An introduction to land surface phenology:

What is it and why is it critical for understanding terrestrial ecosystem dynamics?

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Guest lecture for GEO 409
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Outline of Lecture

1. Stepping Back to See the Whole
    1. The Planetary Macroscope
    2. Remote Sensing of the Vegetated Land Surface
2. Context for Land Surface Phenology (LSP)
    1. What is Phenology?
    2. What is Land Surface Phenology?
3. Drivers of Phenology
    1. Whose Time?
    2. Example from tallgrass prairie: Insolation→AGDD→ANPP
    3. Modeling LSP using a vegetation index and thermal time
4. Land Surface Phenologies at Different Scales
    1. Regional LSPs using MODIS: the case of Kazakhstan
    2. Local scale LSPs using Landsat: the case of Kyrgyzstan
5. LSPs in Cool Earthlight
    1. Passive microwaves also reveal seasonal changes
6. Take Home Points

1. Stepping Back to See the Whole

The Planetary Macroscope

Consider a few seconds worth of starlight on a winter night

http://antwrp.gsfc.nasa.gov/apod/ap090411.html

Here are 40 hours worth of starlight at the same location

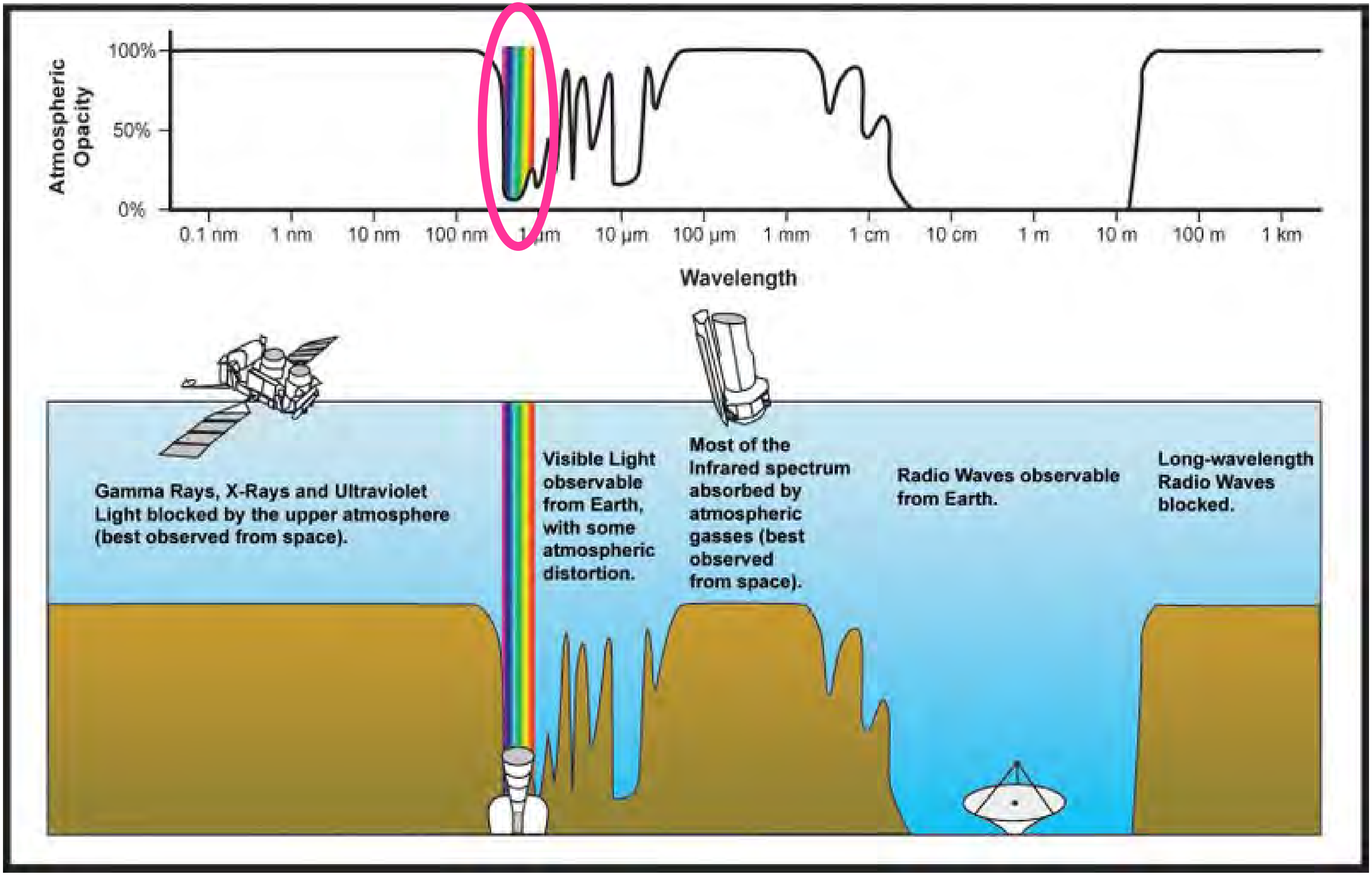
http://antwrp.gsfc.nasa.gov/apod/ap090411.html

Telescopes are "light buckets" gathering **starlight** and integrating it over long periods to reveal faint objects.

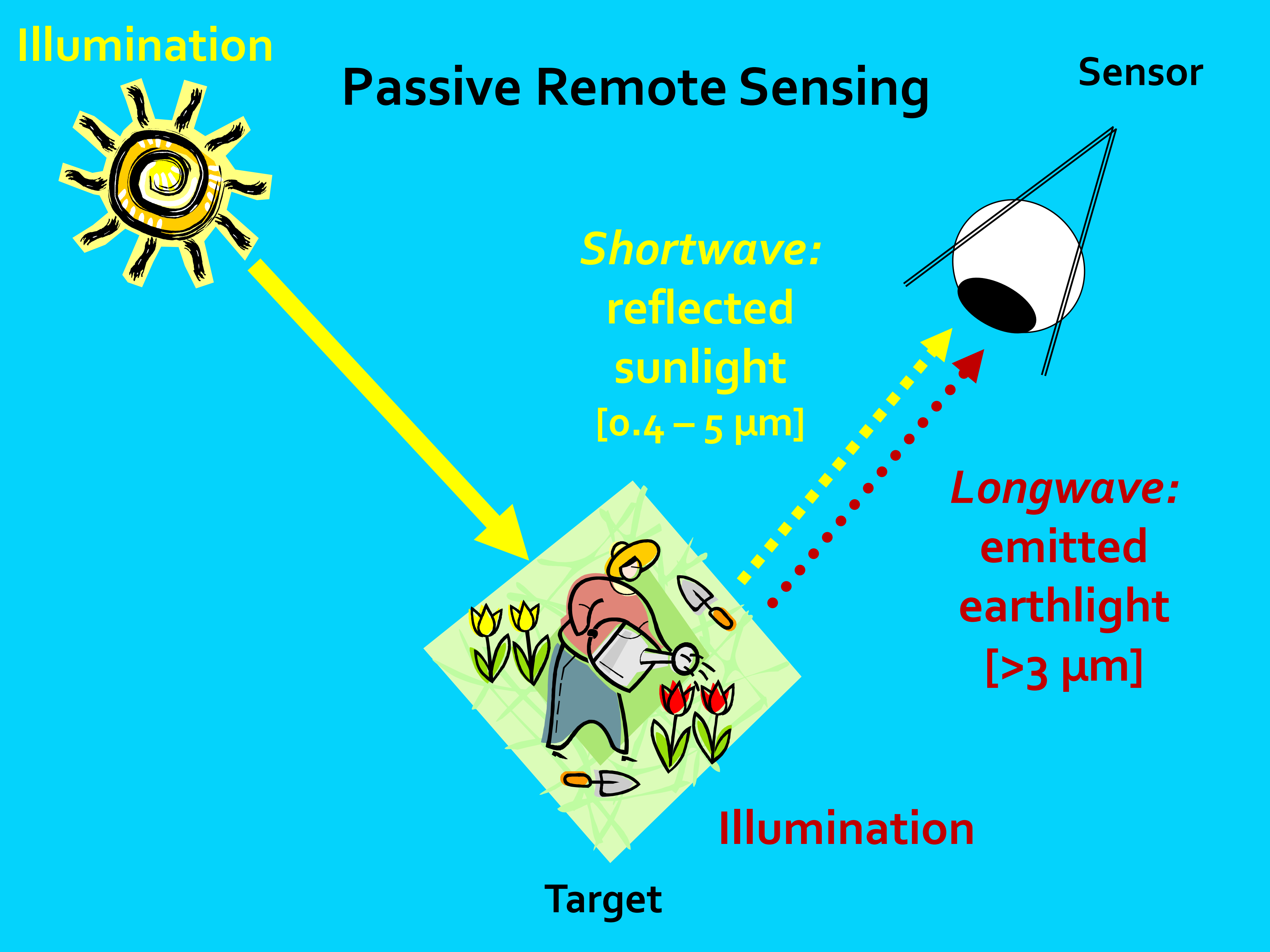
Likewise, **earth-observing sensors** gather and integrate three types of light arising from our planetary surface:

- **Sunlight** (reflected solar radiation)
- **Earthlight** (emitted terrestrial radiation)
- **Humanlight** (backscattering from radars & lidars ***and*** emitted from anthropogenic sources – lighting, gas flares, fishing fleets)

