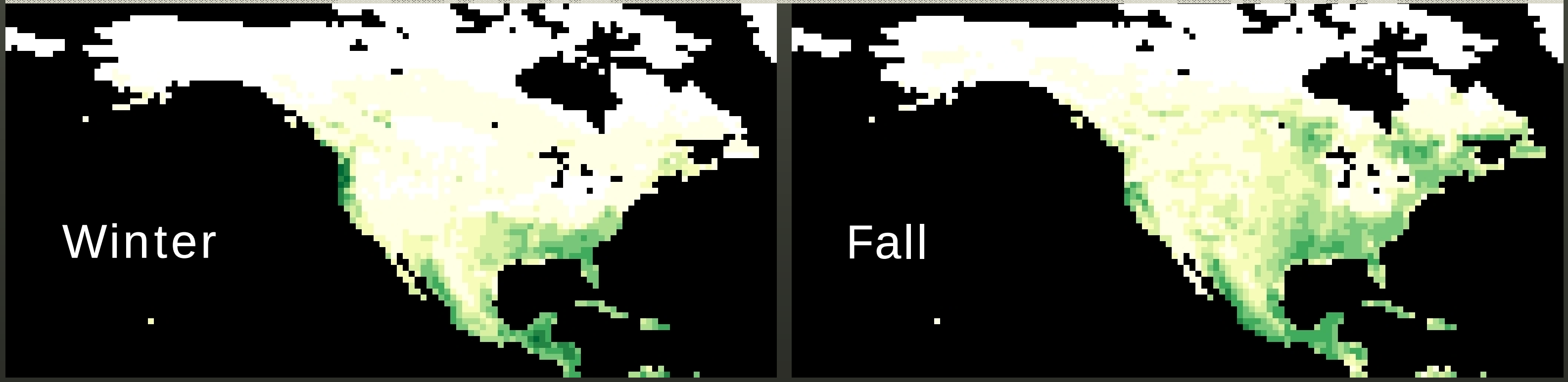
Land Surface Phenology



Green wave, period phenomena

Land Surface Phenology

We have defined land surface phenology as the study of the spatio-temporal patterns of the vegetated land surface as observed by synoptic sensors at spatial resolutions and extents relevant to meteorological processes in the atmospheric boundary layer.



(de Beurs and Henebry, 2005)

AVHRR data

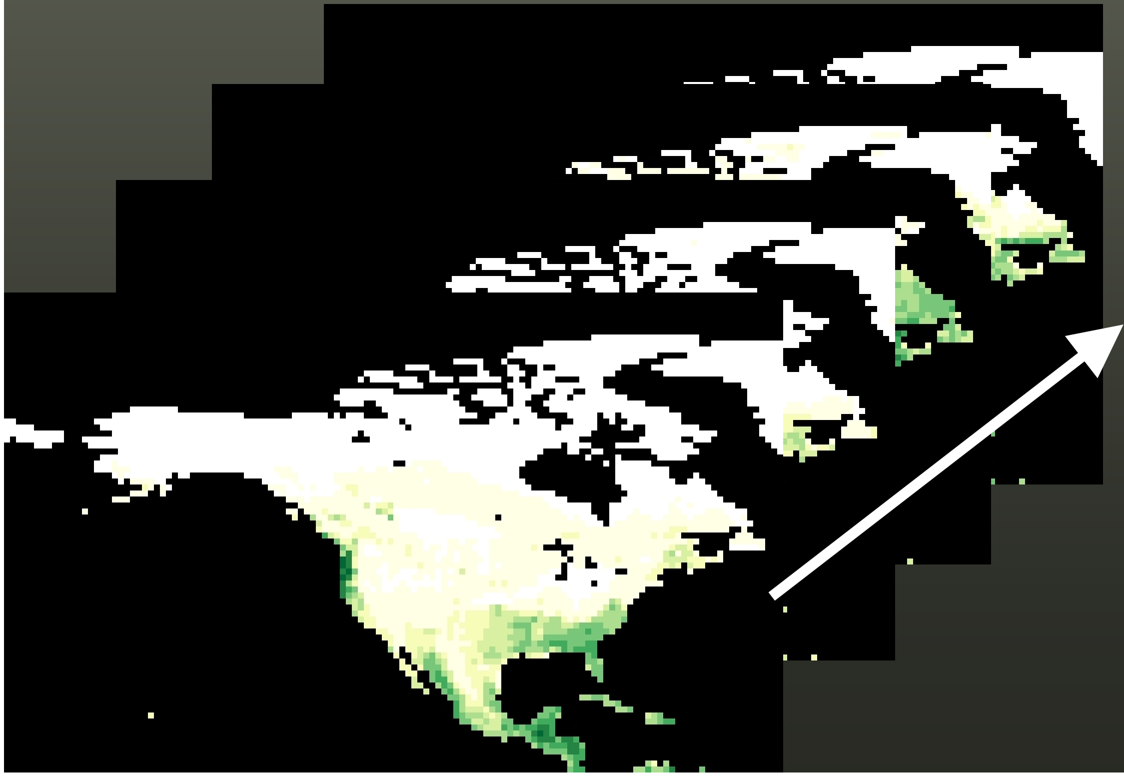
- Long extent (1981-2001 … 2005)
- Normalized Difference Vegetation Index

  NDVI = (NIR – Red)/(NIR + Red)

  ranges from ~0.07 to ~0.95 for vegetated areas

Fine temporal resolution

- 10/15 day Maximum NDVI composites
- 24 - 36 composites / yr

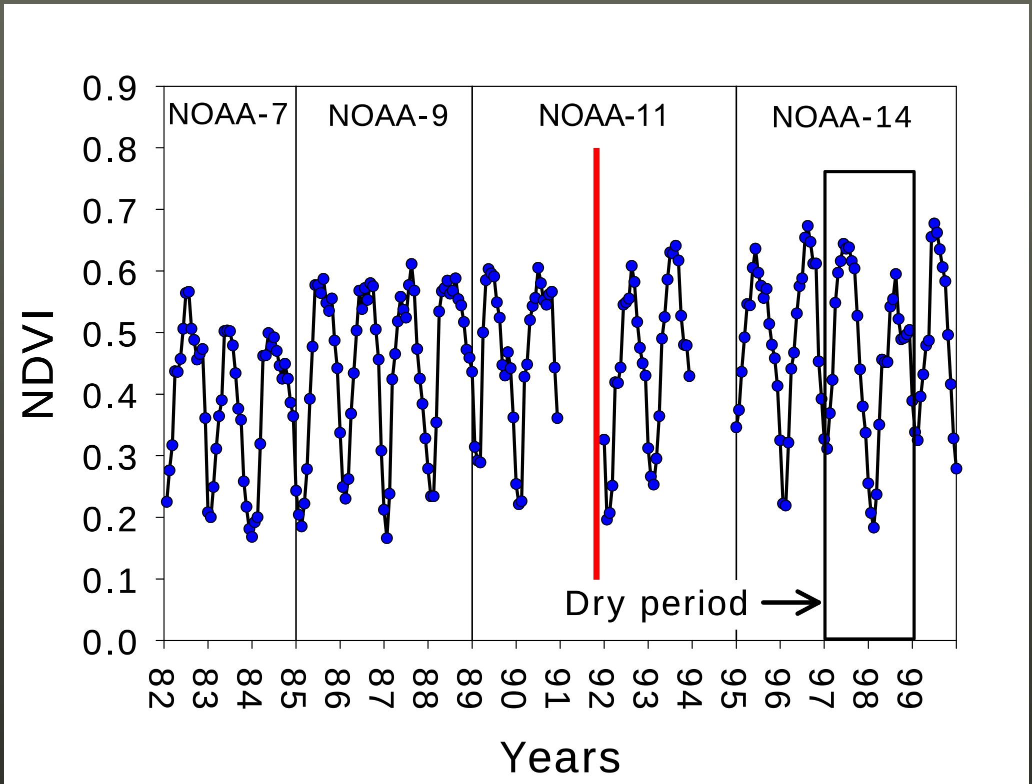


Take advantage of the large amount of observations when analyzing for change!

AVHRR data used in this study

- Standard Pathfinder AVHRR Land (PAL) dataset
- Time period: 4/1982 to 9/1999
- Recorded by AVHRR sensors on 4 satellites (NOAA-7, NOAA-9, NOAA-11, NOAA-14)
- Spatial extent: global
- Spatial resolution: 8 km
- Temporal resolution: 10 day maximum NDVI composites

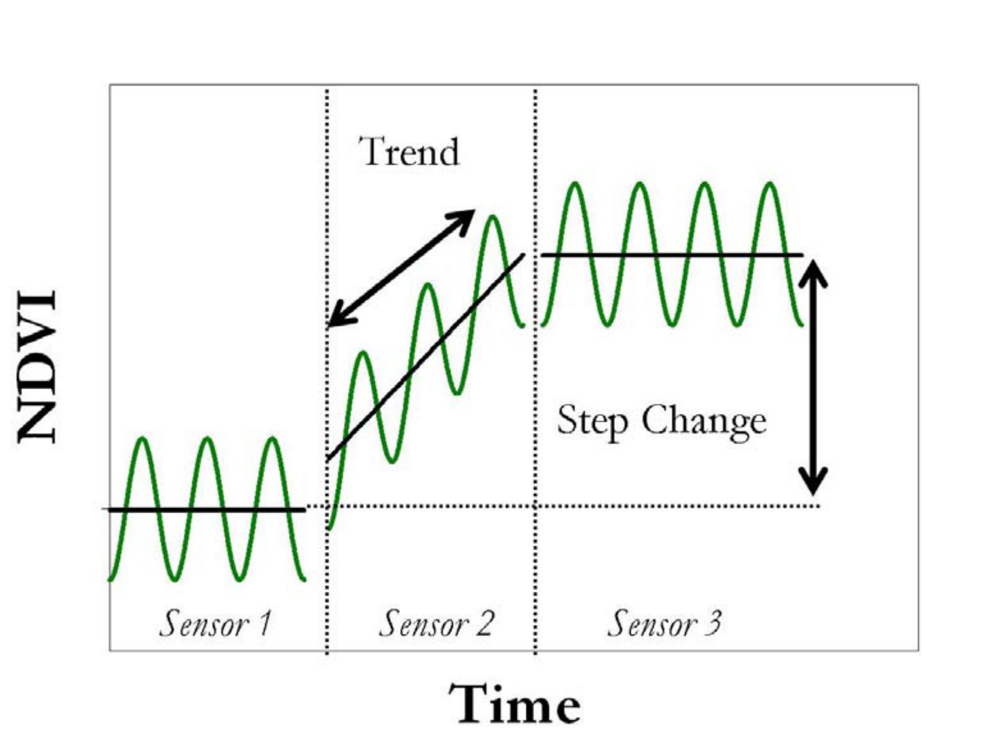
How can we separate the variation in the data?



Land surface phenology changes can result from:

- Sensor changes
- Seasonal variation and interannual variation
- Anthropogenic changes

Specific Questions



Step Change: a significant difference in average NDVI between two (sensor) periods.

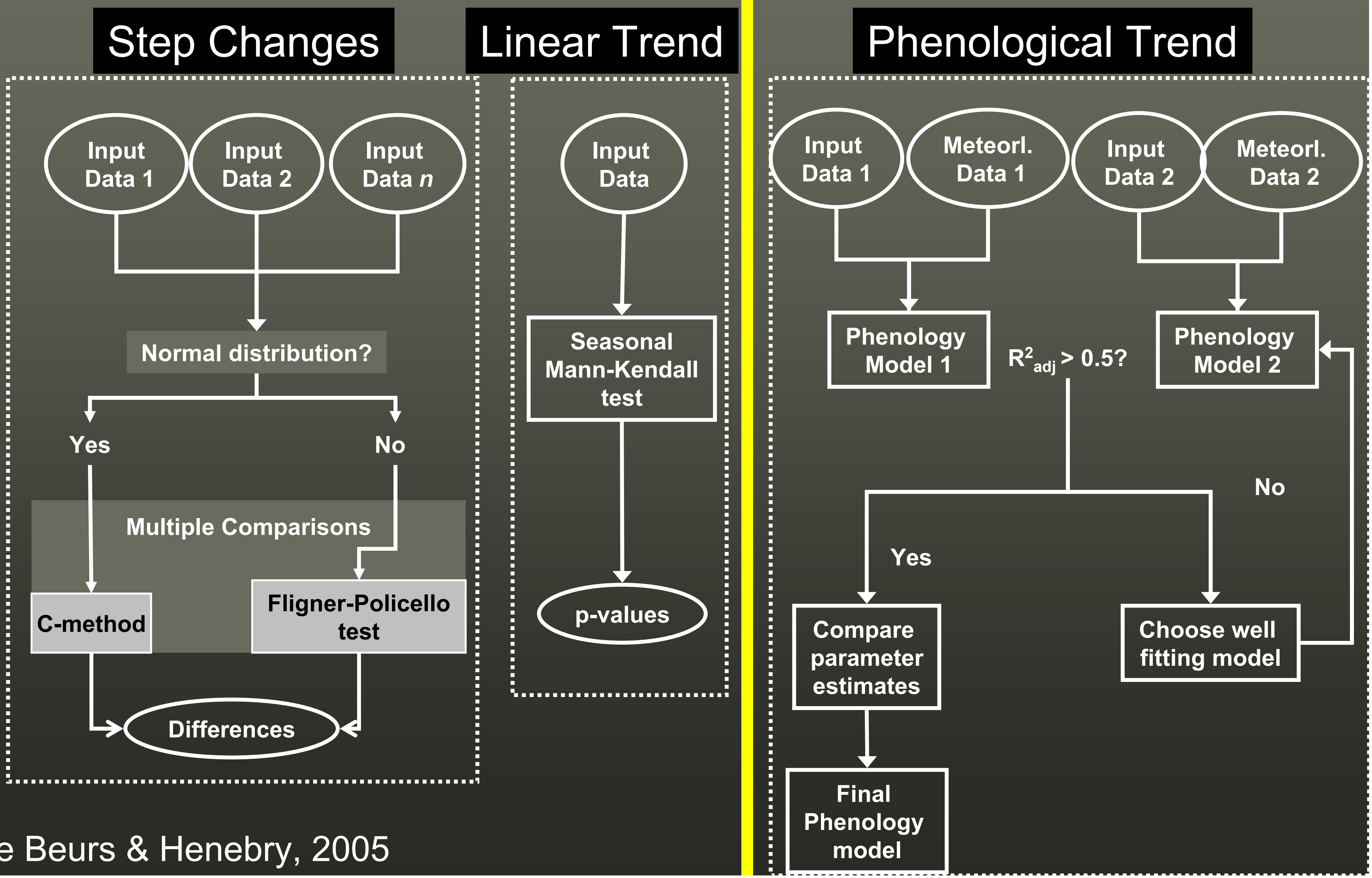
Linear Trend: a series of individually insignificant step changes all in the same direction.

Phenological trend:

Later / Earlier start of season

Later / Earlier peak ---- Higher / Lower peak

Overview Statistical Framework

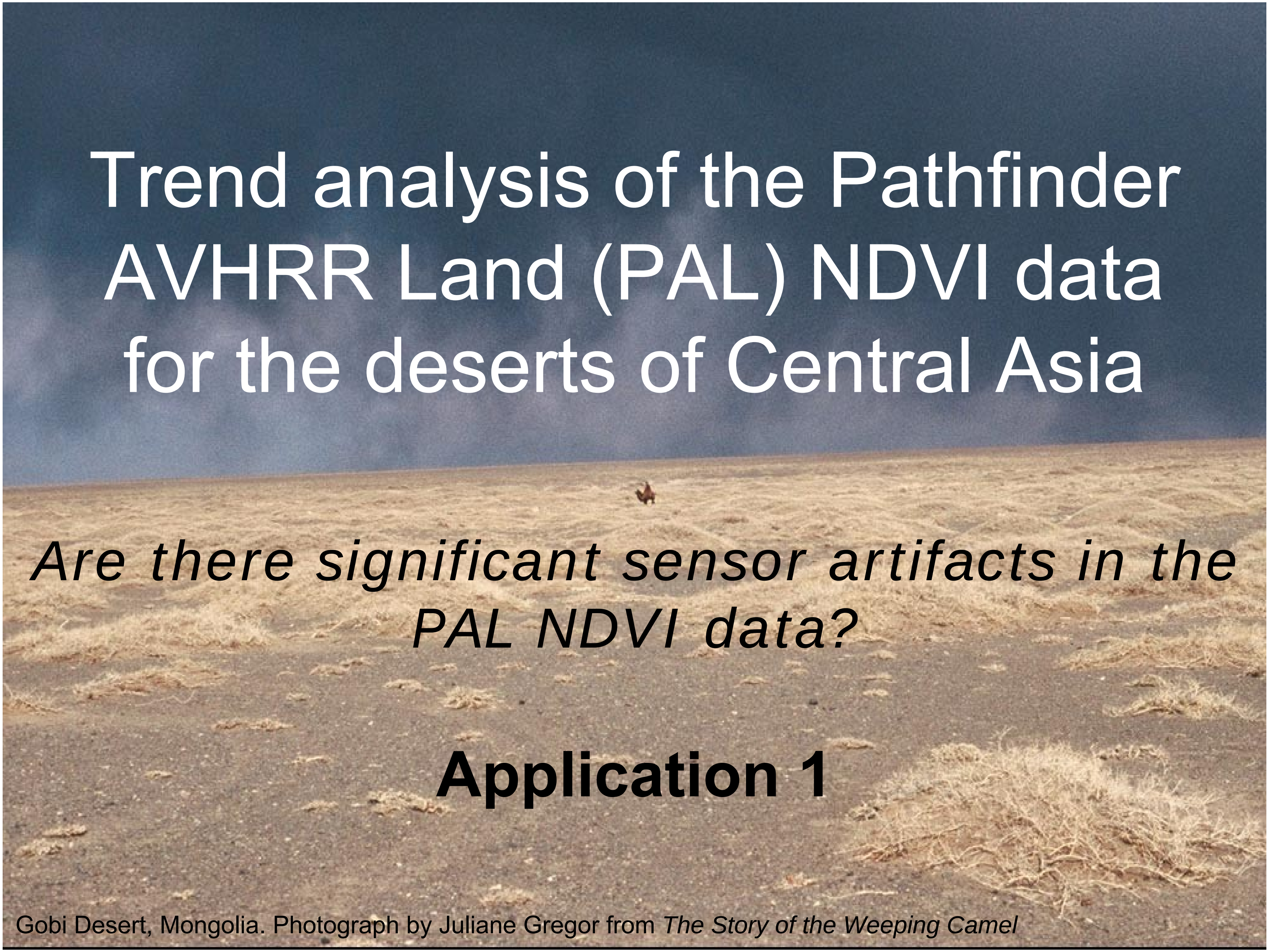


de Beurs & Henebry, 2005

Trend analysis of the Pathfinder AVHRR Land (PAL) NDVI data for the deserts of Central Asia

Are there significant sensor artifacts in the PAL NDVI data?

Application 1



Gobi Desert, Mongolia. Photograph by Juliane Gregor from *The Story of the Weeping Camel*

Variation due to sensor artifacts

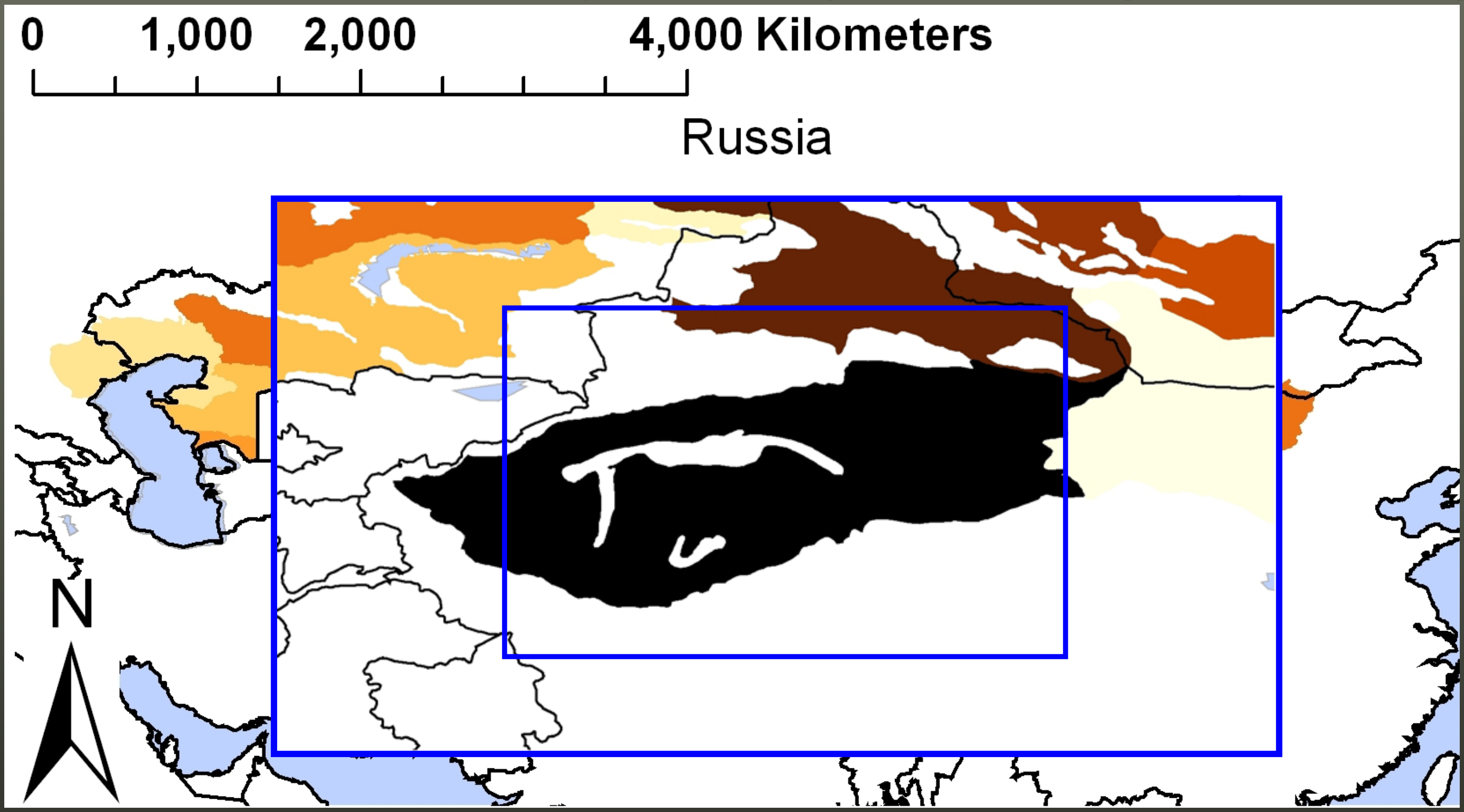
Assumptions:

- The NDVI signal from the desert vegetation has a low interannual variation.
- Therefore, we assume that trends in data retrieved from the desert are due to sensor artifacts.

Determine statistical significance of:

- Step changes (discontinuities) between sensor periods
- Trends within sensor periods

Desert Study Regions (DSR's)



- Deserts – 11 desert ecoregions, selected from the WWF
- Area – more than 2 million km^2
- Climate – Taklimakan Desert was the driest selected desert (precipitation < 10mm/y)

Taklimakan Desert

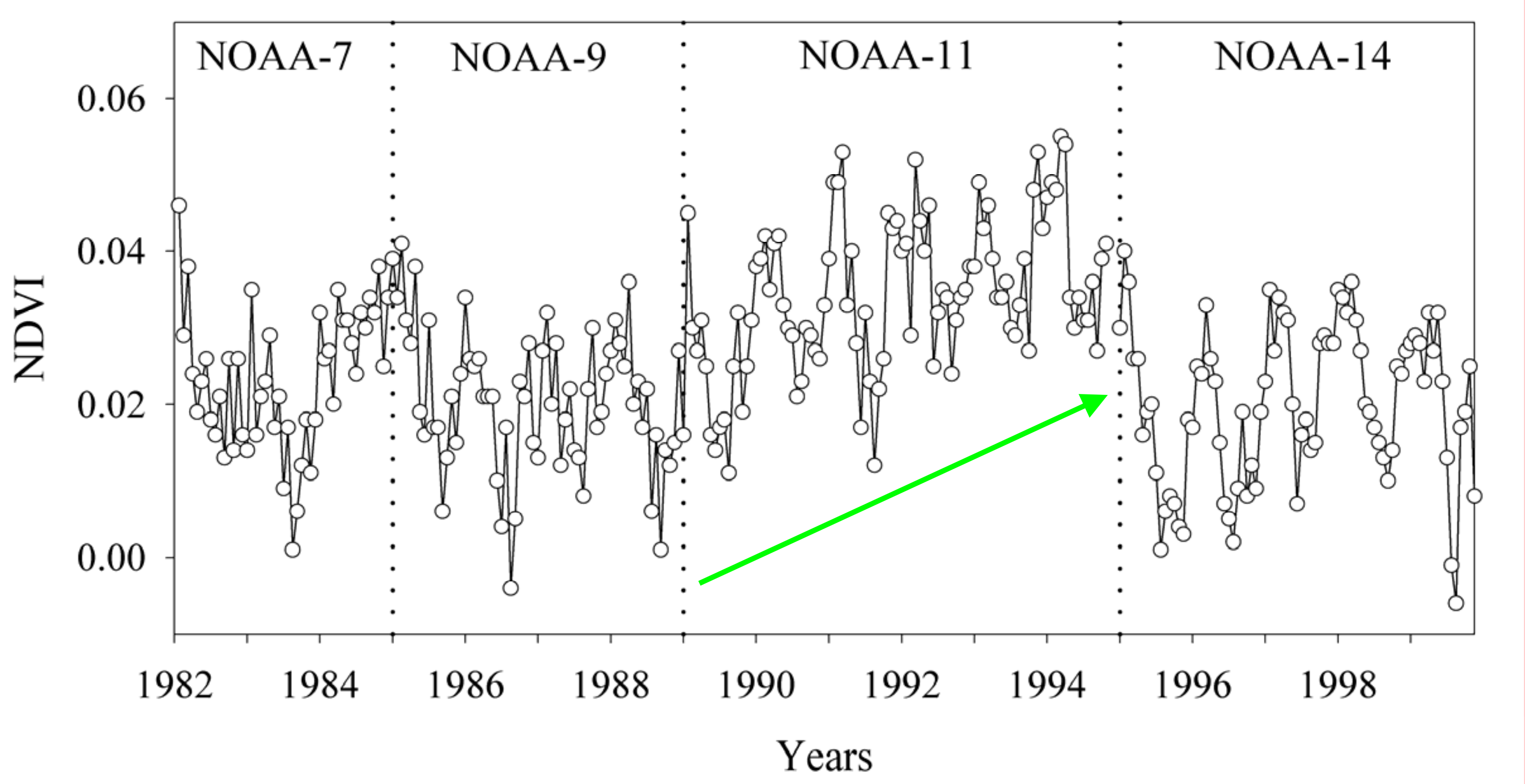
Precipitation (mm/year):

- **Taklimakan desert (<10 mm/year)**
- Sahara desert (5-25 mm/year)
- Mojave desert (65-190 mm/year)
- Sonoran desert (100-300 mm/year)
- Chihuahuan desert (150–400 mm/year)

Photograph by © WWF/Ronald PETOCZ

Photograph by Liang Zhi

Taklimakan Desert



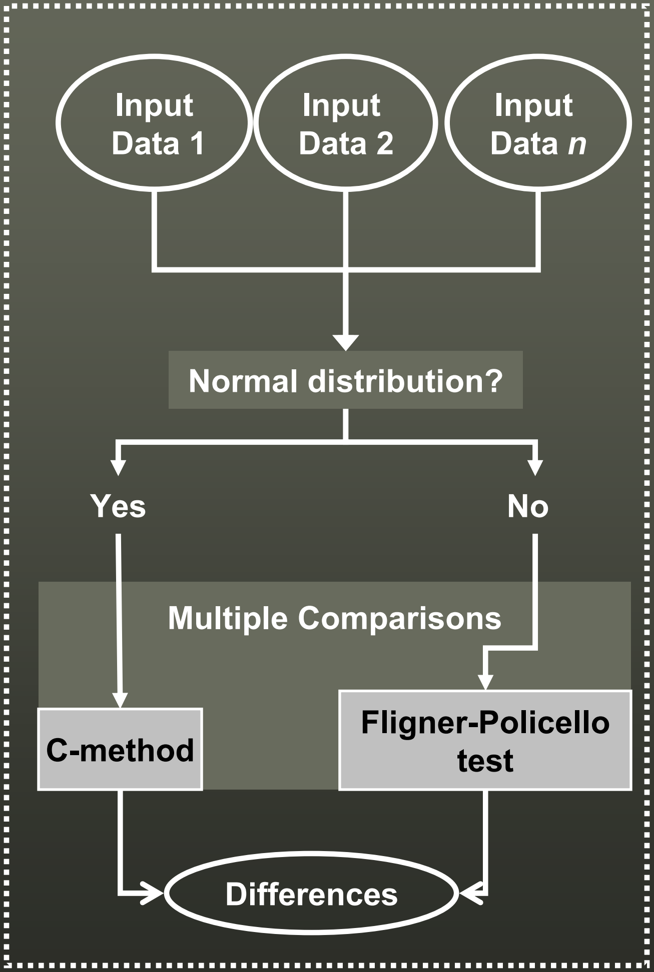
de Beurs and Henebry (2004) IEEE Geoscience and Remote Sensing Letters.