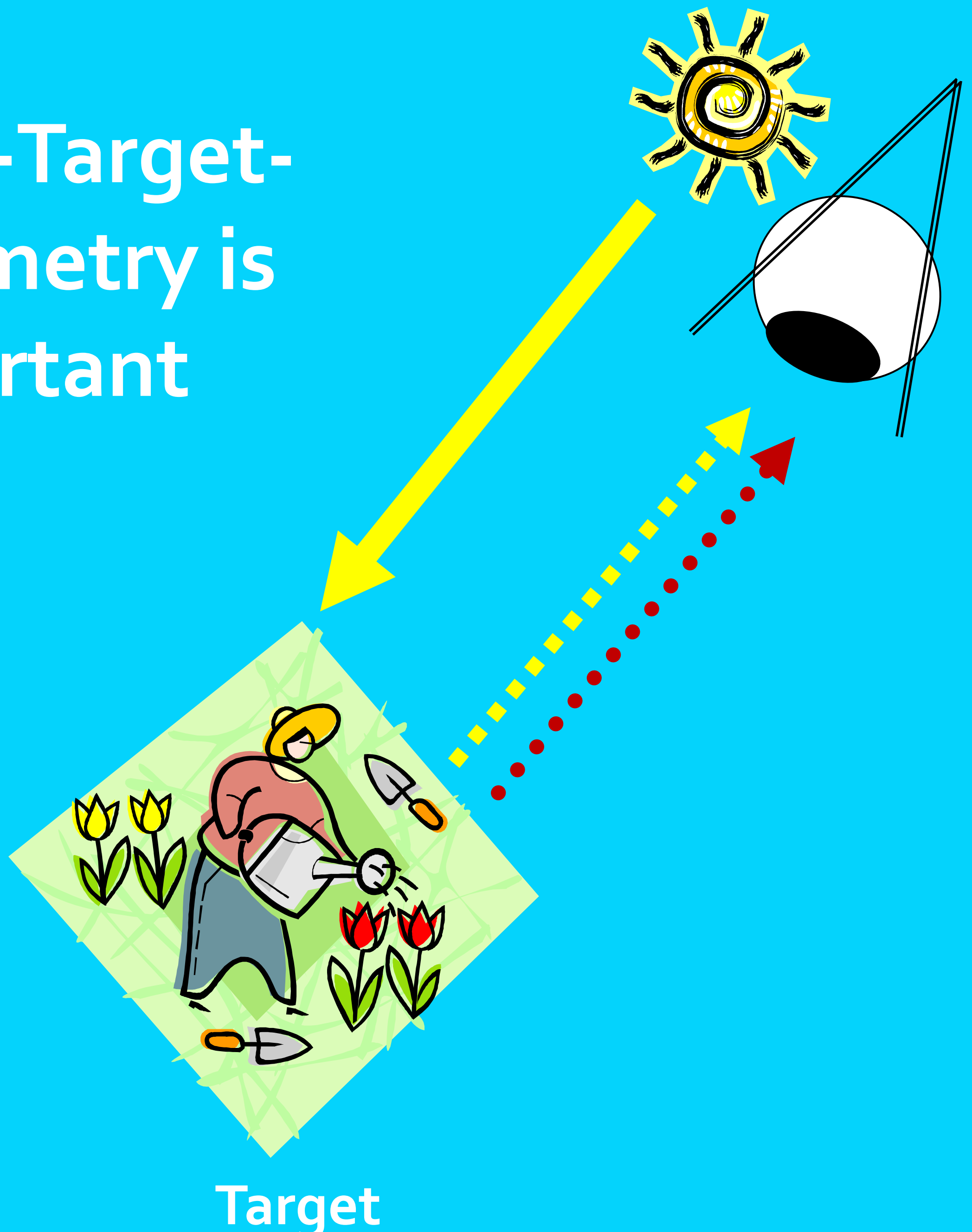
Atmospheric opacity across the electromagnetic spectrum



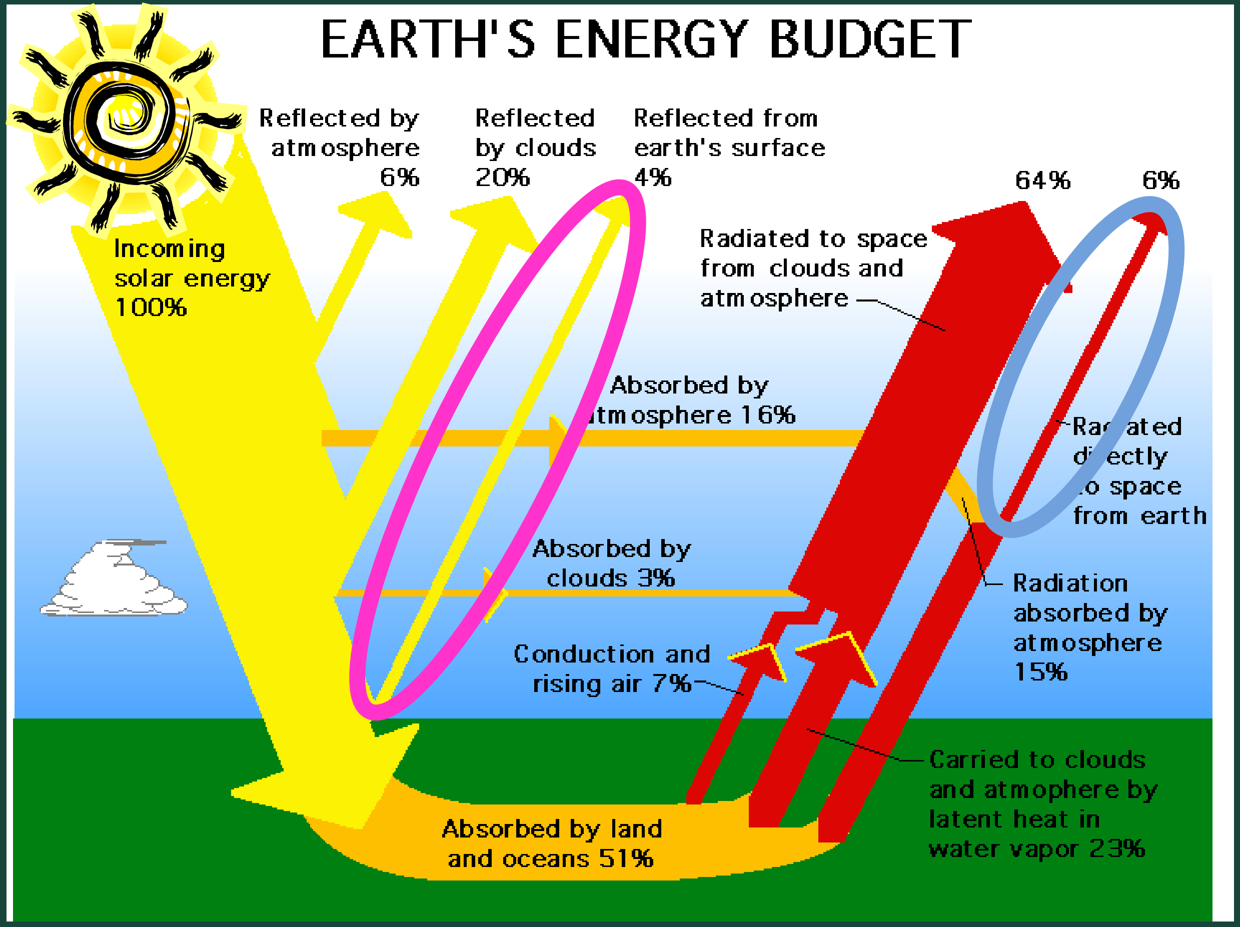
https://en.wikipedia.org/wiki/Visible_spectrum#/media/File:Atmospheric_electromagnetic_opacity.svg


Illumination
Passive Remote Sensing
Sensor
Shortwave:
reflected
sunlight
[0.4 – 5 µm]
Longwave:
emitted
earthlight
[>3 µm]
Illumination
Target

Illumination-Target-Sensor geometry is also important

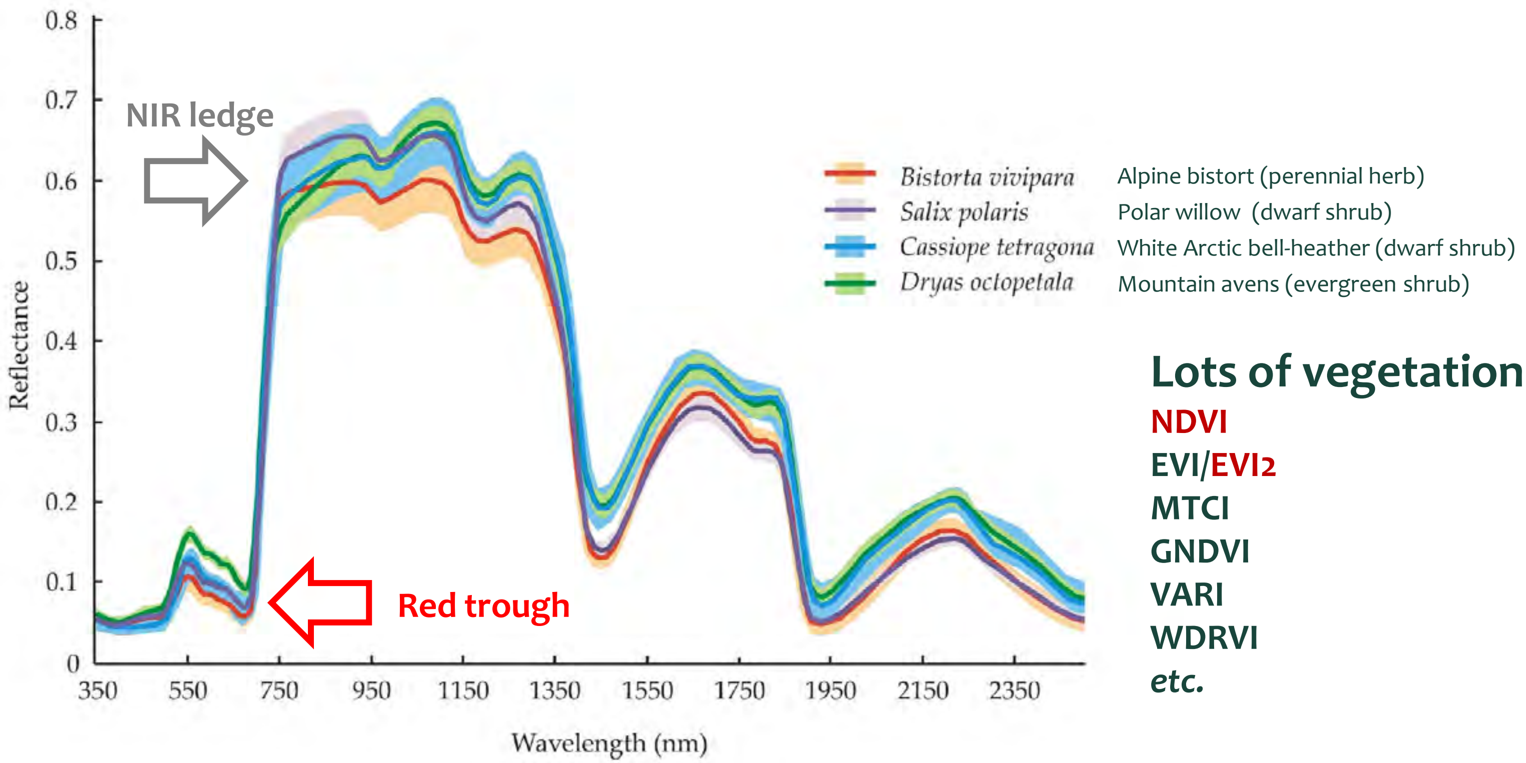


Remote sensing samples just tiny fractions of the reflected solar & emitted terrestrial radiation



So how can we sense vegetation from space?

Because of the sharp difference in reflected sunlight!



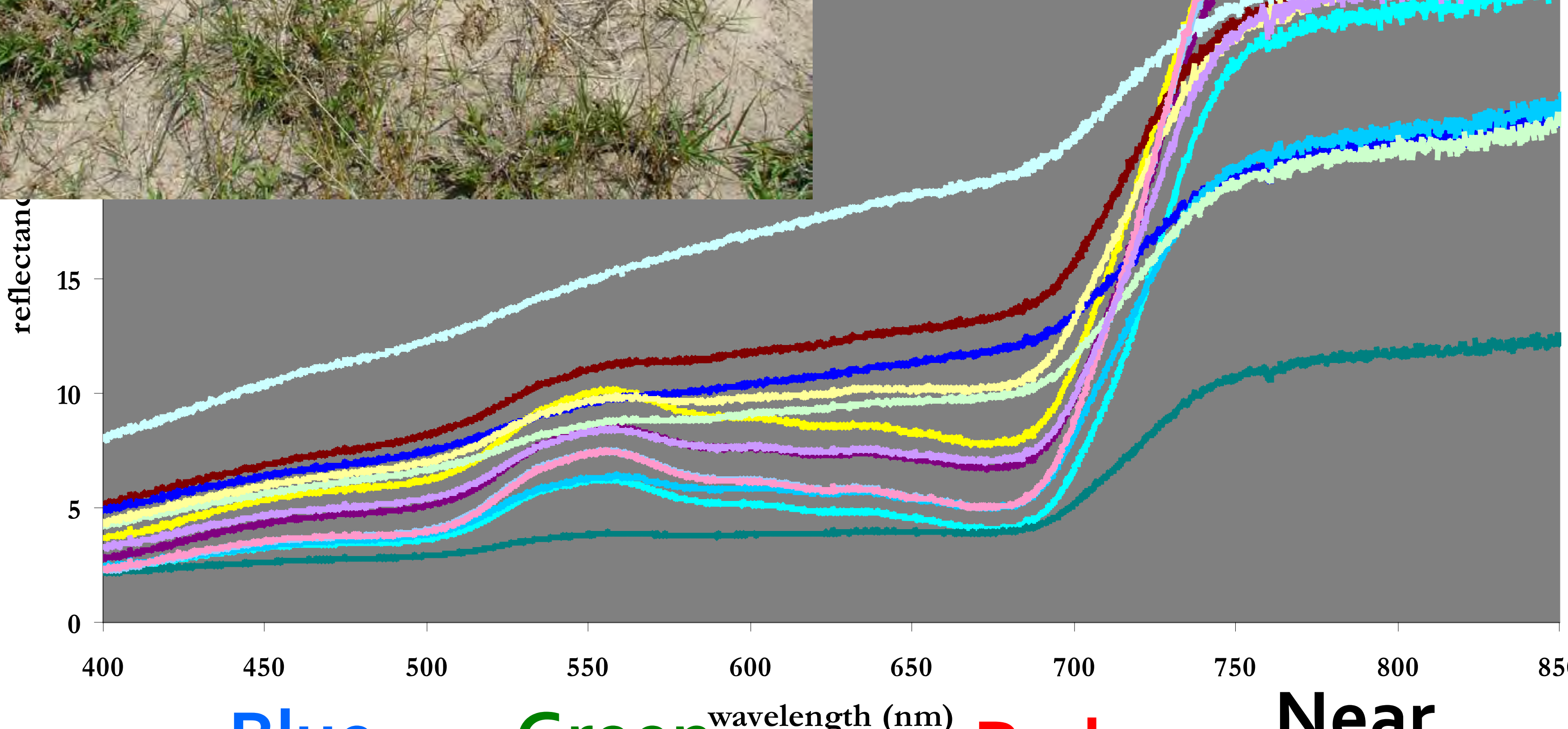
Lots of vegetation indices…

NDVI
EVI/EVI2
MTCI
GNDVI
VARI
WDRVI
etc.

NDVI=(NIR-red)/(NIR+red)

source: Zagajewski, B., Tømmervik, H., Bjerke, J.W., Raczko, E., Bochenek, Z., Kłos, A., Jarocińska, A., Lavender, S. and Ziółkowski, D., 2017. Intraspecific differences in spectral reflectance curves as indicators of reduced vitality in high-arctic plants. *Remote Sensing*, 9(12), p.1289.

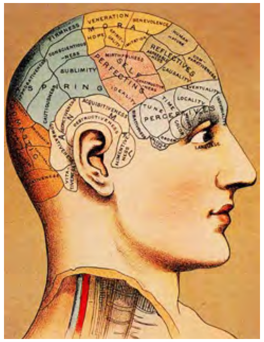
tra collected in the
dhills, June 2004



Blue Green Red Near infrared

2. Context for Land Surface Phenology (LSP)

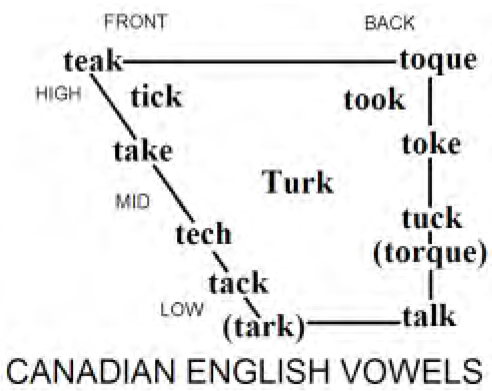
What is *phenology*?

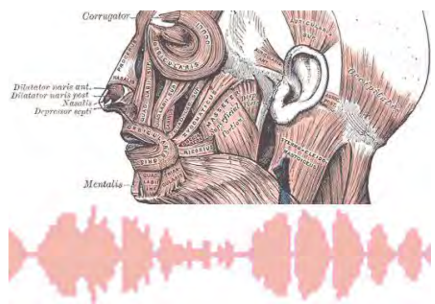


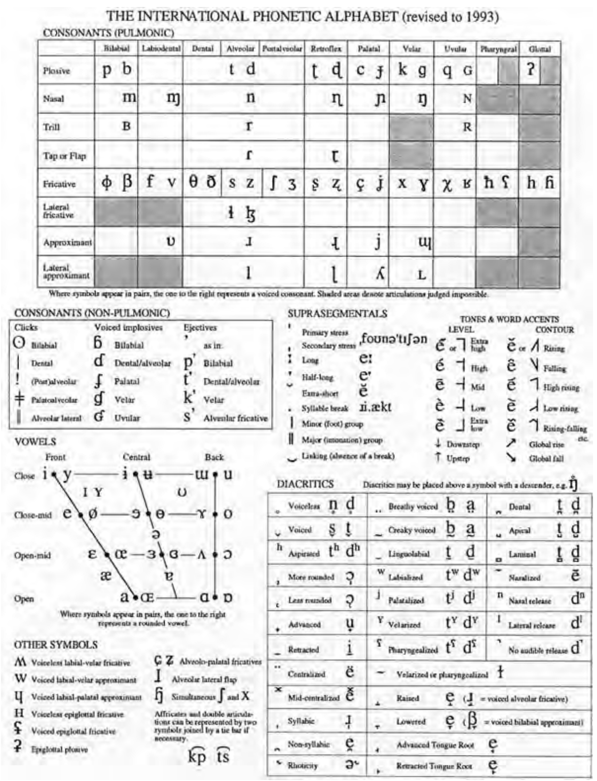
It is not a misspelling of ***phrenology*** !

What is phenology?

Or *phonology* !







Phenology is the study of

i. the **timing** of recurring biological events,
ii. the causes of their **timing**,
iii. their **relationship** to biotic and abiotic forces, and
iv. the inter-relations among **phases** of the same or different species.

US/IBP Phenology Committee, 1973

Source: Lieth, H. 1974. Purposes of a phenology book. Pp 3-19. In: (H. Lieth, ed.) Phenology and Seasonality Modeling. New York: Springer-Verlag. 444 pp.

Phenology, in short, is a “horizontal science” which transects all ordinary biological professions. Whoever sees the land as a whole is likely to have an interest in it.

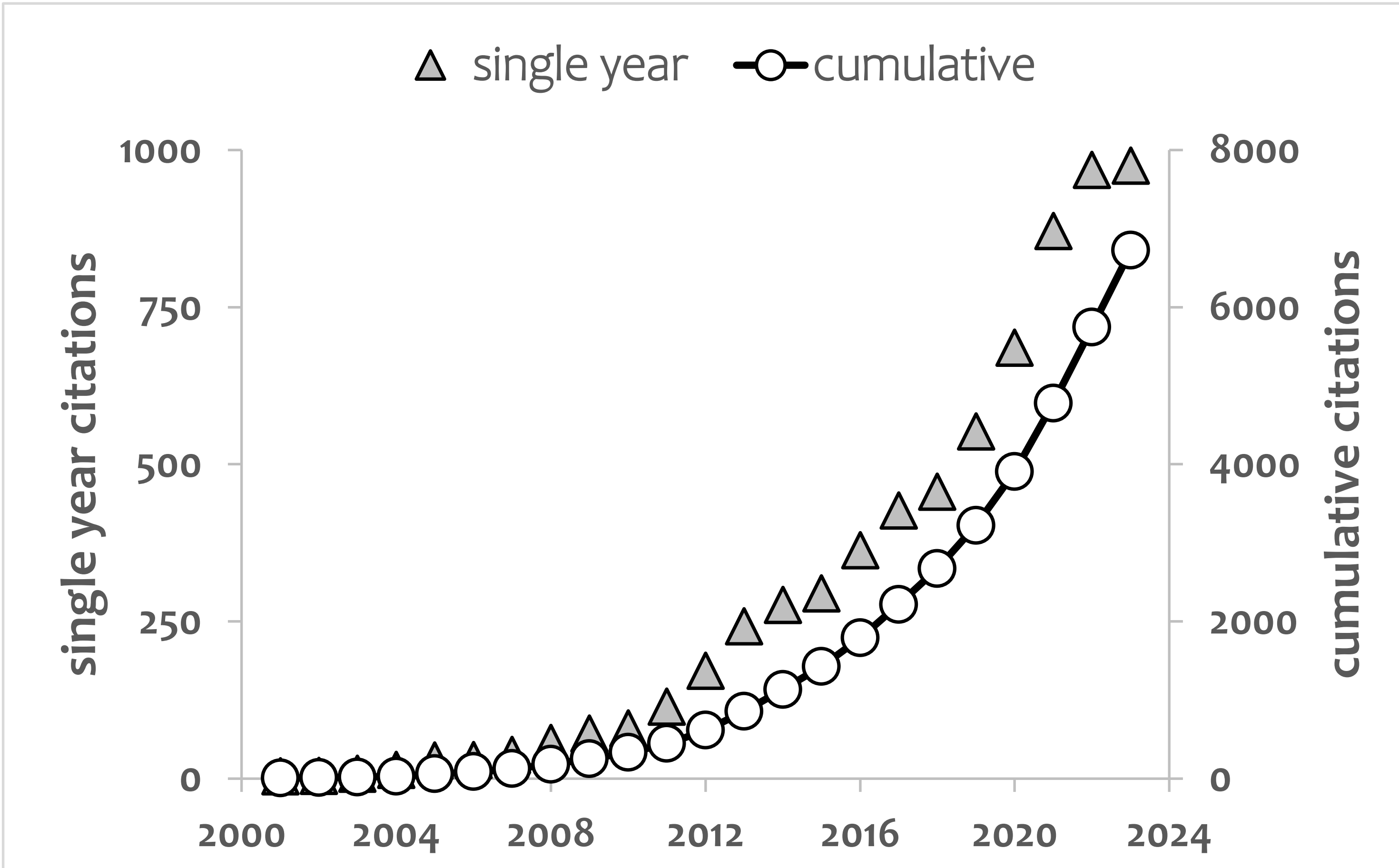
Aldo Leopold & Sara E. Jones

Source: Leopold A, SE Jones, 1947. A phenological record for Sauk and Dane Counties, Wisconsin, 1935-1945. *Ecological Monographs* 17(1):81-122.