Are there step changes in the image time series?

Assumptions of standard parametric tests:

- Equal population variances
- Normality
- Equal sample sizes

Violations can increase type 1 or type 2 error rates!

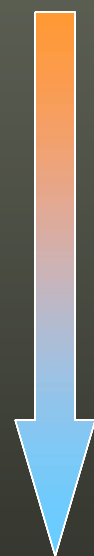


C-method and Fligner-Policello test are robust against violations.

Step change: Central Asian deserts

	Multiple Comparisons					
DR	7-9	7-11	7-14	9-11	9-14	11-14
1		**		**		**
2		**	**	**		**
3	**			**	**	**
4		**		**		**
5		**		**		**
6		**		**		**
7						
8		**		**		**
9		**		**		**
10		**	**	**	**	**
11		**				

Dry (< 10 mm/year)



Wet (~ 200 mm/year)

Significant artifacts affect the PAL data from NOAA-11.

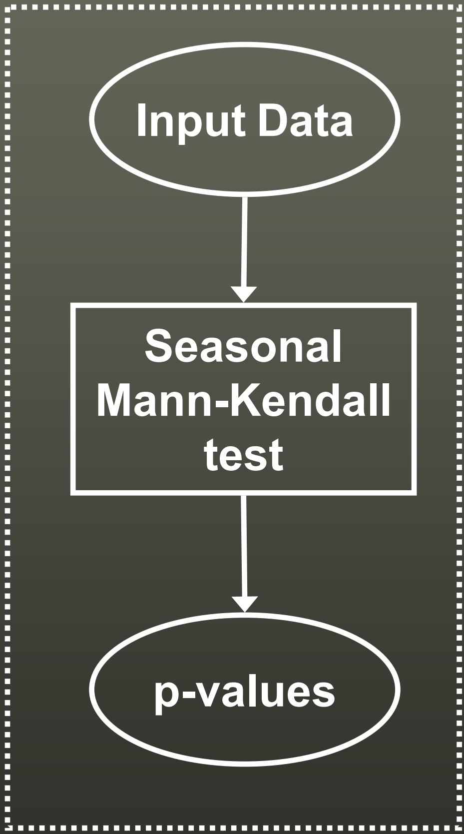
α = 0.05, dunn-sidák correction has been applied.

Is there a linear trend in the image time series?

Assumptions of standard trend tests:

Residuals should be →

- Independent
- Normal
- Random
- Mean = 0
- Equal variance for all years



Violations can increase type 1 or type 2 error rates!

→ Seasonal Mann-Kendall test corrected for autocorrelation is robust against violations.

Trends: Central Asian deserts

	Trend Test			
DR	7	9	11	14
1			**	
2			**	
3			**	
4	**		**	**
5			**	
6			**	
7		**	**	
8			**	
9			**	
10			**	
11		**	**	

Dry (< 10 mm/year)

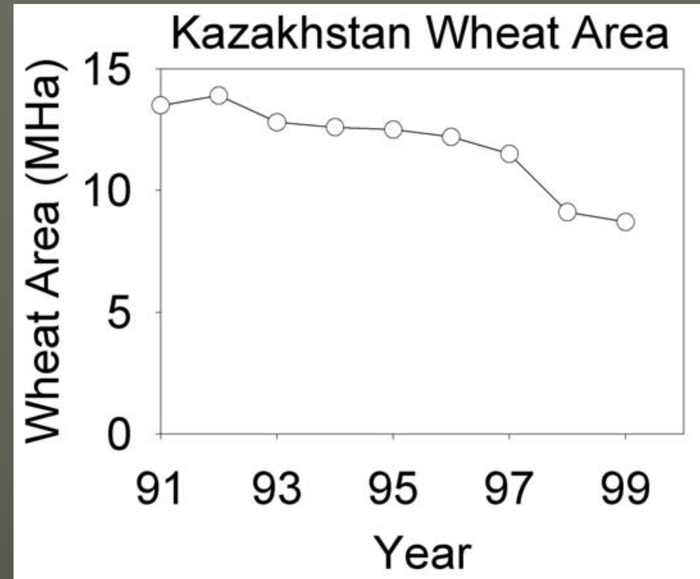
No significant sensor artifacts affect the PAL data from NOAA-7, NOAA-9 and NOAA-14.

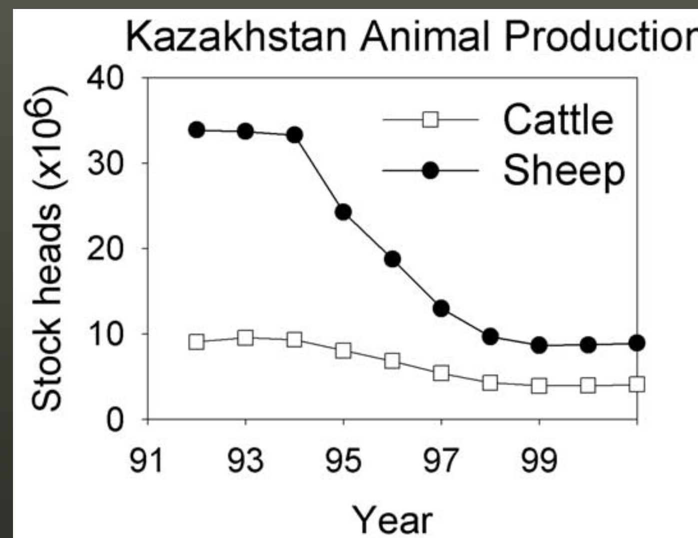
Wet (~ 200 mm/year)

$\alpha = 0.05$

Significant artifacts affect the PAL data from NOAA-11.

Western Kazakhstan: March 2004





- In 1991 the economic and political institutions of the Soviet Union collapsed → Kazakhstan became a newly independent state
- Area – 2.72 million km^2
- Climate – strongly continental
- Population – ~ 16 million (36% work in agricultural sector)
- Subsets (1600 km^2) in each of the 19 Ecoregions (WWF)

Were the land cover changes that occurred in Kazakhstan after 1991 of sufficient magnitude to alter the land surface phenology?

Modeling land surface phenology

Temperate climates:

- At beginning of temperate growing season, plants are typically light-limited or constrained by insolation.
- Average daily temperature can be a good surrogate for insolation in temperate subhumid to semiarid climates.
- Tracking NDVI as a function of Accumulated Growing Degree Days (AGDD) instead of days of the year, we can reduce interannual variation due to weather.

Weather data

- Too few meteorological stations available
- Temperature data from the (NCEP –NCAR) Reanalysis project are used instead **http://wesley.wwb.noaa.gov/ncep_data/**
- Daily min and max temperature data at 2 m (°K)
- Spatial extent: global
- Spatial resolution: roughly 2° by 2° lat/lon

Accumulated Growing Degree Days

We calculated growing degree days as follows:

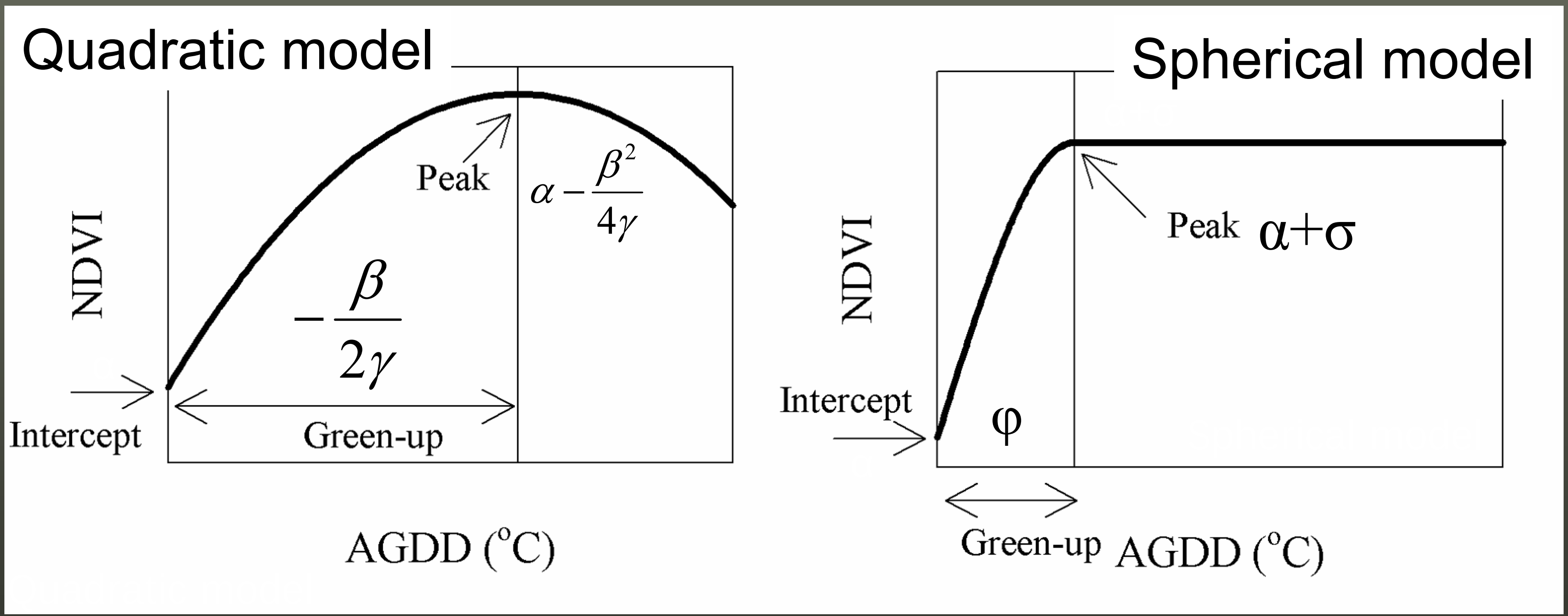
- Growing degree-days:
  $(T_{max} + T_{min}) / 2$ base 0 °C

- Accumulated growing degree-days:
  $AGDD = \sum_{t=1}^{365} GDD_t$ from 01JAN, if $GDD_t > 0$