Some Useful Distinctions & Categories

- **Phenology is distinct from seasonality:** biotic vs. abiotic temporal patterns. But seasonality can affect phenology and phenology can affect seasonality.
- **Land surface phenology:** the seasonal pattern of variation in vegetated land surfaces observed from remote sensing.
- **Land surface phenologies are distinct from phenologies:** observing electromagnetic radiation at coarse spatial resolution results in a mixture of signals that combines biotic and abiotic components.
- LSPs are linked to **the timing and magnitude of energy and water exchanges** between the land surface and the atmospheric boundary layer.

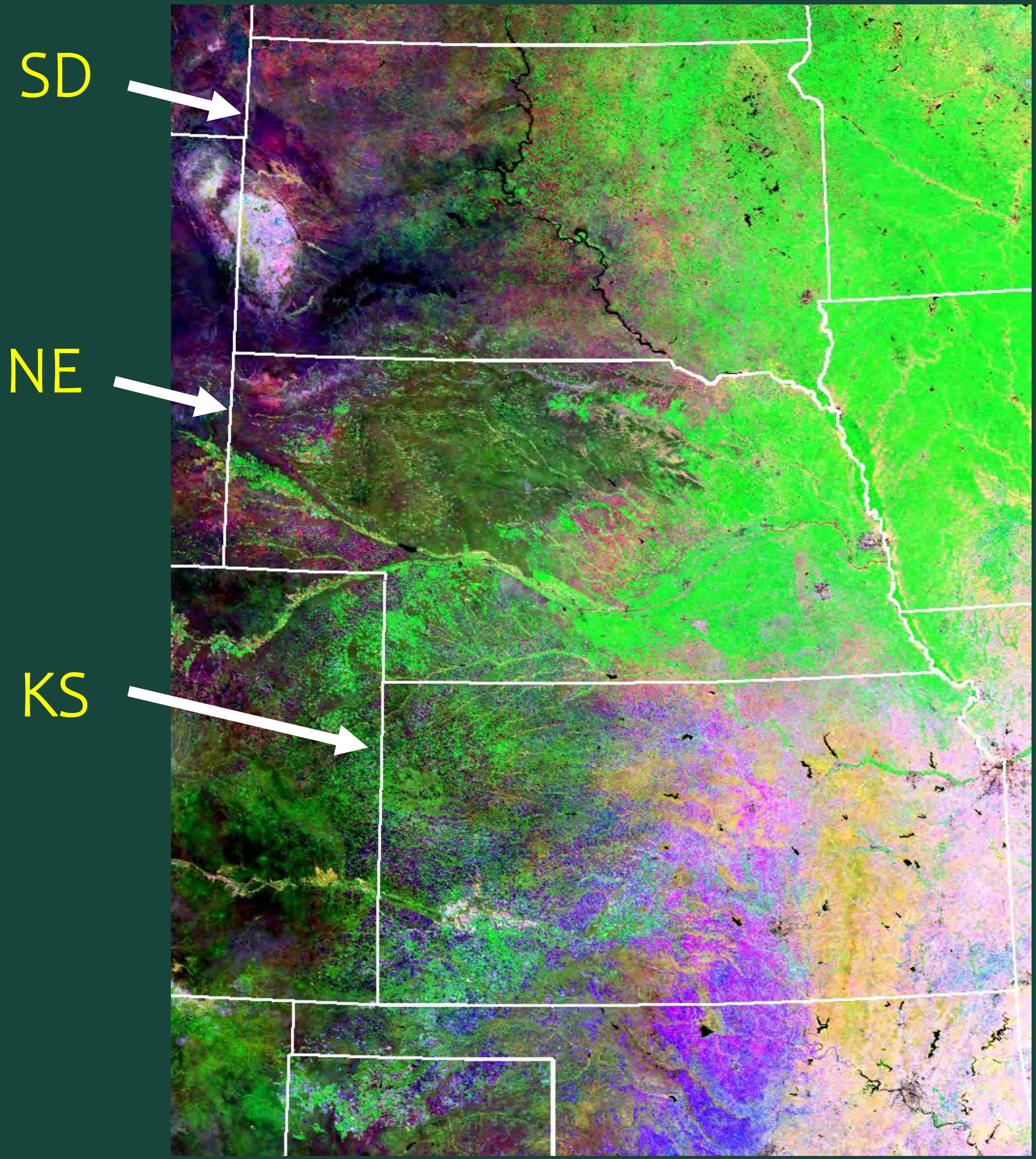
Temporal profile from 2000-2023 in Google Scholar citations to the phrase "land surface phenology"



source: Henebry GM & KM de Beurs (2025) *Remote Sensing of Land Surface Phenology: Progress, Challenges, Prospects*. Chapter 19 in (MD Schwartz, editor) Phenology: An Integrative Environmental Science, 3rd edition. Springer.

Key surface types for LSPs:

- **Ever-green** (conifers; rain forests; lawns & golf courses)
- **Spring-green** (deciduous trees; crops; grasses; annuals)
- **Rain-green** (semiarid to arid grasslands; arid shrublands)
- **Never-green** (barren; ice; hyperarid deserts; urban deserts)



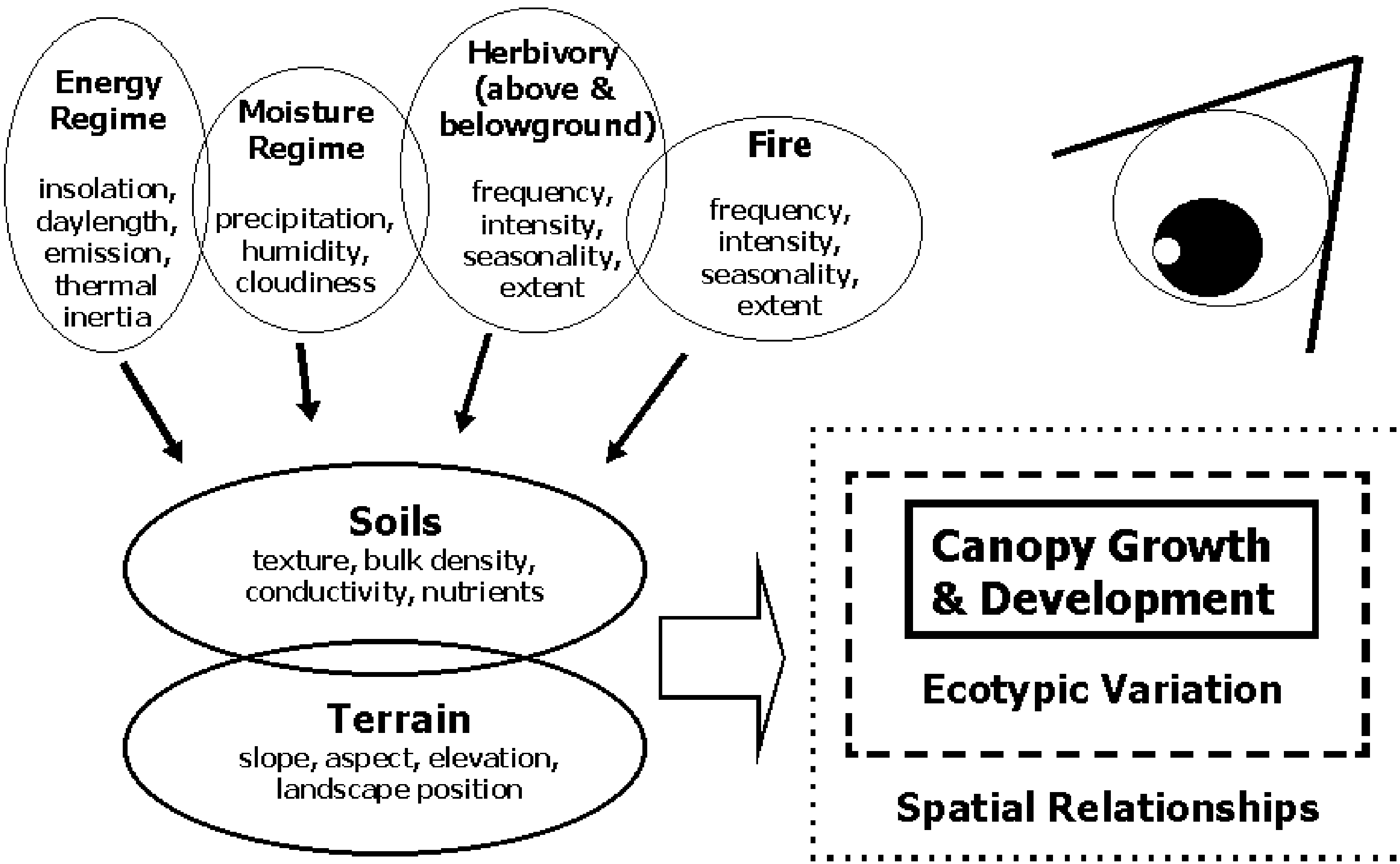
A false-color composite reveals differential *Land Surface Phenologies* due to land use

MODIS NBAR* NDVI
@ 1km in 2004
Red = 08May
Green = 27July
Blue = 08March

*Nadir BRDF (Bidirectional Reflectance Distribution Function) Adjusted Reflectance

3. Drivers of Phenology

Grassland phenologies emerges from the interactivity of multiple influences



Source: Henebry, G.M. 2003. Grasslands of the North American Great Plains. In: Phenology: An Integrative Environmental Science (M.D. Schwartz, editor). Kluwer, New York. pp. 157-174.

as filtered through the specifics of spatial relationships, genetic heritage, and the process of observation.

Whose time do we use?

If phenologies are all about the timings of recurrent biological events, then whose "clock" and "calendar" should track that time?

Calendars are human-centered.

Do plants pay attention to our calendars?

Can we link vegetation dynamics to a calendar that takes weather into account?

In phenological studies, it is often convenient to summarize recent weather into measures that can relate to plant growth and development.

Accumulated Growing Degree-Days (also known as **thermal time**) weights the passage of days by the quantity of "growing degrees" – that portion of the 24-hr temperature range that is useful for plant growth.

The calculation of AGDD is simple:

(1) $AvgTemp_t = (MaxTemp_t + MinTemp_t)/2$

(2) $AGDD_t = AGDD_{t-1} + \max[(AvgTemp_t - Base),0]$

The base value depends on the organism under consideration:

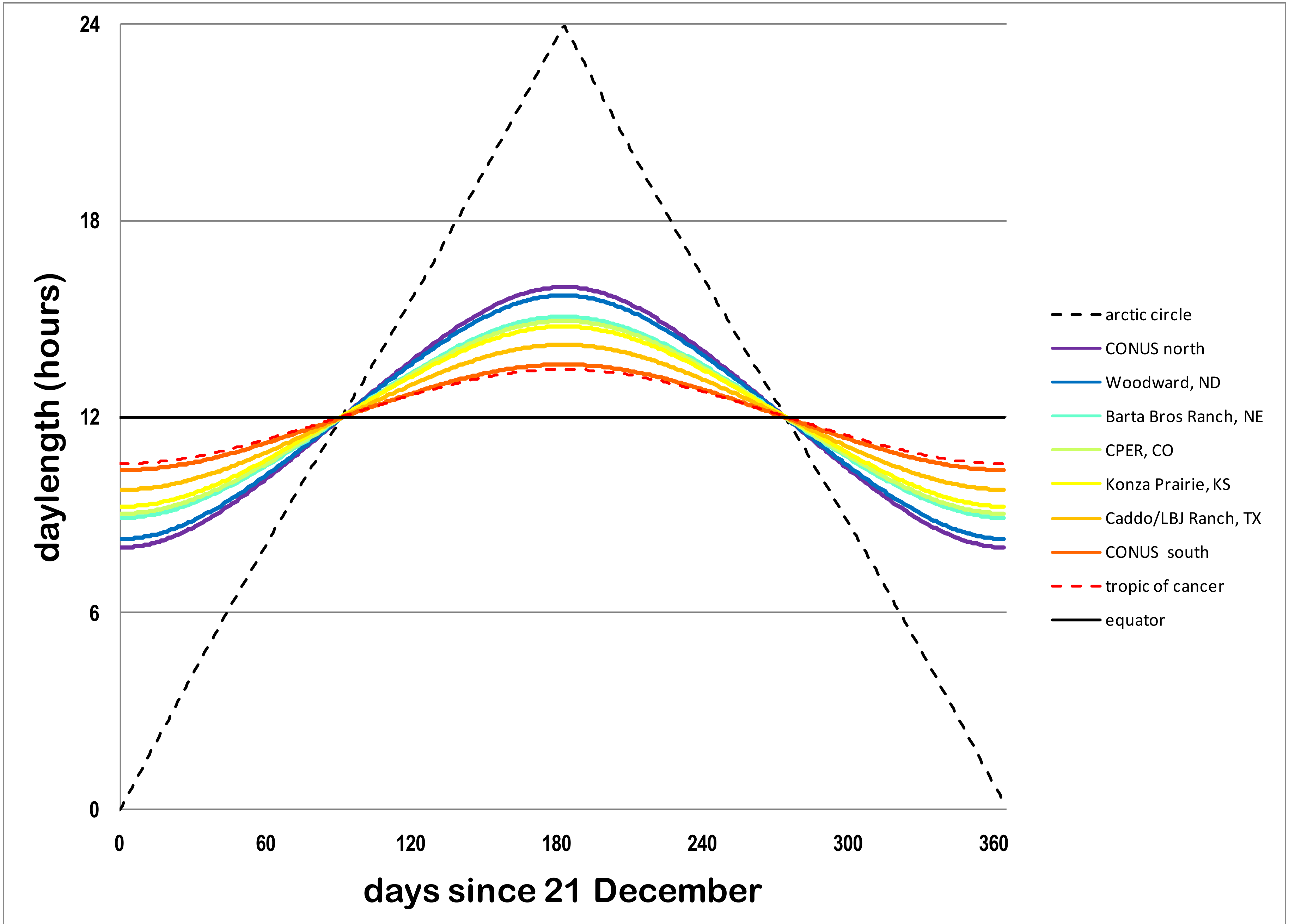
- a base of 0 °C for perennial grasslands (and alfalfa);
- a base of 4 °C for cool season crops (*e.g.*, winter wheat/barley/canola); and
- a base of 10 °C for warm season crops (*e.g.*, corn/soy/sunflower).

In the northern hemisphere, the convention is to start accumulating at the beginning of the year, with each 01JAN resetting the accumulation. [In crop models the thermal time can start at planting.]

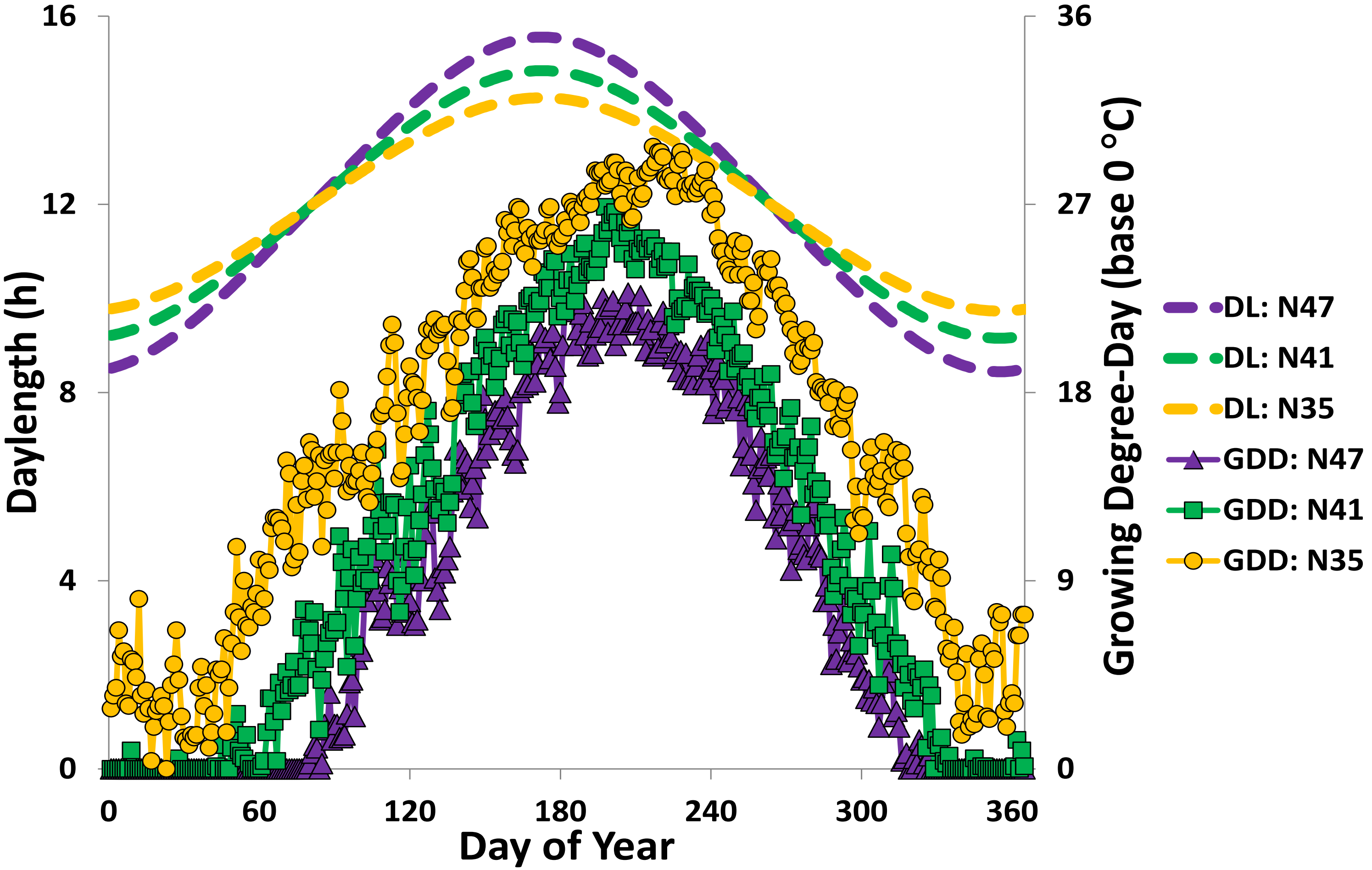
Although AGDD are handy for temperate and boreal systems, the approach is not very useful in tropical or arid systems where phenological timing is associated with:

- available moisture;
- internal carbohydrate pools;
- co-evolved relationships (e.g., pollinators & frugivores); or
- other non-thermal triggers.

Annual cycle of daylength across CONUS

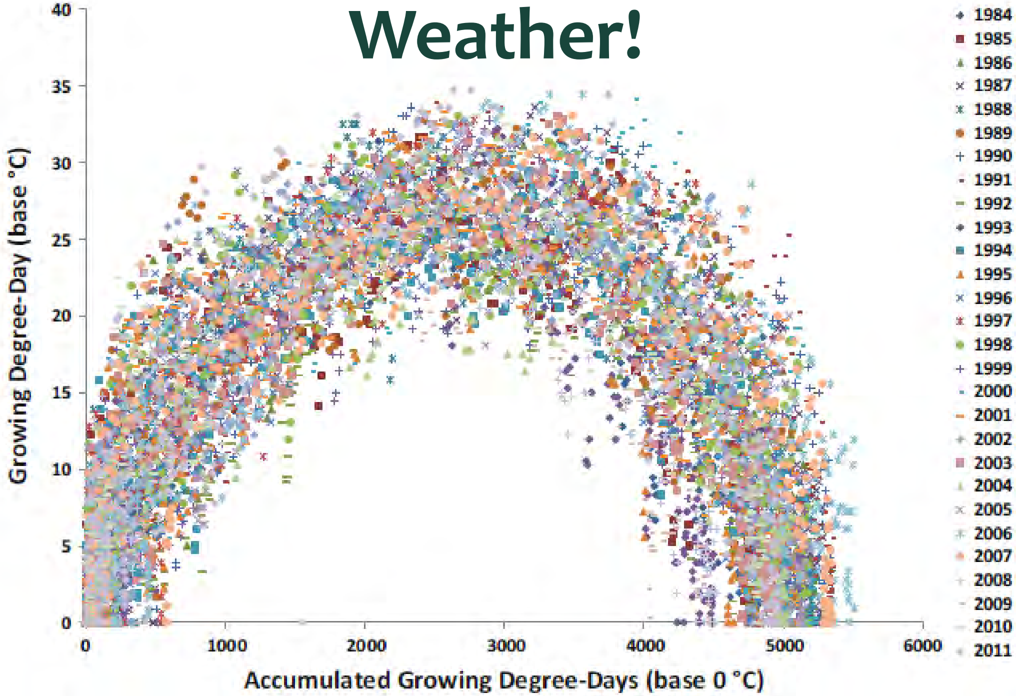


Both insolation and growing degree-days exhibit simple shapes across the middle latitudes



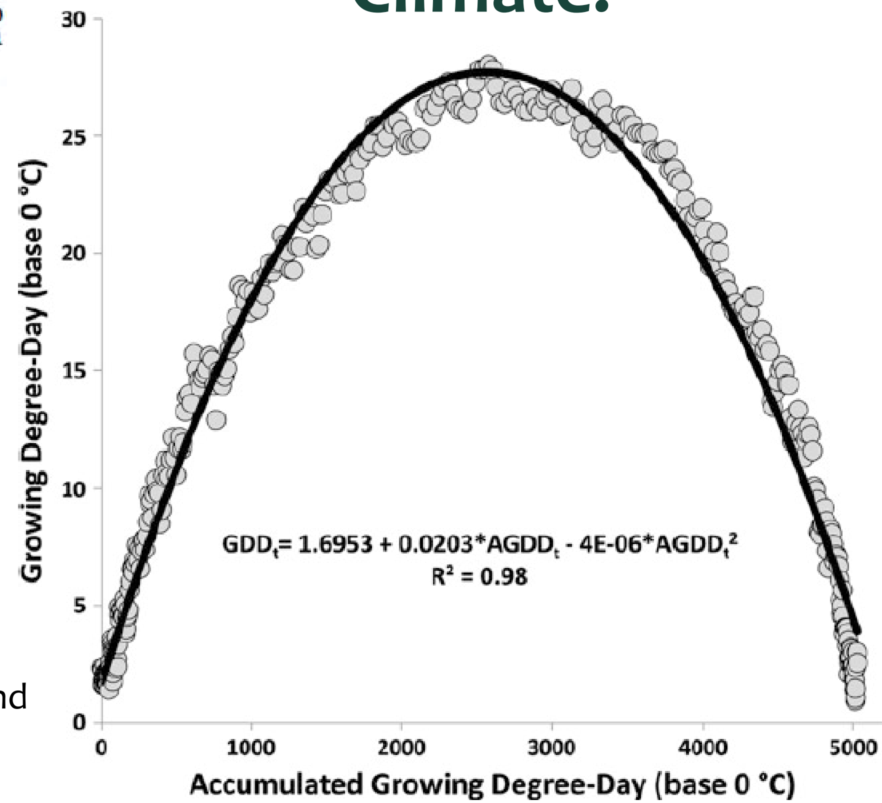
Henebry GM. 2013. Phenologies of North American Grasslands and Grasses. In: (MD Schwartz, ed.) Phenology: An Integrative Environmental Science, 2e. Springer. Chapter 11, pp. 197-210.