We summarized the data in 10 day composites

Phenology models

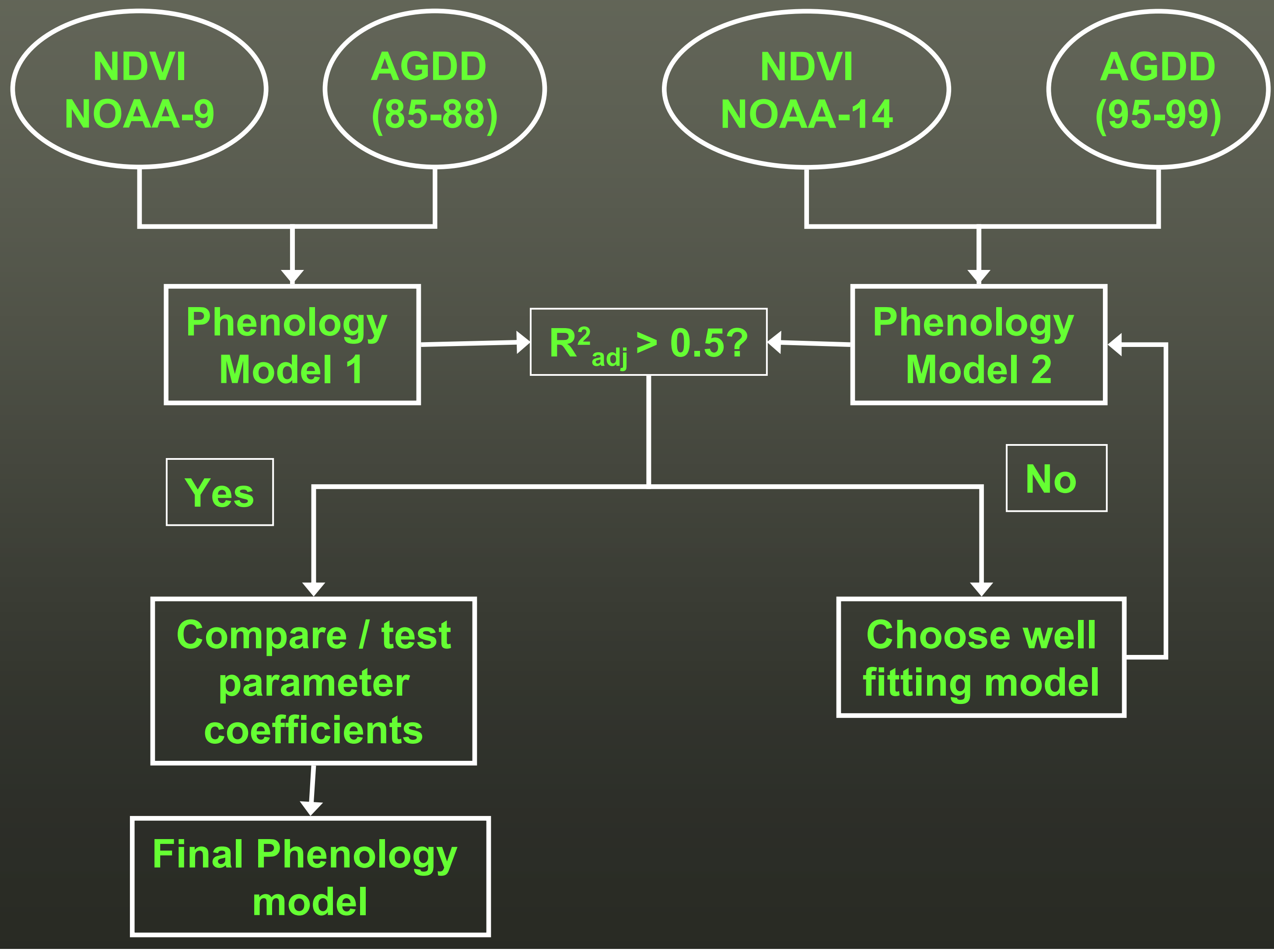
$$NDVI = \alpha + \beta AGDD + \gamma AGDD^2$$



$$NDVI = \begin{cases} \alpha + \sigma\left(1.5\frac{AGDD}{\varphi} - 0.5\left(\frac{AGDD}{\varphi}\right)^3\right) & \text{if AGDD} < \varphi \\ \alpha + \sigma & \text{if AGDD} > \varphi \end{cases}$$

AGDD = Accumulated Growing Degree Days

How do you detect change in land surface phenology?



Compare / test parameter coefficients

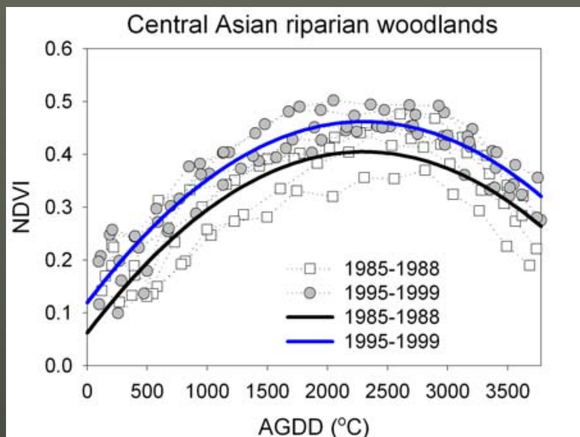
Change analysis for quadratic models

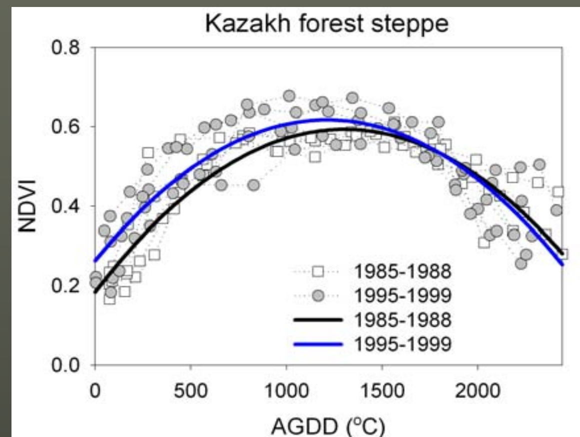
- There is 1 possibility of no change between periods.
- There are 14 possible combinations of change given 2 quadratic models.
- We distinguish three change types:
  - Intercept coefficients increase / decrease
  - Intercept and slope coefficients increase / decrease
  - All parameter coefficients increase / decrease

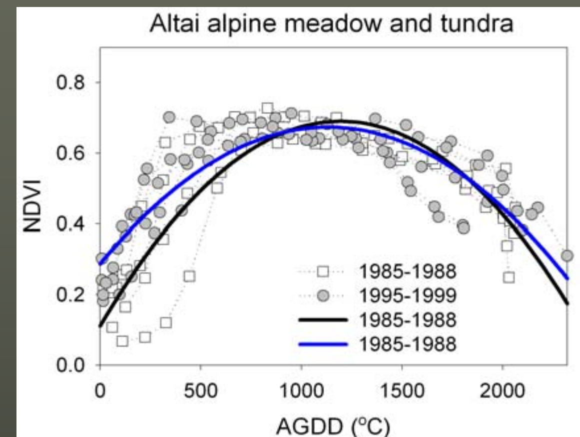
$$NDVI = \alpha + \beta AGDD + \gamma AGDD^2$$

Observed Changes –
all parameter coefficients increase

$0.74 < R^2 < 0.86$



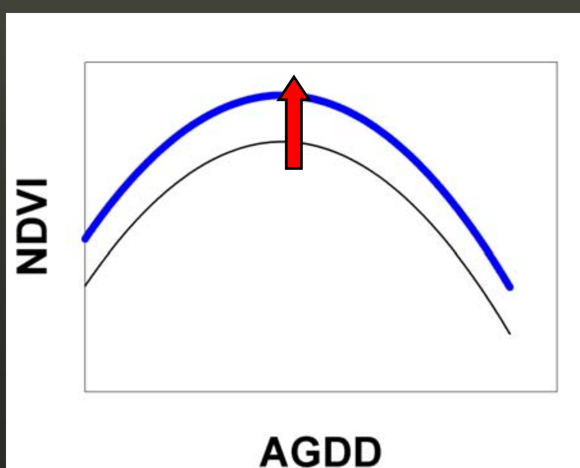


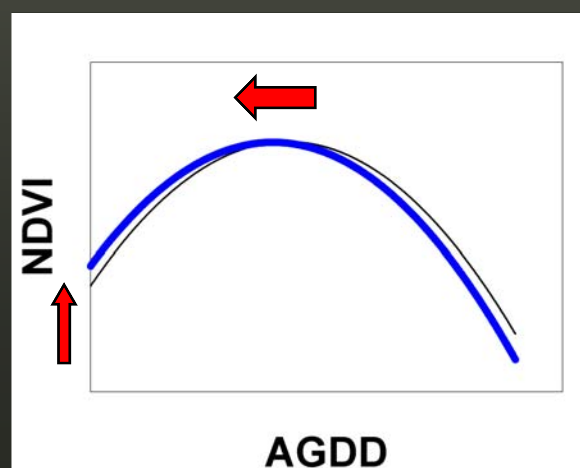


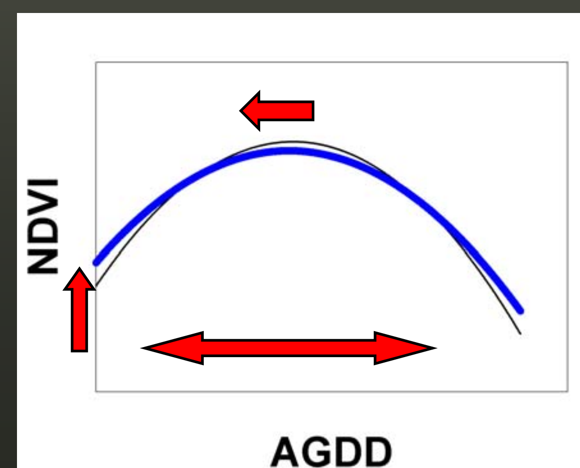
Earlier start of season

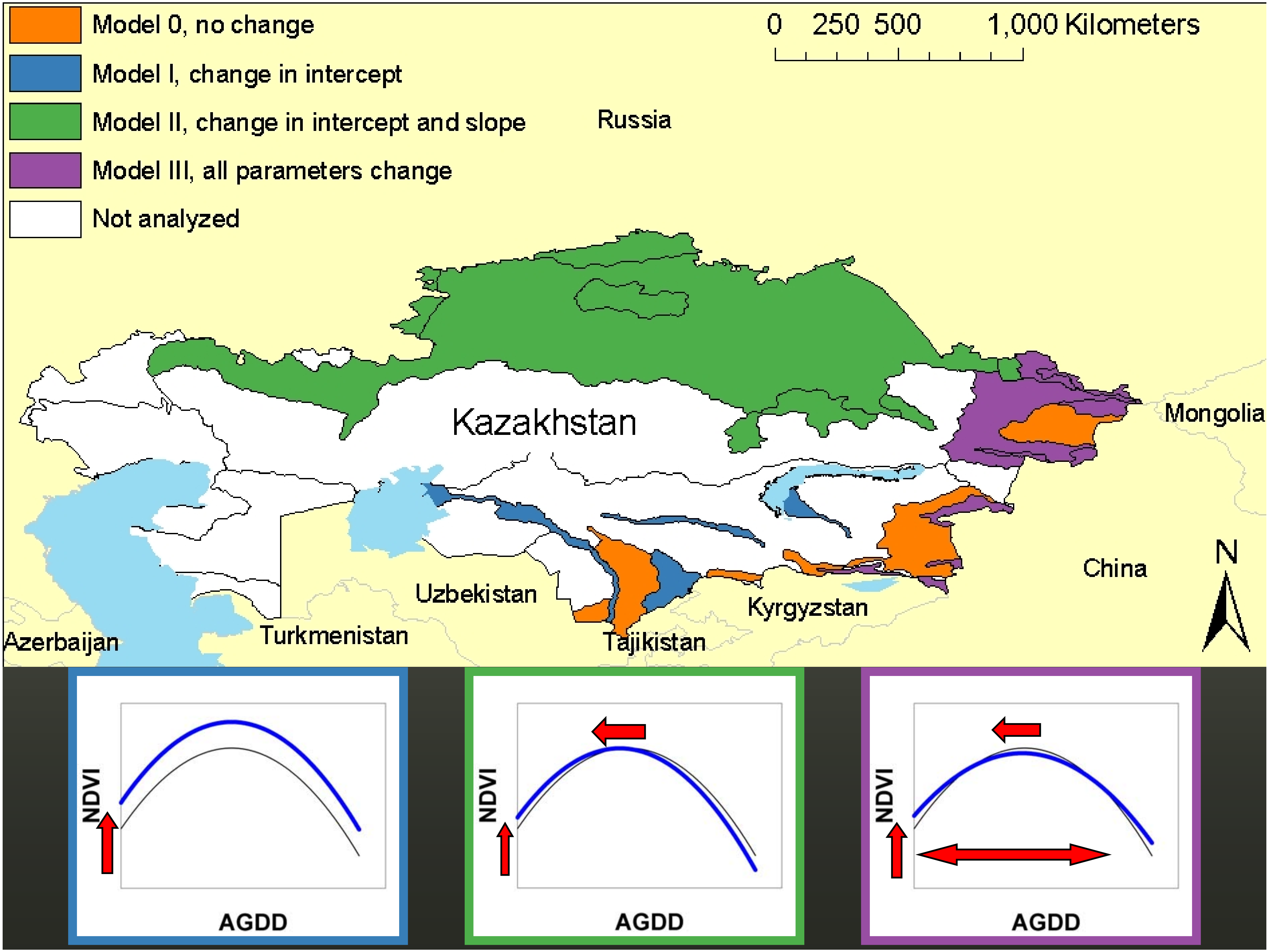
Earlier start of season & earlier peak

Earlier start of season & earlier peak & longer season





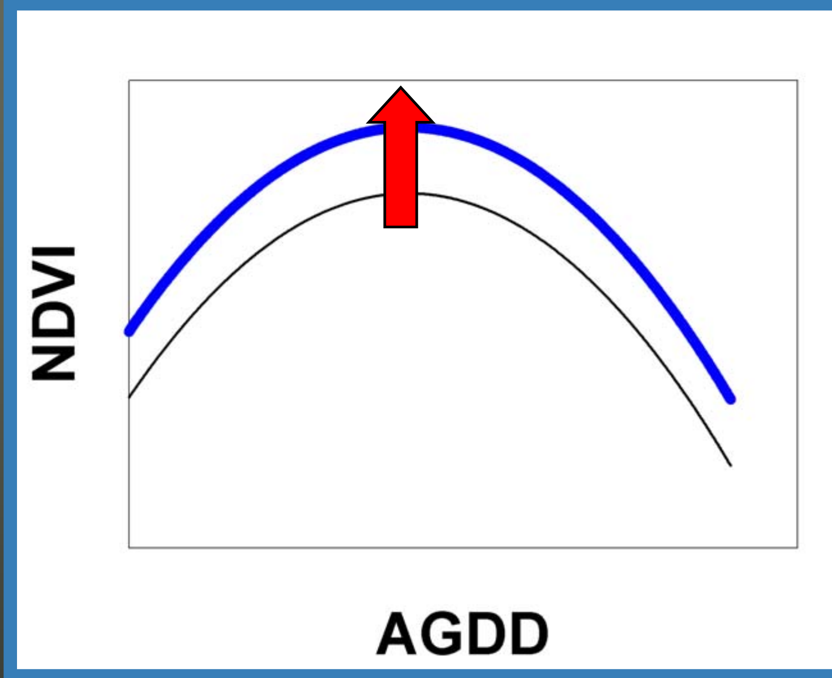




Model 0, no change
Model I, change in intercept
Model II, change in intercept and slope
Model III, all parameters change
Not analyzed
0 250 500 1,000 Kilometers
Russia
Kazakhstan
Mongolia
China
N
Uzbekistan
Kyrgyzstan
Tajikistan
Turkmenistan
Azerbaijan
NDVI
AGDD
NDVI
AGDD
NDVI
AGDD