Weather!



← Growing degree-days (base 0 °C) as a function of accumulated growing degree-days (AGDD) for Manhattan, KS 1984-2011

Climate!

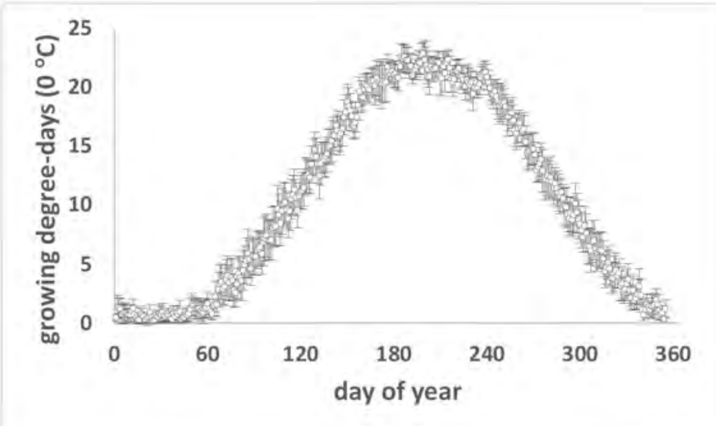


This parabolic pattern is repeated across the temperate mid-latitudes.

Mean GDD (base 0 °C) as a function of AGDD for Manhattan, KS 1984-2011 →

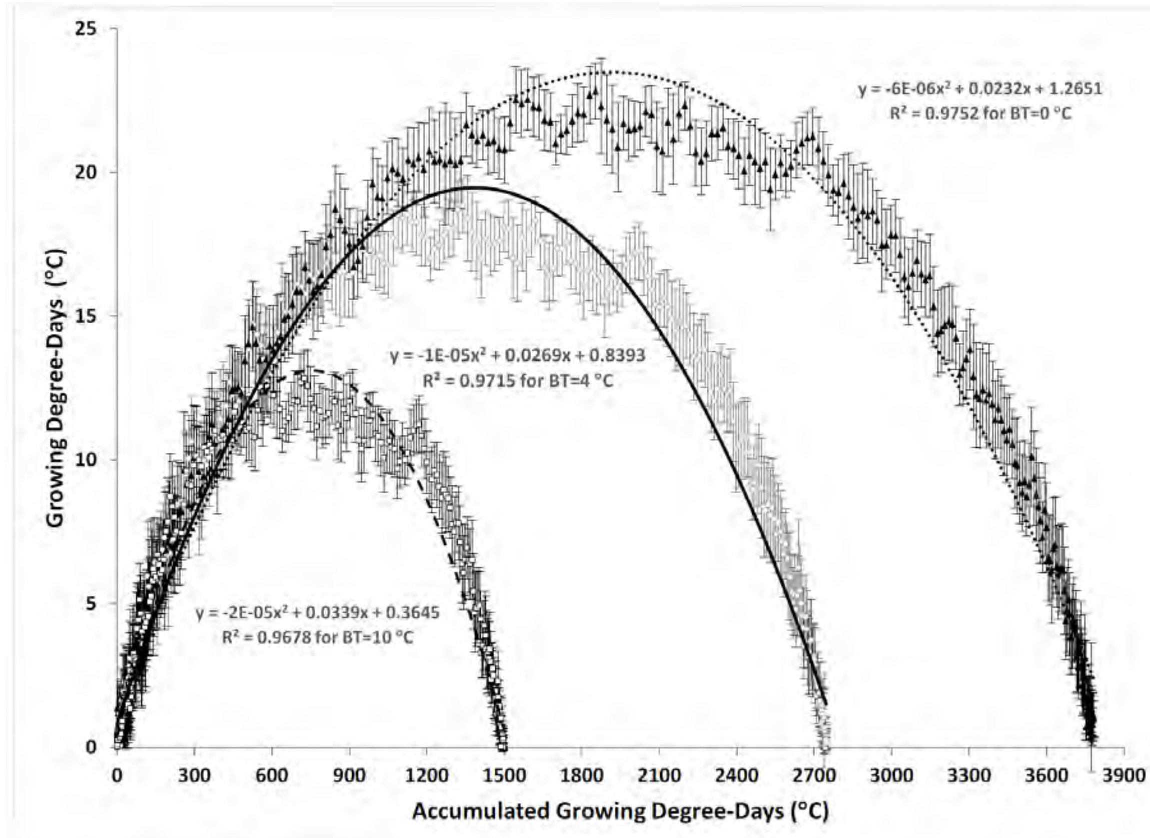
Henebry GM. 2013. Phenologies of North American Grasslands and Grasses. In: (MD Schwartz, ed.) Phenology: An Integrative Environmental Science, 2e. Springer. Chapter 11, pp. 197-210.

MSU's Kellogg Biological Station near Battle Creek, MI



← Average growing degree-days (GDD using base temperature 0 °C) calculated from daily air temperature data at the KBS weather station for 1988-2023. Error bars show ±2SEM.

Average daily growing degree-days (±2SEM) and accumulated growing degree-days calculated from the KBS weather station data using three different base values (0 °C, 4 °C, 10 °C) with each accumulation restarting at 01JAN. →



Modeling Land Surface Phenology by Thermal Time

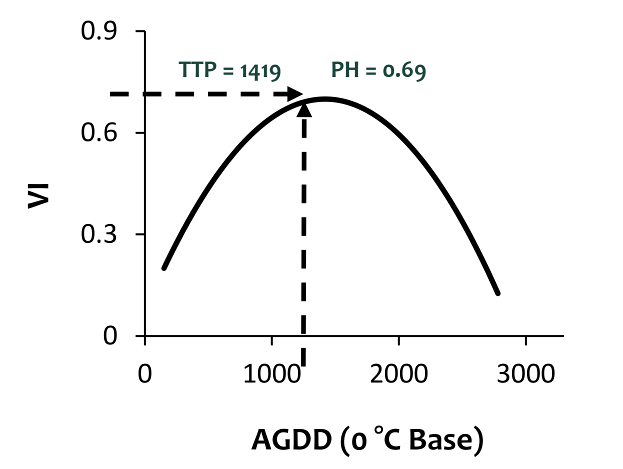
We model LSPs in herbaceous landscapes using the Convex Quadratic (CxQ) model

The CxQ model links a VI *(here NDVI or EVI2)* to the annual progression of accumulated growing degree-days (AGDD):

$$VI_t = \alpha + \beta \times AGDD_t + \gamma \times AGDD_t^2$$

AGDD is a measure of thermal time derived from periodic mean temperature above a base temperature threshold *(here 0 °C)*:

$$AGDD_t = AGDD_{t-1} + \max[(AvgTemp_t\text{-}BaseTemp),0]$$



We calculate two phenometrics for each year from the fitted parameters coefficients for the intercept (α), slope (β), and quadratic (γ) terms:

- **Peak Height (PH)** is the modeled maximum VI

$$PH = \alpha - (\beta^2/4\gamma)$$

- **Thermal Time to Peak (TTP)** is the amount of AGDD needed to reach PH, tracking the duration of green-up phase

$$TTP = -\beta/2\gamma$$

4. Land Surface Phenologies at Different Scales

Did the collapse of the Soviet Union affect the spring green-up in Kazakhstan?

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Available online at www.sciencedirect.com

SCIENCE DIRECT

Remote Sensing of Environment 89 (2004) 497–509

Remote Sensing of Environment

www.elsevier.com/locate/rse

Land surface phenology, climatic variation, and institutional change: Analyzing agricultural land cover change in Kazakhstan

Kirsten M. de Beurs, Geoffrey M. Henebry*

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Received 18 February 2003; received in revised form 3 November 2003; accepted 10 November 2003

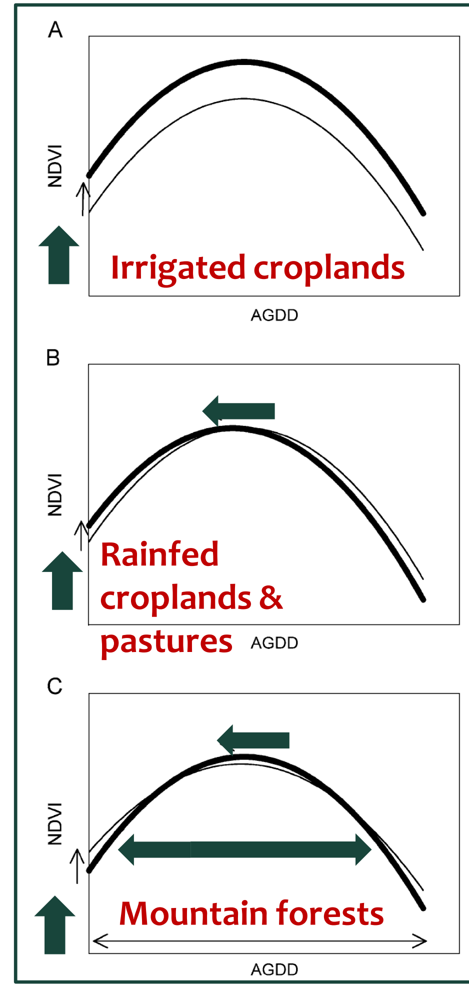
Fitted AVHRR NDVI time series to quadratic functions of thermal time (calculated from NCEP/NCAR reanalysis data) and compared pre-collapse to post-collapse models.