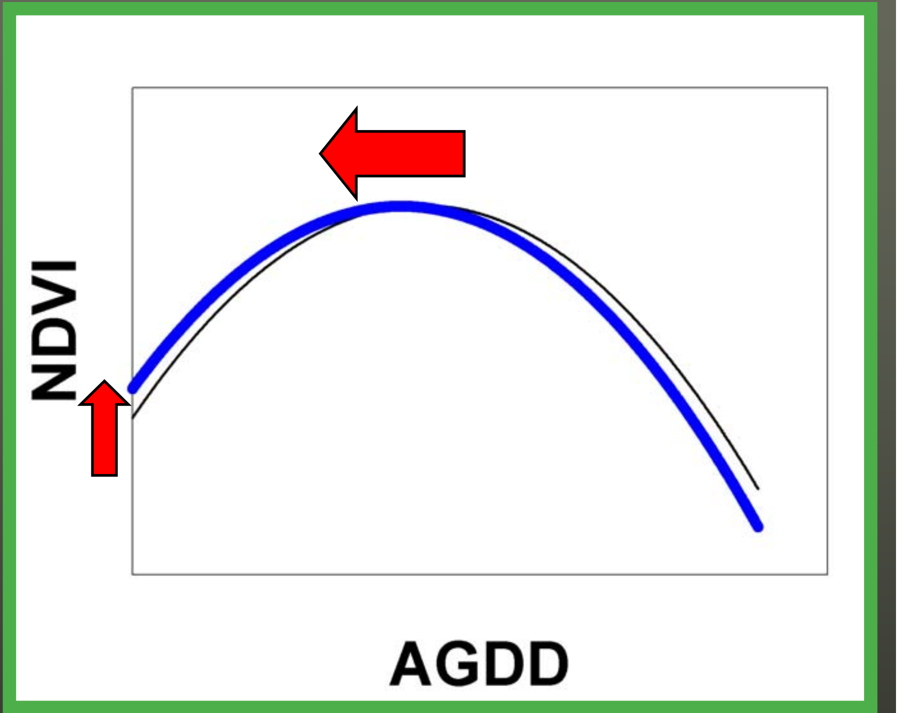
Change Attribution – Ecoregions with irrigated crops

- Overall increase in NDVI.
- Irrigated croplands assumed not water stressed.
- Irrigated croplands are intensively managed.
- Inter-annual variation of crop production can be greater and efficiencies can be lower under centralized planning than under private ownership (Brada & King 1986, 1993).
- Decentralized agricultural decision-making could better respond to local conditions.



Change Attribution – Steppe Ecoregions

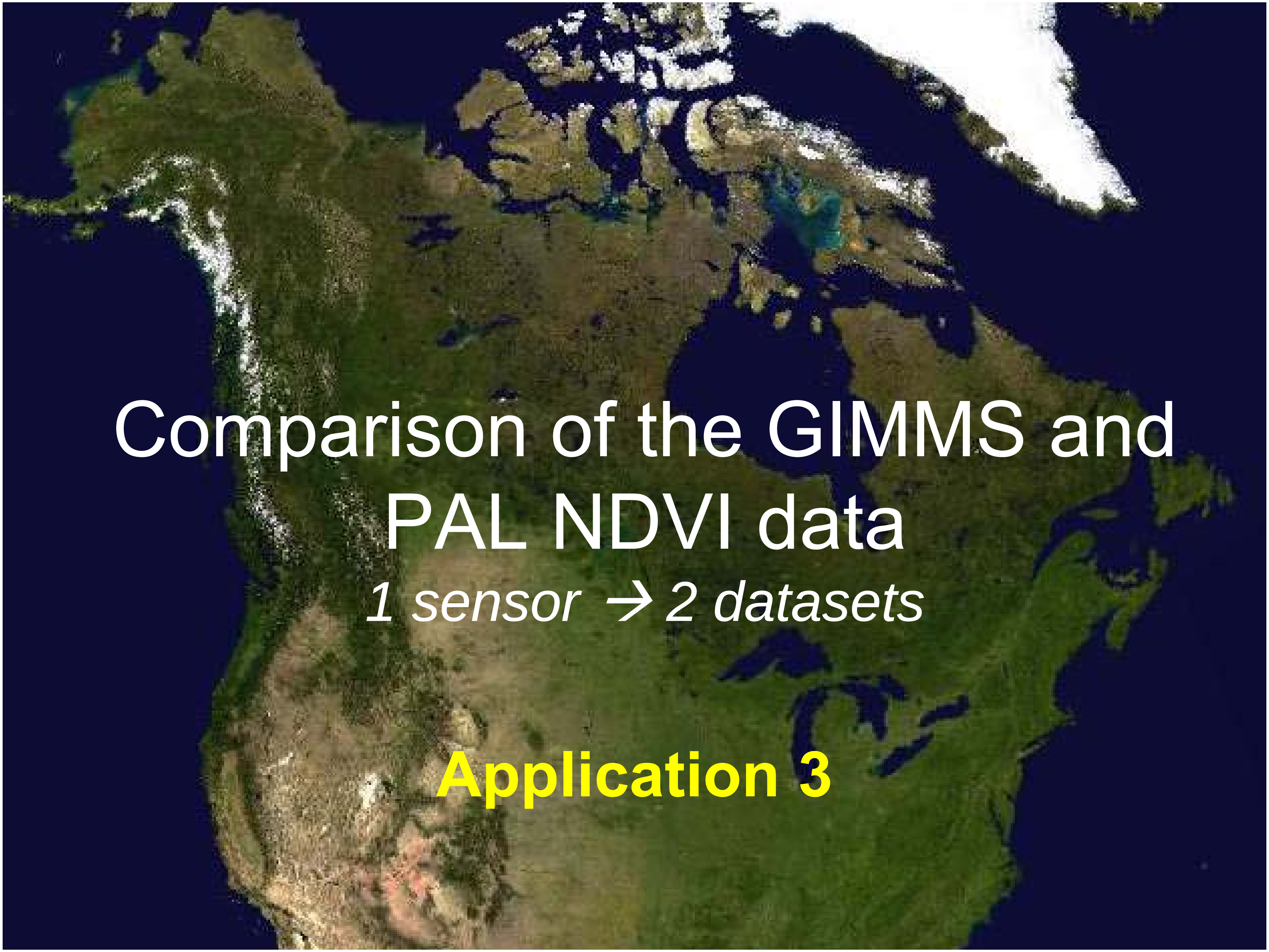
- Higher greenness for low AGDD, equal period of greenness, earlier green-up.
- Grain area reduction was 33%.
- 70% decrease in sheep production and thus grazing pressure → land was not added to rangeland.



Agricultural de-intensification: increase of weedy species and native grasslands due to reduced grazing pressure (Meng et al., 2000)

Conclusions – Application 2

- PAL NDVI data allows comparisons between time periods before and after institutional change.
- Straightforward statistical analyses reveal differences in land surface phenology before and after institutional change.
- We reach comparable results for a different spatial partitioning: 7 agricultural study regions.
- The results using the agricultural study regions are consistent but more dramatic than using the WWF ecoregions.
- We have detected a change in land surface phenology which we can attribute to land cover land use change following institutional change.



Comparison of the GIMMS and PAL NDVI data

1 sensor → 2 datasets

Application 3

Key aspects in comparative analysis of land surface phenology

- Several NDVI datasets have been developed for the study of land surface phenology.
- It is often unclear which dataset is the most appropriate to use.
- The need to compare datasets is increasingly important.
- The coarse resolution and the temporal compositing inhibit ground validation.

It may not be possible to determine which dataset portrays the land surface dynamics “better”.

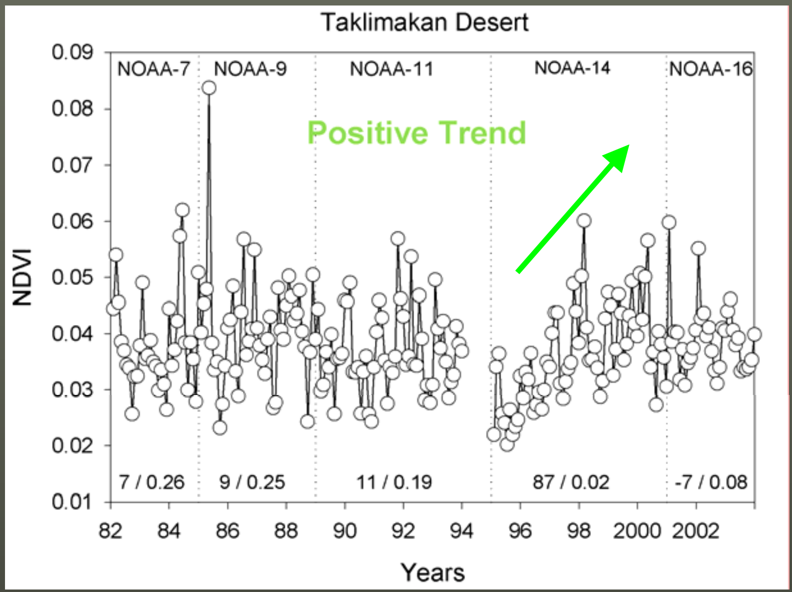
PAL & GIMMS

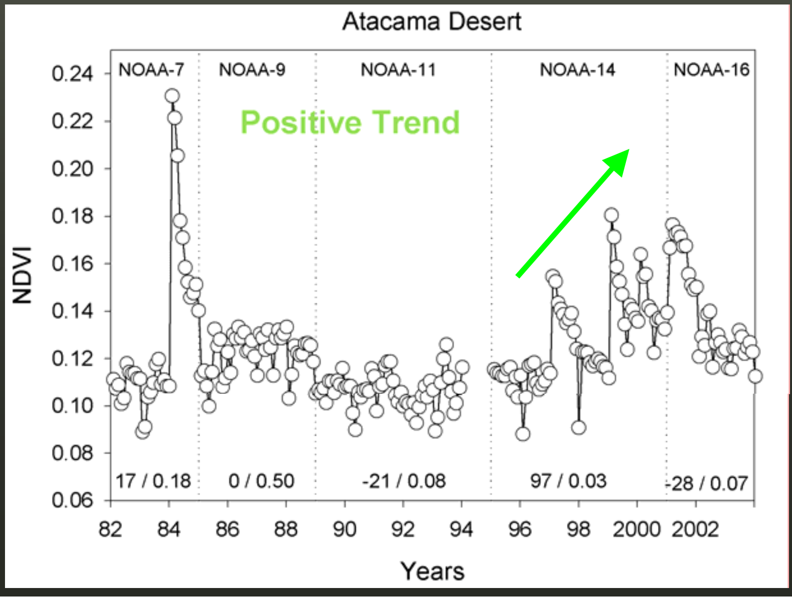
- The Pathfinder AVHRR Land (PAL) maximum Normalized Difference Vegetation (NDVI) 10-day composites.
- The Global Inventory Modeling and Mapping Studies (GIMMS) satellite drift corrected and NOAA-16 incorporated 15-day composite NDVI dataset.
- Both datasets have 8 kilometer resolution.
- The data is recorded by sensors on 5 satellites: NOAA-7, NOAA-9, NOAA-11, NOAA-14 and NOAA-16.

Land surface change analysis

- Here I will compare the conclusions about land surface phenology changes resulting from GIMMS NDVI and PAL NDVI.
- Sensor calibration is usually performed on stable desert targets.
- Artifacts have been found in the PAL NDVI data
- Also the GIMMS data reveal some profound artifacts.