Although are 14 possible ways for the 3-parameter CxQ LSP model to change, we detected significant changes only in three ways:

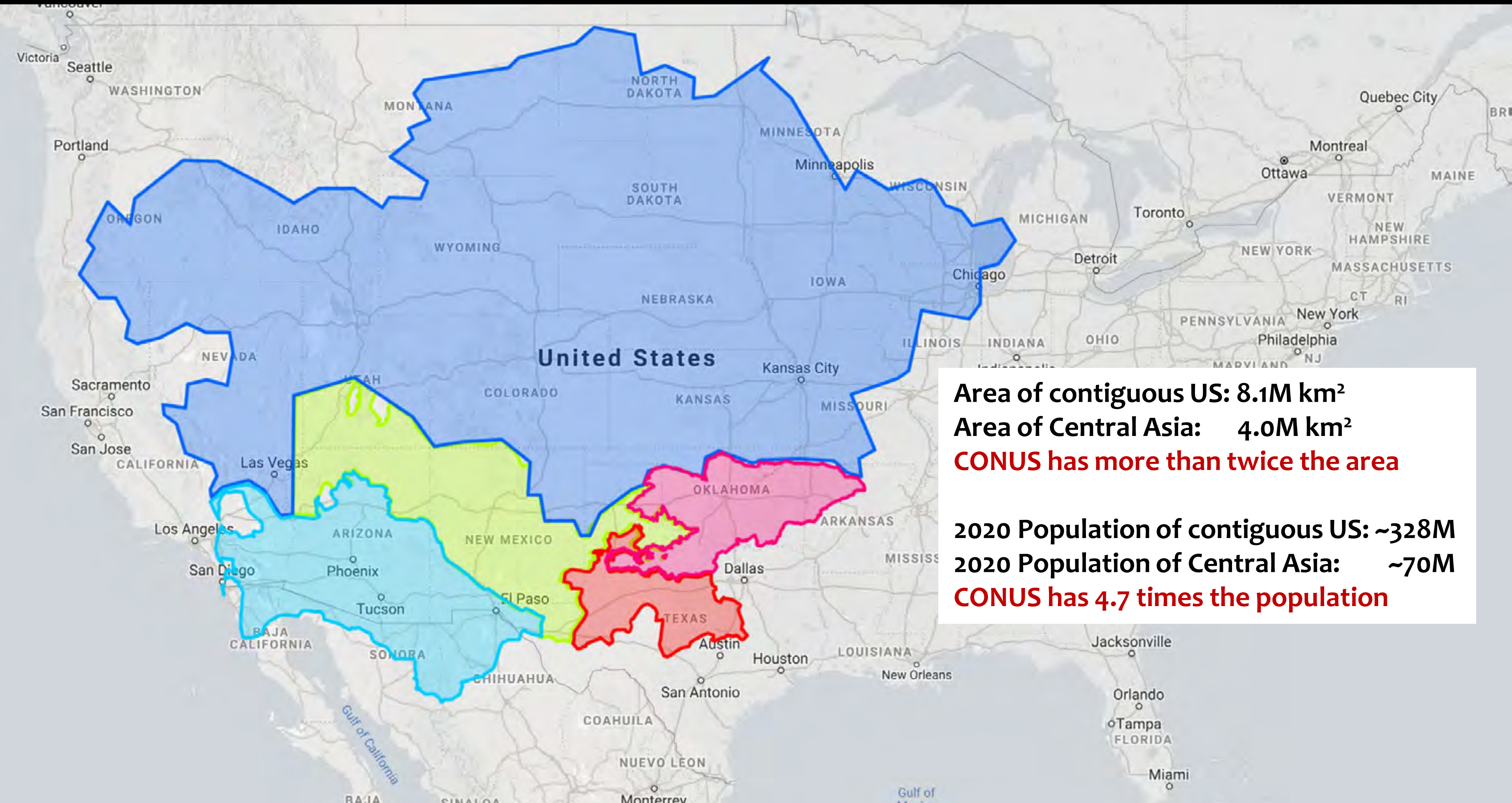
(A) increase in intercept only, or

(B) increases in both intercept & slope, or

(C) increases in intercept, slope, and quadratic coefficients.



Central Asia is large in area and sparsely populated

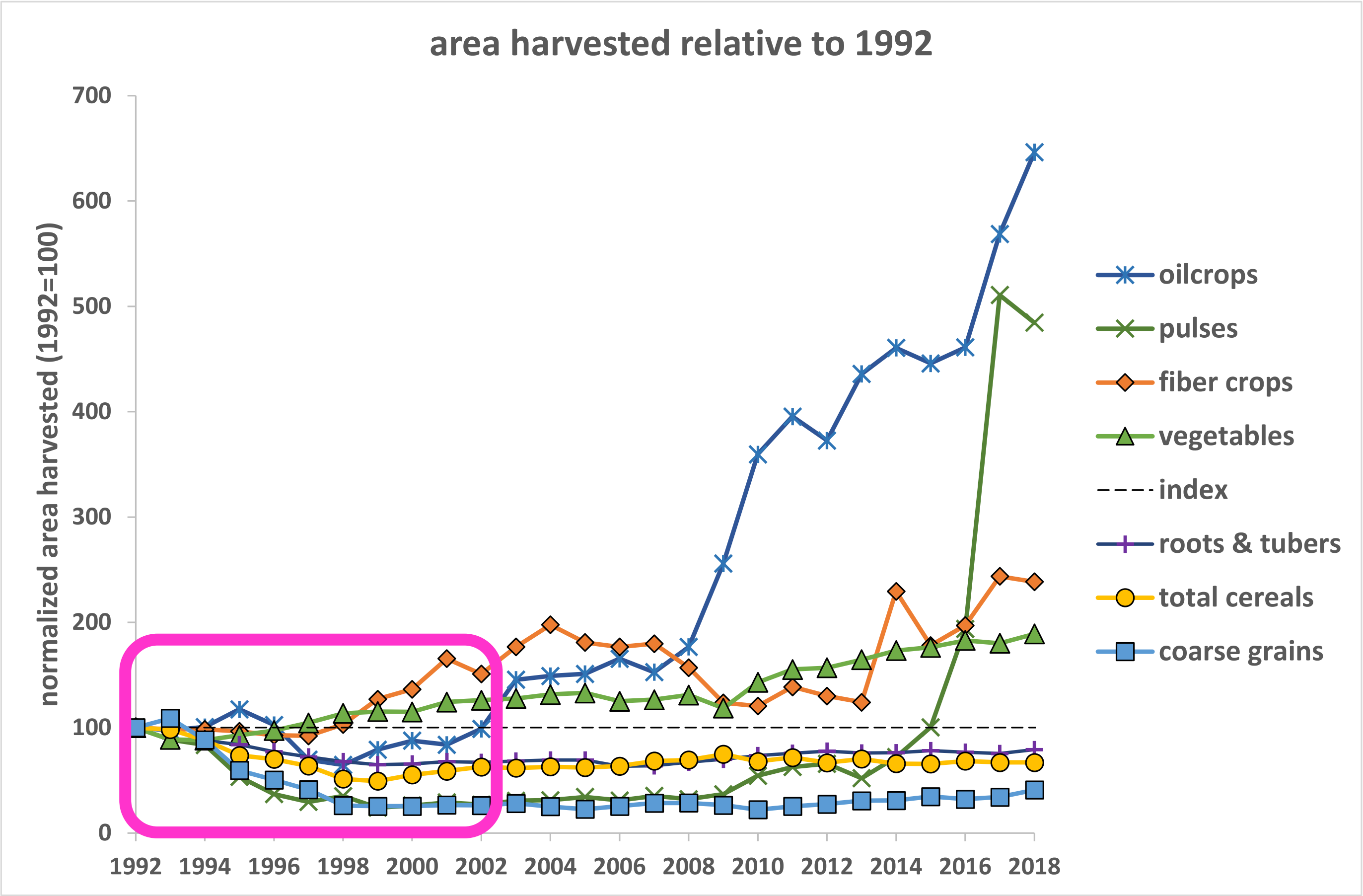


Area of contiguous US: 8.1M km²
Area of Central Asia: 4.0M km²
CONUS has more than twice the area

2020 Population of contiguous US: ~328M
2020 Population of Central Asia: ~70M
CONUS has 4.7 times the population

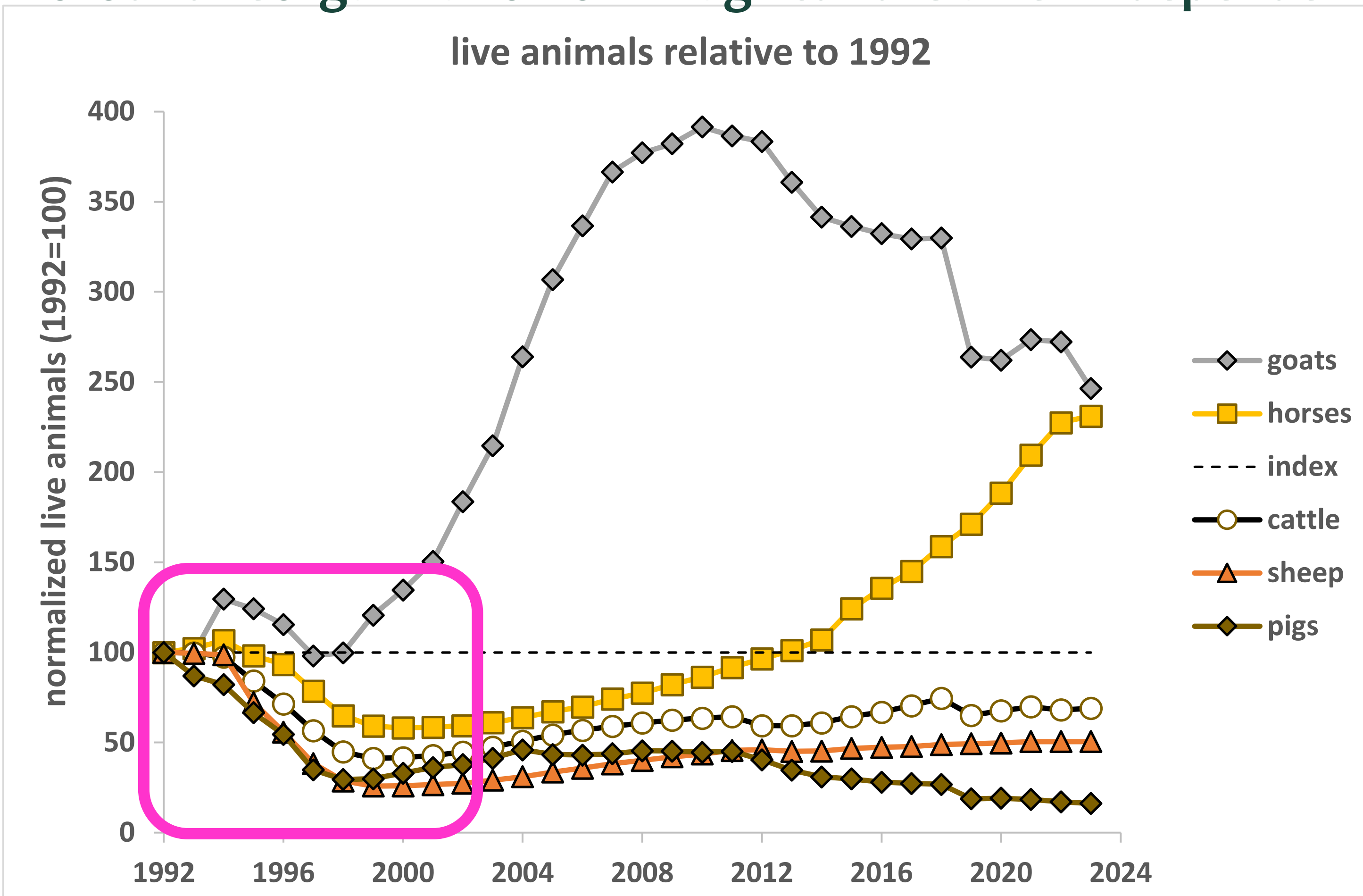
https://www.thetruesize.com
https://www.thetruesize.com