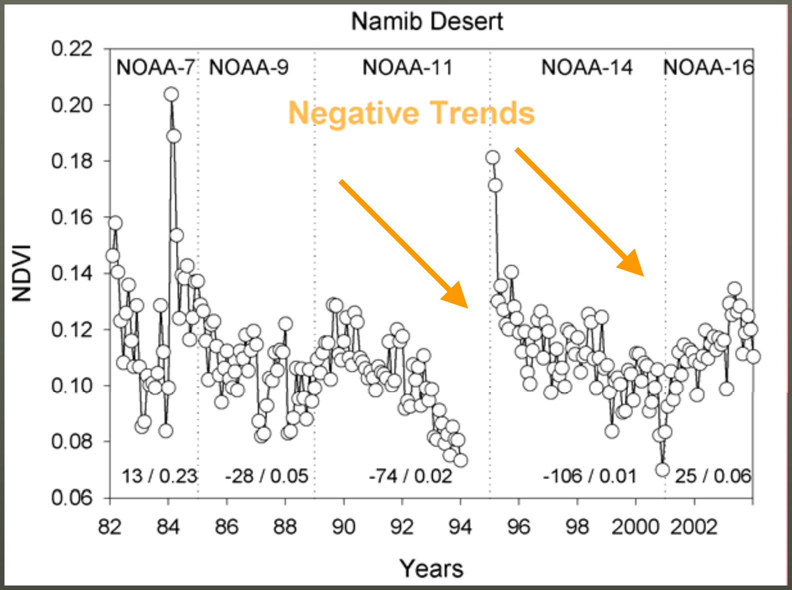
GIMMS desert artifacts

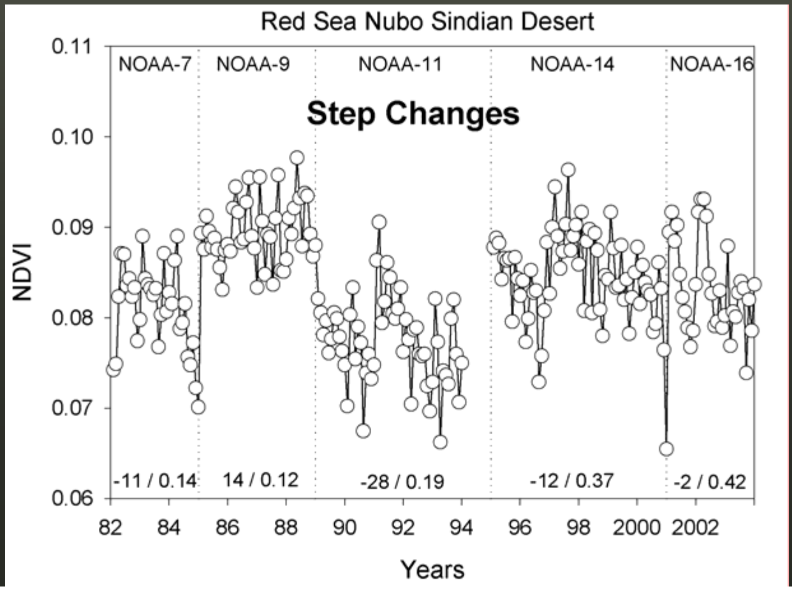




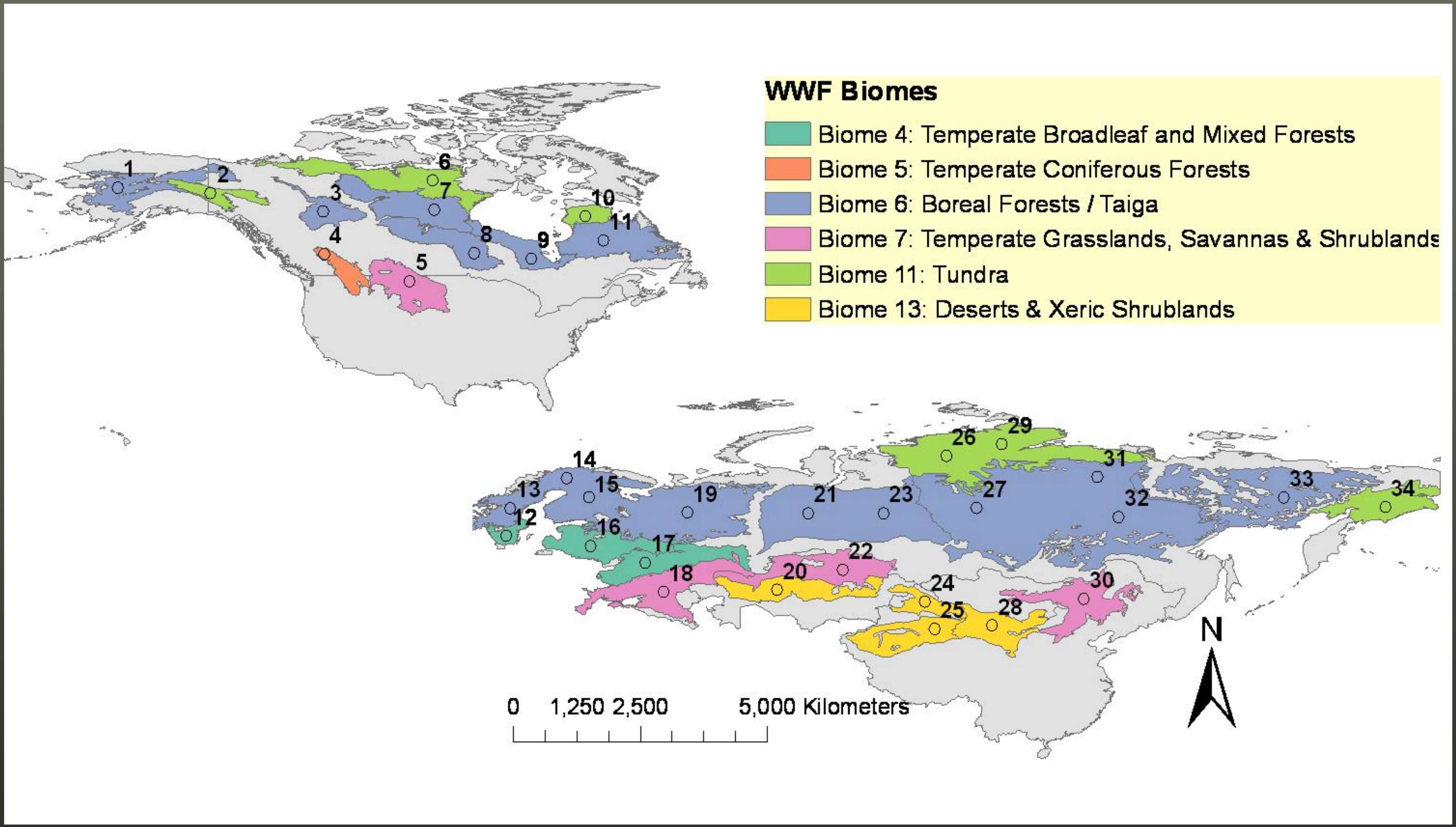
Me! Atacama Desert: May 2001

GIMMS desert artifacts



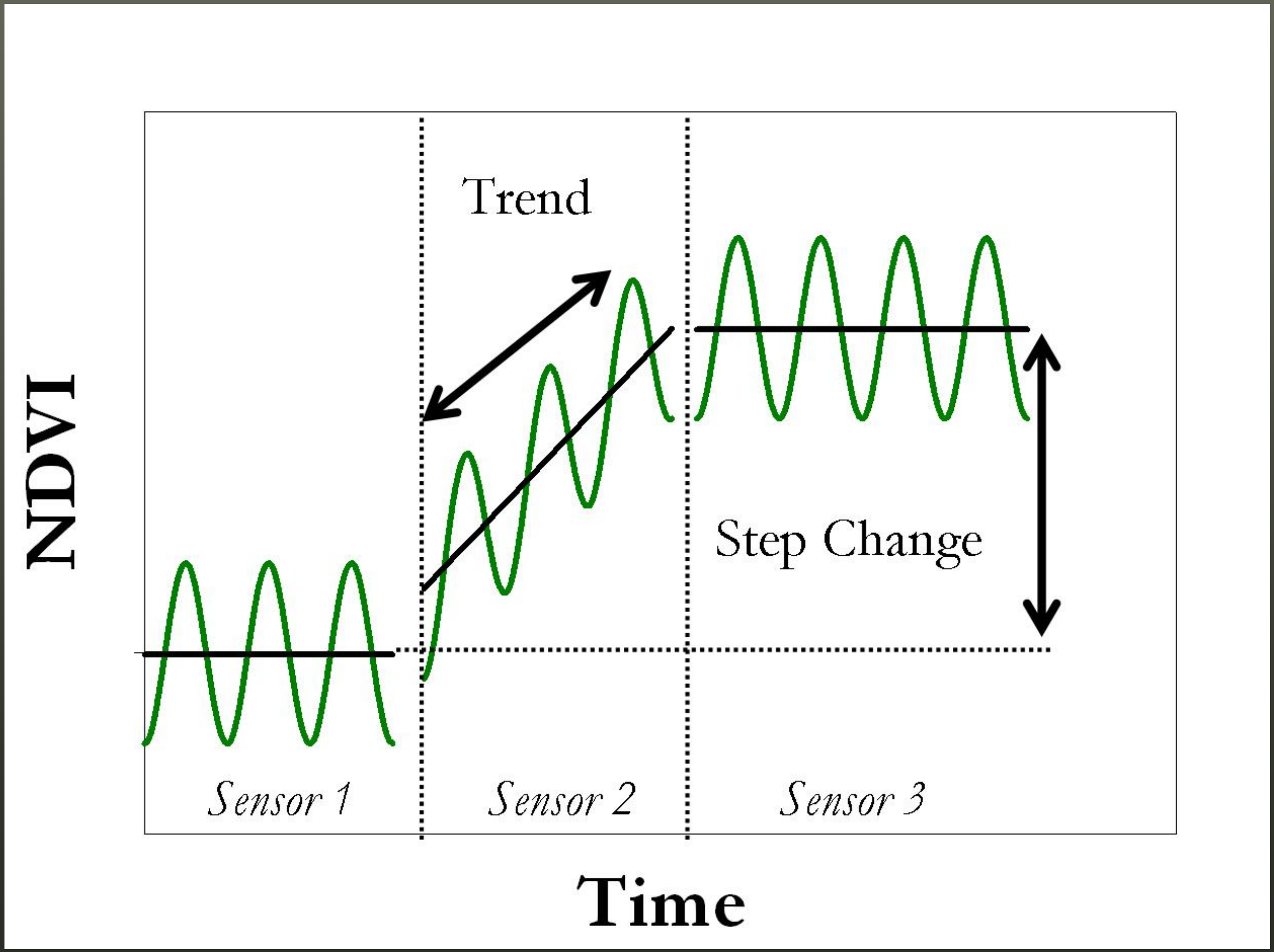


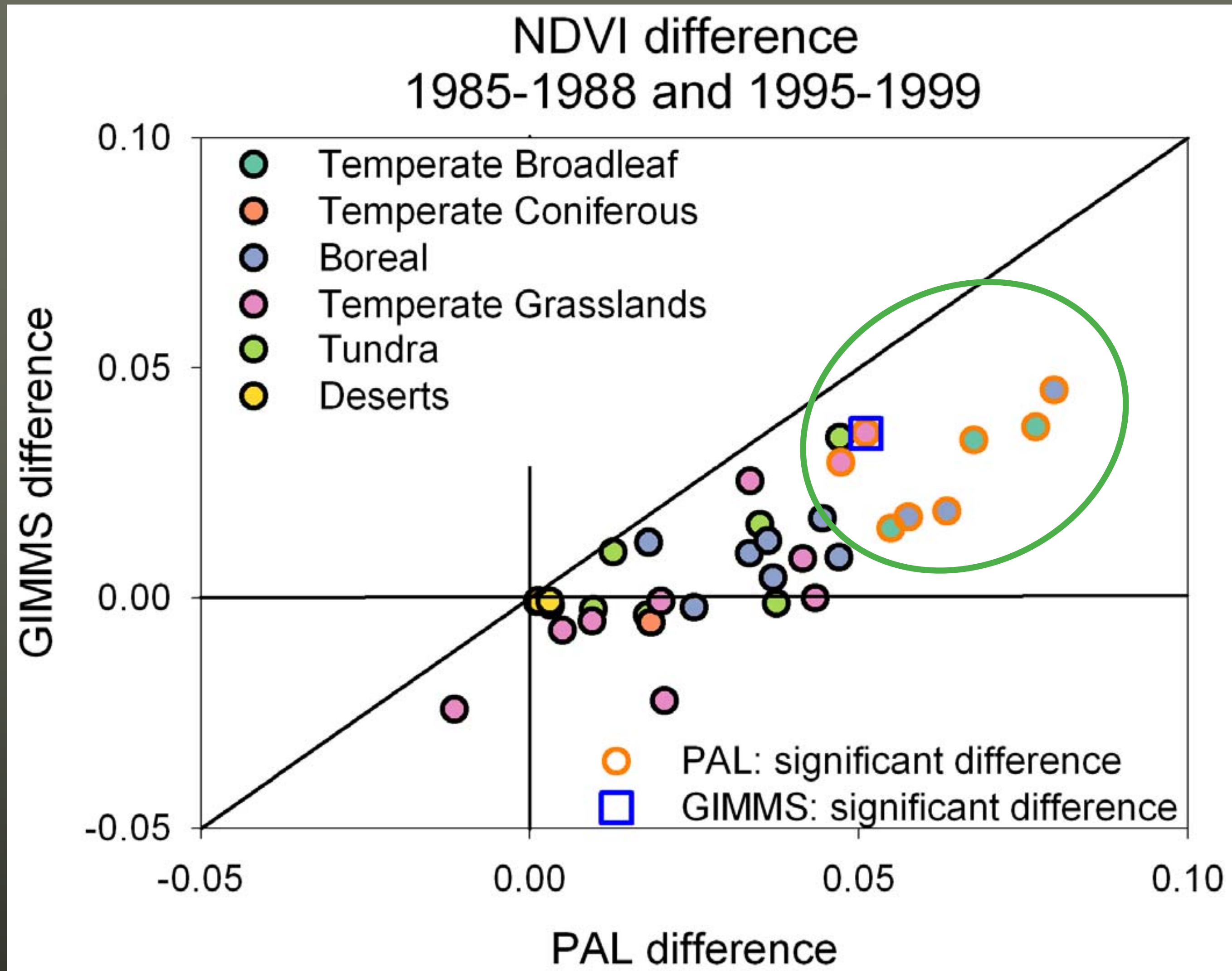
Study Regions



- 11 study regions in North America; 23 study regions in Northern Eurasia.
- 6 different WWF biomes.
- Area of each circular study region : ~ 48,000 km^2 (~760 pixels).

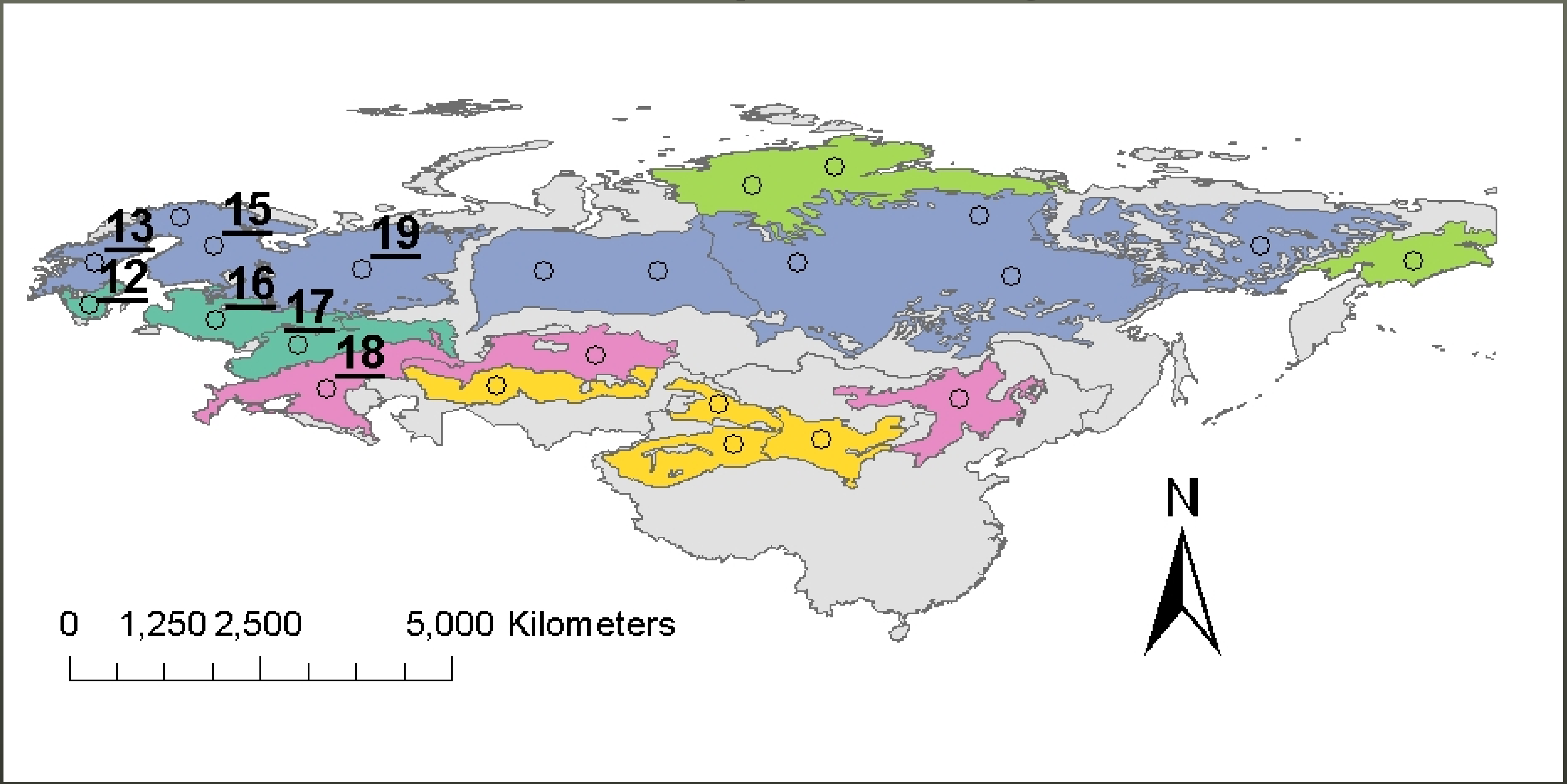
Step Changes





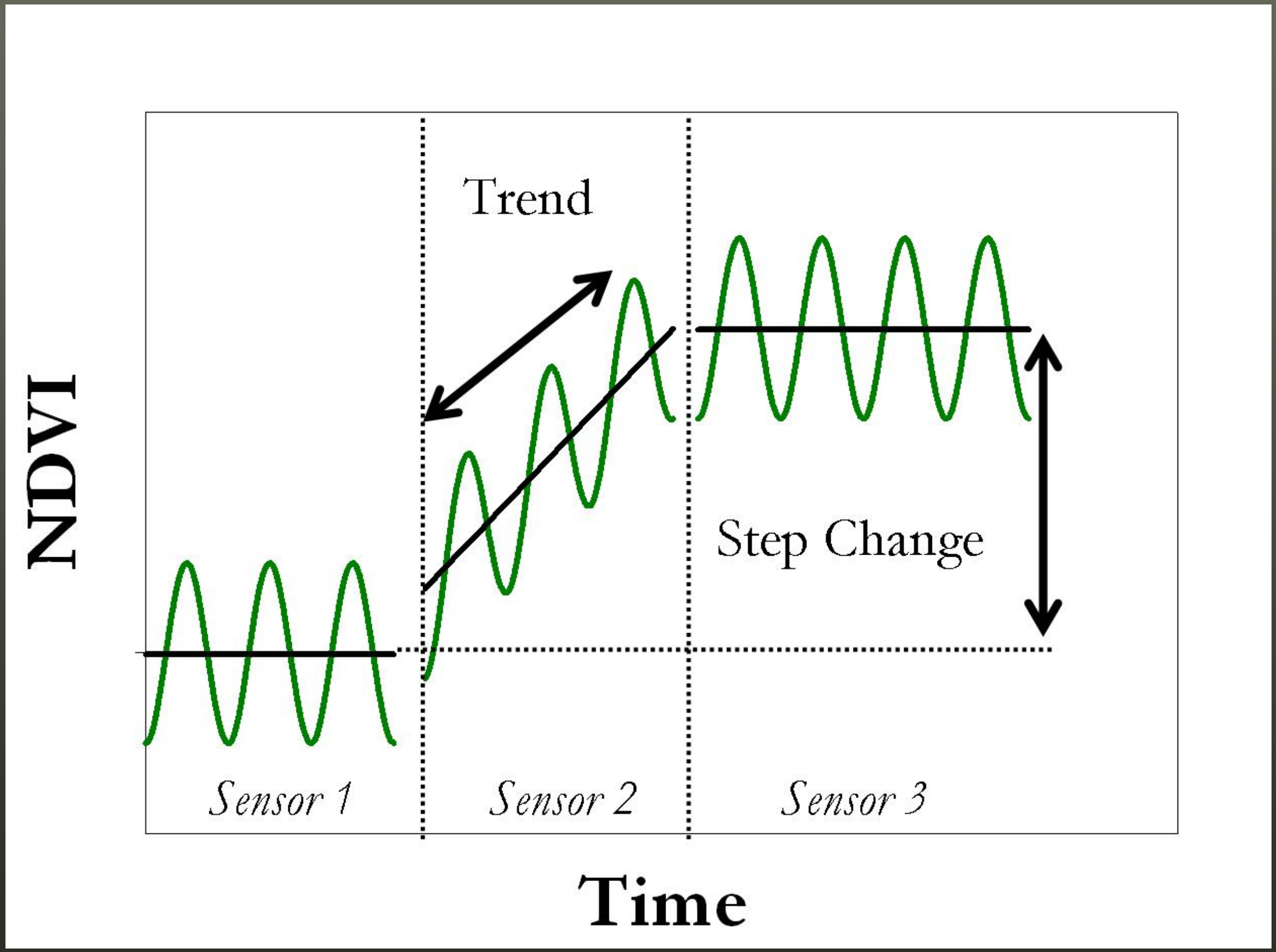
- Observations close to zero indicate small changes between (85-88) and (95-99).
- PAL difference is always > GIMMS difference → all regions are below 1:1 line.
- Boreal forests and temperate broadleaf forests show largest change.
- GIMMS: 1 significant step change; PAL: 8 significant step changes.

PAL step changes

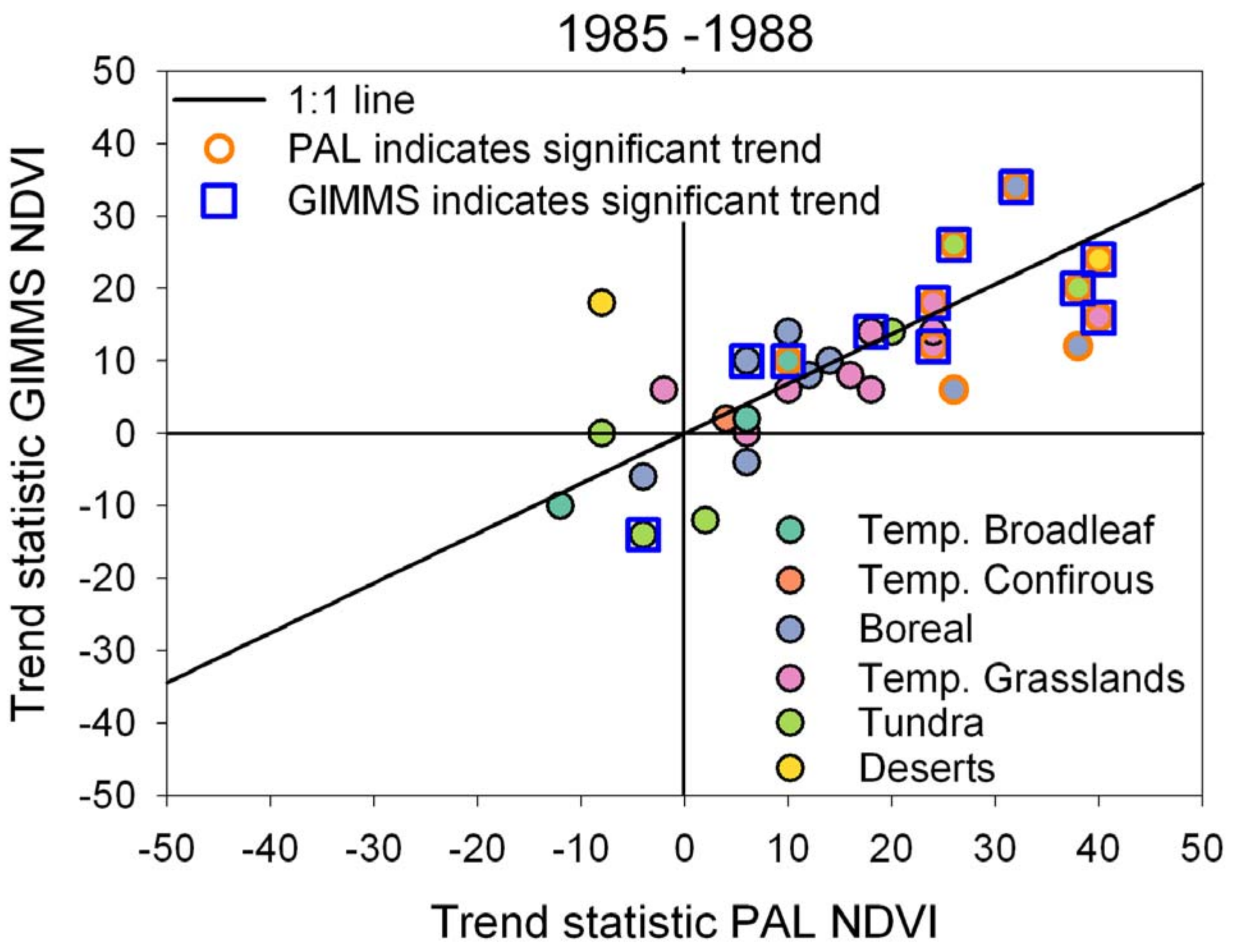


- There are 7 regions with a significant increase in PAL but NOT in GIMMS.
- The regions are divided over 3 biomes.
- The regions are spatially coherent and all located in the west of Northern Eurasia.
- Widespread significant increase in PAL NDVI in the western part of Northern Eurasia that is not apparent in the GIMMS NDVI data.

Trends



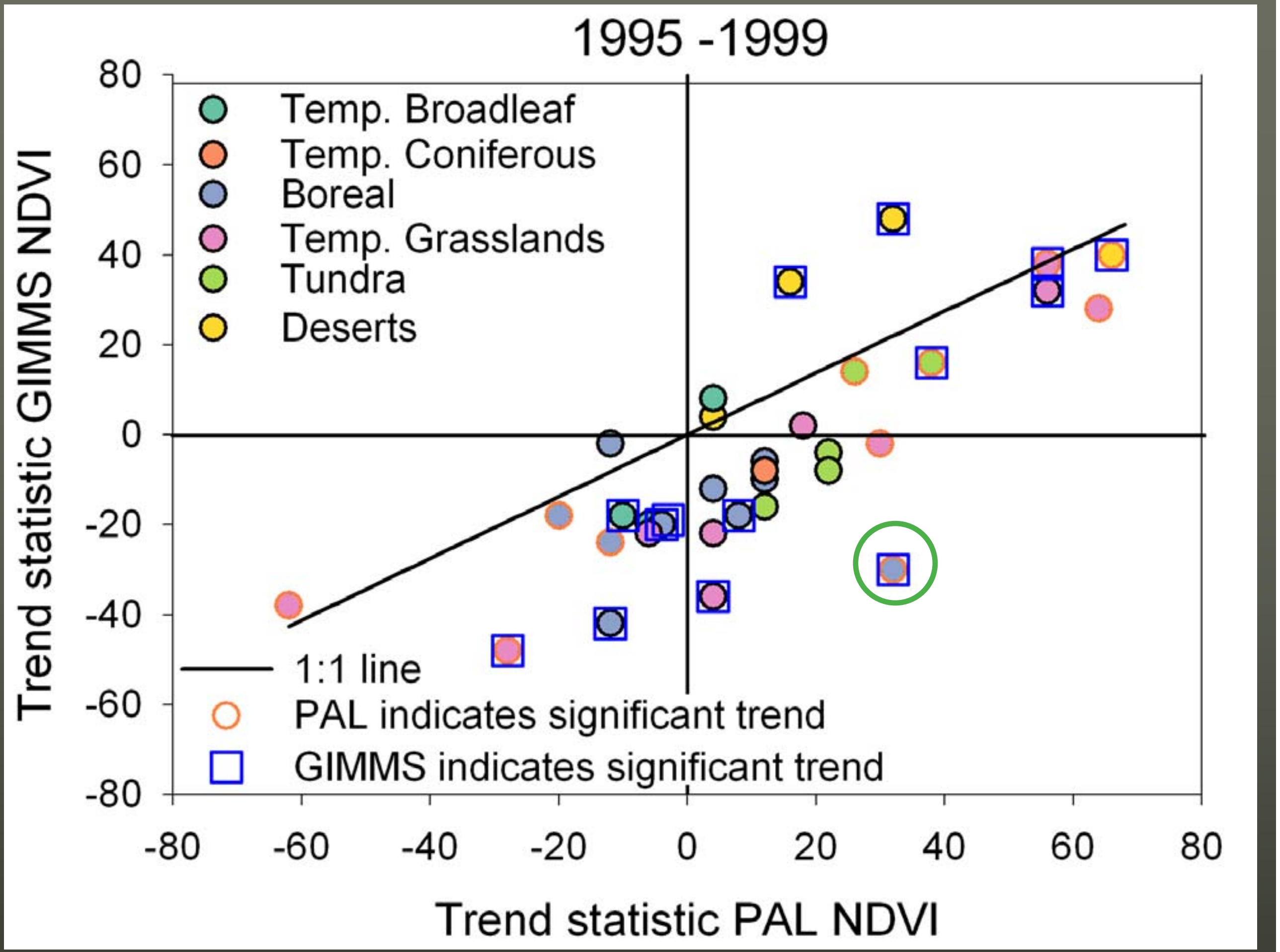
- Most regions show slight positive to significant positive trend.
- Three regions show a negative trend in both datasets.
- There are 12 regions with a significant positive trend, 8 have a significant trend in both datasets.



- 2 regions have a significant trend in GIMMS and NOT in PAL.
- 2 regions have a significant trend in PAL and NOT in GIMMS.

In the 1985-1988 period, there is an overall agreement between both datasets

- GIMMS trends are generally lower than PAL trends.
- 19 regions with a significant trend, just 4 have a significant trend in both datasets.
- 9 regions showed a significant trend in GIMMS and NOT in PAL.

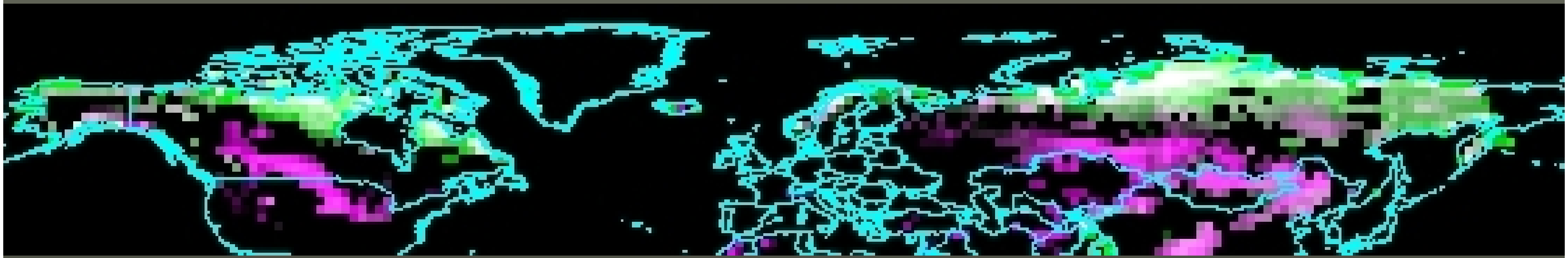


- 5 regions revealed a significant trend in PAL and NOT in GIMMS.
- 1 region where the datasets contradict each other →

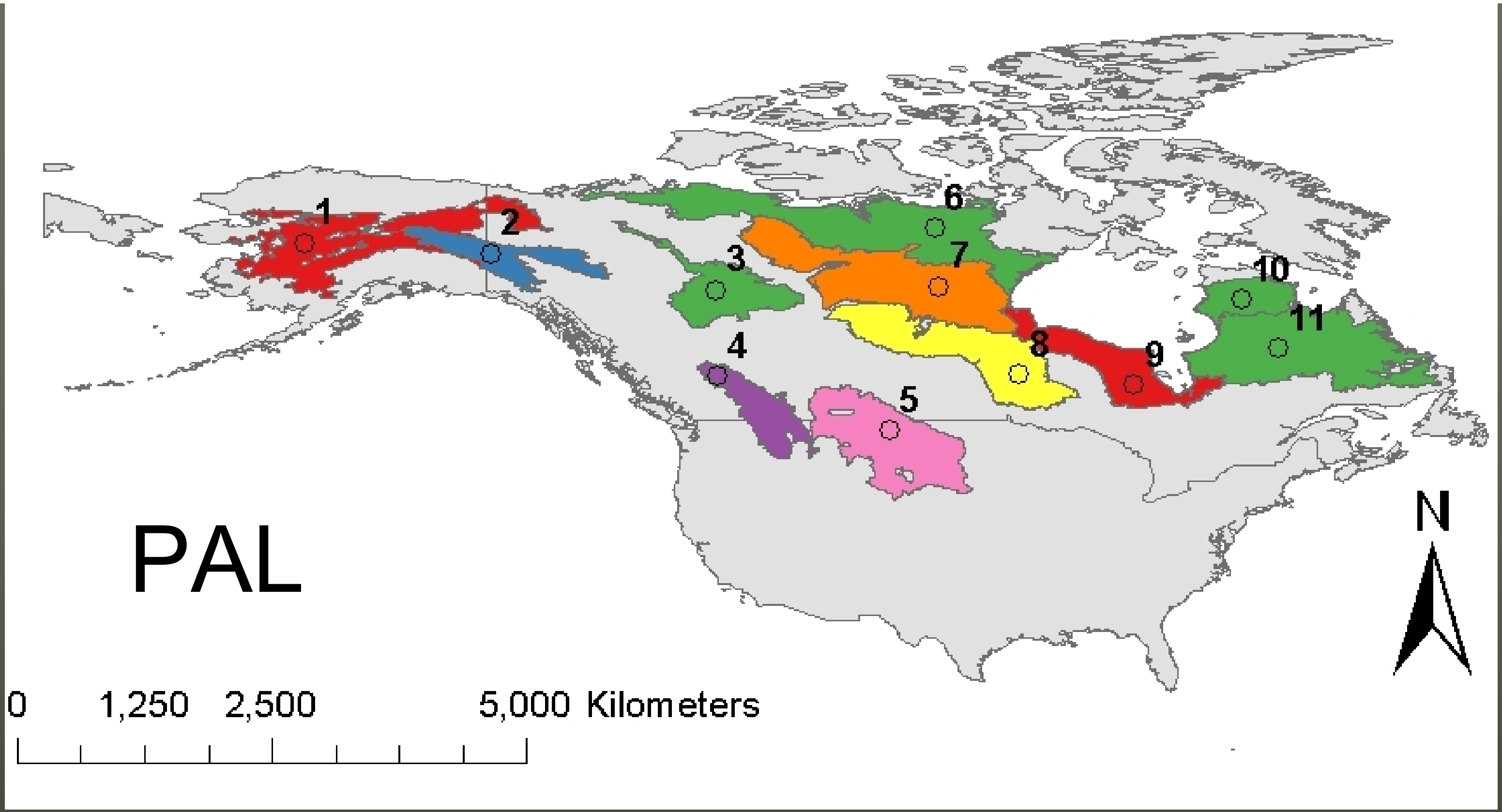
PAL significant positive trend : GIMMS significant negative trend.

In the 1995-1999 period, the datasets present wide varying conclusions!

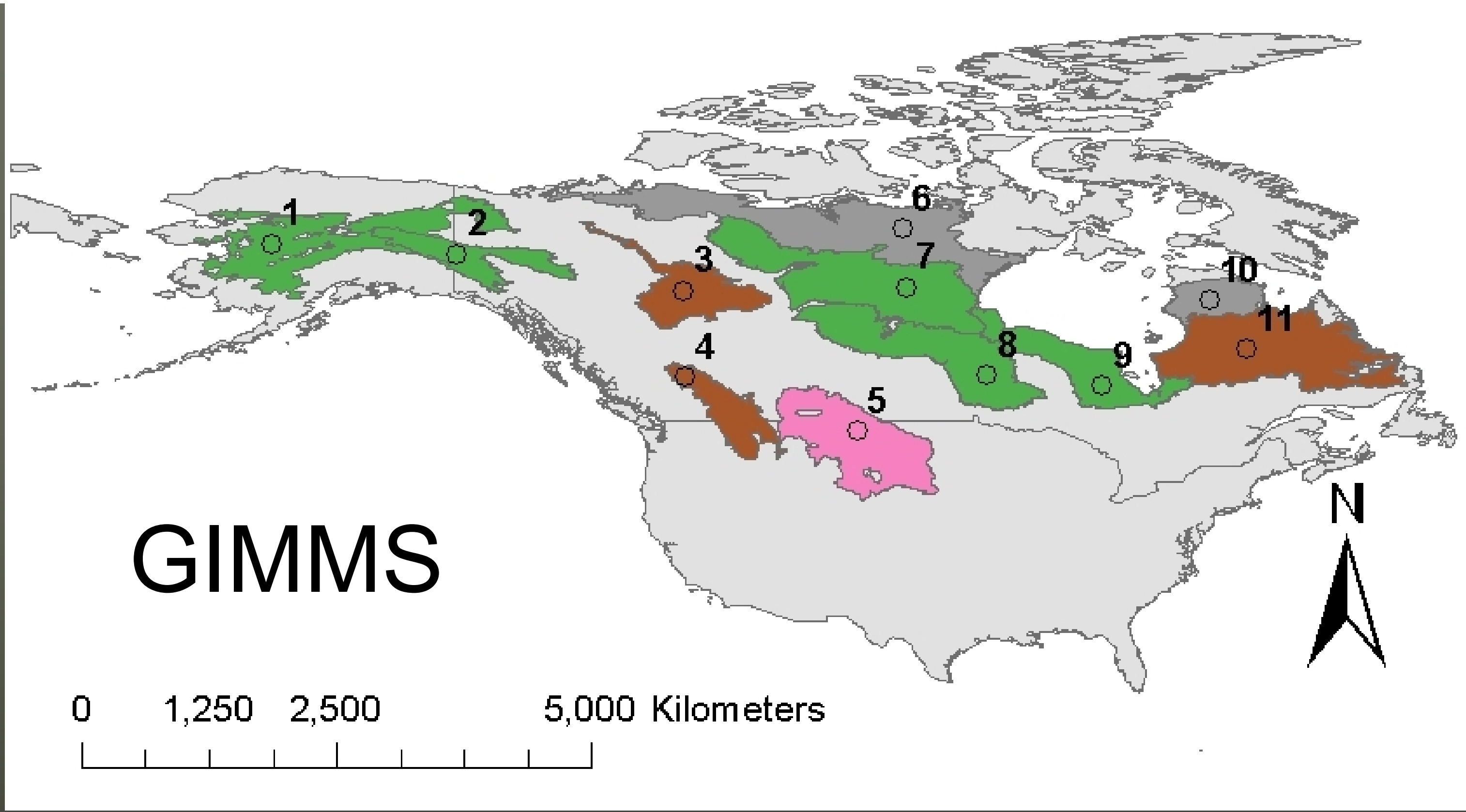
Quadratic and Spherical Regression Model Results



- Quadratic models fit well to the phenology of agricultural and herbaceous vegetation.
- Woody vegetation types (including tundra) are better fit with a nonlinear spherical model.
- Some areas are fit well with either model.
- The area are not fit by either model.



	Response of model based on 1995-1999 compared to the model based on 1985-1988
(green)	No Change
(blue)	Higher NDVI at the start of the growing season
(red)	Peak NDVI reached at less AGDD
(brown)	Peak NDVI reached at more AGDD
(yellow)	Higher NDVI peak
(purple)	Higher NDVI at the start of the growing season, peak NDVI reached at less AGDD
(orange)	Lower NDVI at the start of the growing season, peak NDVI reached at less AGDD, lower NDVI peak
(grey)	Lower NDVI at the start of the growing season, lower NDVI peak
(pink)	Quadratic model: lower NDVI at the start of the growing season, peak reached for more AGDD, higher NDVI peak



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Conclusion 1 – Application 3

- The presented statistical framework can be applied for the intercomparison of PAL and GIMMS NDVI.
- We compared change behavior instead of absolute NDVI pixel values.
- The datasets revealed different step changes, trends and phenological changes.
- It important to explore the source of the differences.

Conclusion 2 – Application 3

- GIMMS data may have received more precise corrections, but has this resulted in a more accurate dataset?
- GIMMS data shows many significant artifacts were we would not expect them while at the same time the data shown no change where we expect to see change.

Overall Conclusions - 1

- It is extremely important to have methods that are capable of distinguishing between expected variability and significant change.
- The presented statistical framework for the analysis of long image time series consists of robust techniques for:
  - step change analysis
  - temporal trend analysis
  - modeling of LSP and analysis of LSP change
- The focus of most analyses presented here was on the NOAA NDVI data. The methods can also be applied to other data types.

Overall Conclusions - 2

- Significant artifacts remain visible in the PAL NDVI NOAA-11 data.
- Data from the other PAL sensors have sufficient quality for land surface change analysis.
- The GIMMS data also reveal several significant artifacts over multiple desert regions.
- The statistical framework resulted in multiple lines of evidence indicating that:

  the disestablishment of the Soviet agricultural sector lead to such widespread de-intensification of agriculture in Kazakhstan that there have been significant changes in the land surface phenology throughout much of the country.

Further Questions-1

- How would the spatial structure of the landscape change as a result of change in land surface phenology?
- What proportion of the unexplained variation in the land surface phenology can be attributed to precipitation variability?
- What proportion of the unexplained variation can be attributed to large atmospheric oscillation patterns?
- How does the regional climate change as a result of land surface phenology change?

Further Questions-2

- How should the land surface phenology models look for other regions such as:
  - Tropical regions
  - Double cropped regions
  - Southern Hemisphere
- Is the statistical framework capable of distinguishing between climate variability and anthropogenic change in other regions?

Publications

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- The Global Inventory Modeling and Mapping Studies (GIMMS) Satellite Drift Corrected and NOAA-16 incorporated NDVI monthly 1981 data were downloaded from the Global Land Cover Facility of the University of Maryland.
- NCEP Reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov/

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Questions?