Profound reorganization of KZ agriculture after independence



Source: FAOSTAT 2024

Profound reorganization of KZ agriculture after independence



Source: FAOSTAT 2024

IOP Publishing Environmental Research Letters
Environ. Res. Lett. 4 (2009) 045012 (11pp) doi:10.1088/1748-9326/4/4/045012

Dual scale trend analysis for evaluating climatic and anthropogenic effects on the vegetated land surface in Russia and Kazakhstan

K M de Beurs[1], C K Wright[2] and G M Henebry[2]

[1] Department of Geography, Virginia Polytechnic Institute and State University, 107 Major Williams Hall, Blacksburg, VA 24061, USA
[2] Geographic Information Science Center of Excellence (GIScCE), South Dakota State University, 1021 Medary Avenue, Wecota Hall 506B, Brookings, SD 57007-3510, USA

Handled the problem of "false green-up" due to snowmelt to determine season length ➔

Assessed significant trends in greening and browning across northern Eurasia. ➔

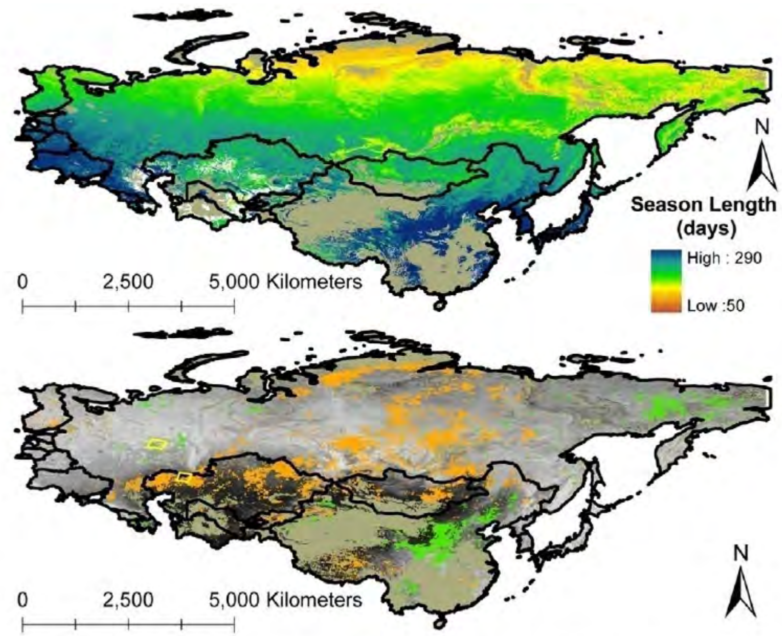


Figure 2. (Top) Average length of season based on the average SOS and average EOS computed from NDII composites from 2001 to 2007. White areas in the map have a retrieved length of season less than 50 days. Tan areas are masked out due to a lack of data or a lack of seasonality. (Bottom) Vegetation trends from 2000 to 2008 revealed by NASA MODIS sensors at 0.05° spatial resolution. Areas outlined in orange and green indicate highly significant ($p \leqslant 0.01$) negative and positive trends, respectively. Areas in tan were excluded from analysis. Areas in shades of gray did not exhibit highly significant trends. Underlying grayscale image is the average NDVI over the study period, darker areas indicate lower average NDVI. The yellow boxes indicate the areas in Russia and Kazakhstan selected for finer scale analysis.

Increasing greenness in Russia due to cropland abandonment

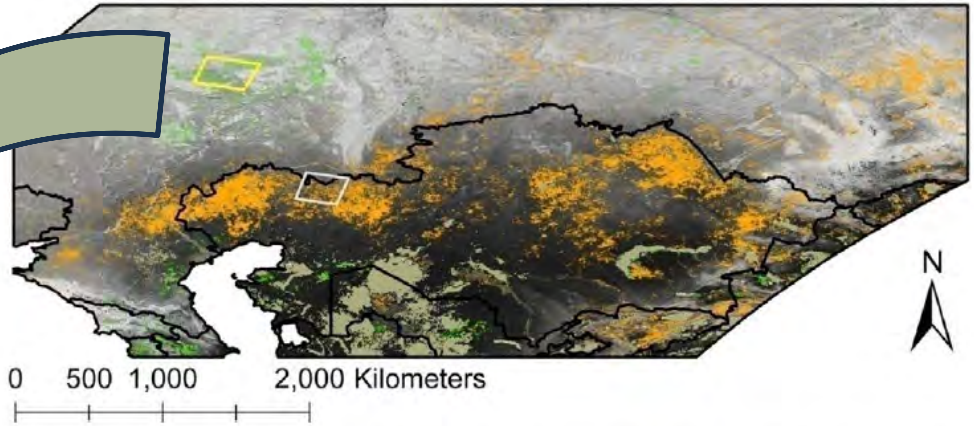


Figure 3. Vegetation trends from 2000 to 2008 revealed by NASA MODIS sensors at 500 m spatial resolution. Areas outlined in orange and green indicate highly significant ($p \leqslant 0.01$) negative and positive trends, respectively. Areas in tan were excluded from analysis. Areas in shades of gray did not exhibit highly significant trends. Underlying grayscale image is the average NDVI over the study period, darker areas indicate lower average NDVI, lighter areas indicate higher average NDVI. The yellow and white boxes in the figure indicate the areas in Russia (yellow) and Kazakhstan (white) selected for finer scale analysis.

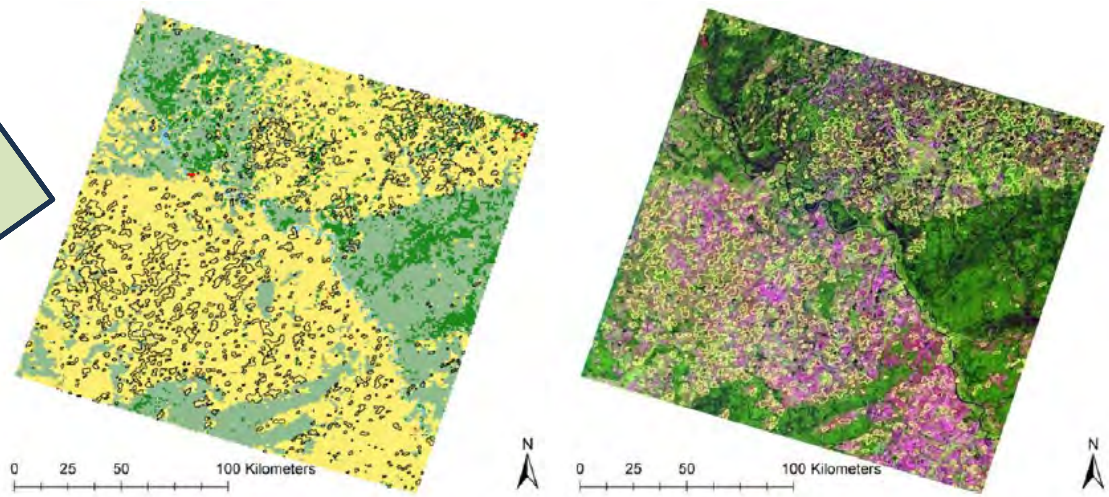
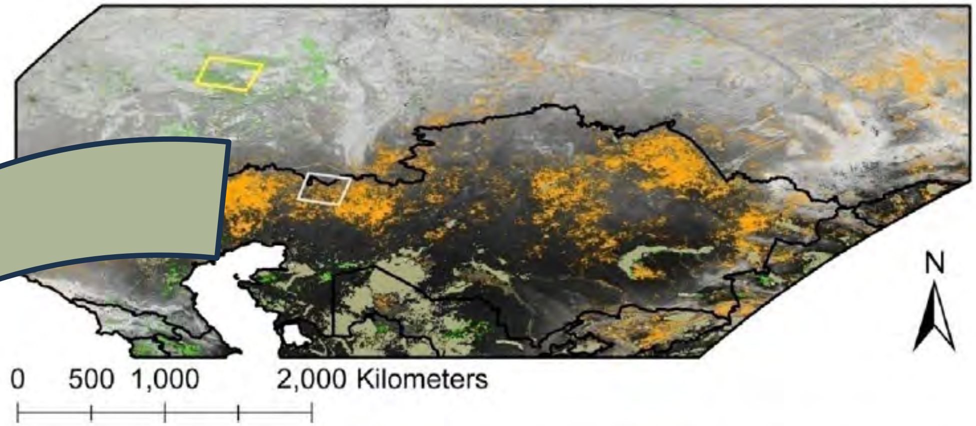


Figure 5. (Left) MOD12 land cover data at 1 km spatial resolution at the study area in Russia. The black outlines on the image indicate the positive trends found with the 500 m NDVI trend analysis. The three main classes are evergreen needleleaf forests (dark green), mixed forests (light green) and croplands (yellow). (Right) Corresponding Landsat TM image from World Reference System 2 coordinates path 172 and row 20. Image was captured on 16th August, 2007 and displayed with bands 5, 4, 3 as r/g/b. The pink/purple color clearly corresponds with the agricultural areas, whereas the darker green areas correspond with the forested regions. The yellow outlines indicate the positive trends found with the 500 m NDVI trend analysis.

Decreasing greenness in Kazakhstan due to drought



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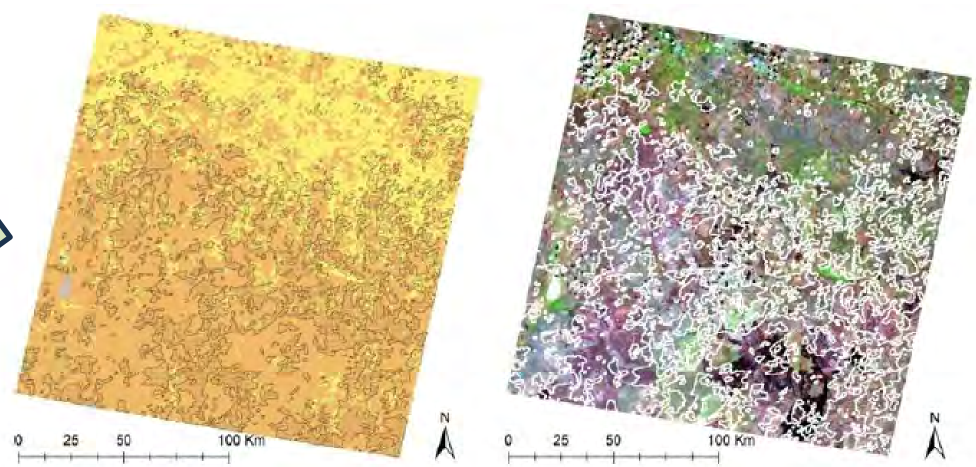
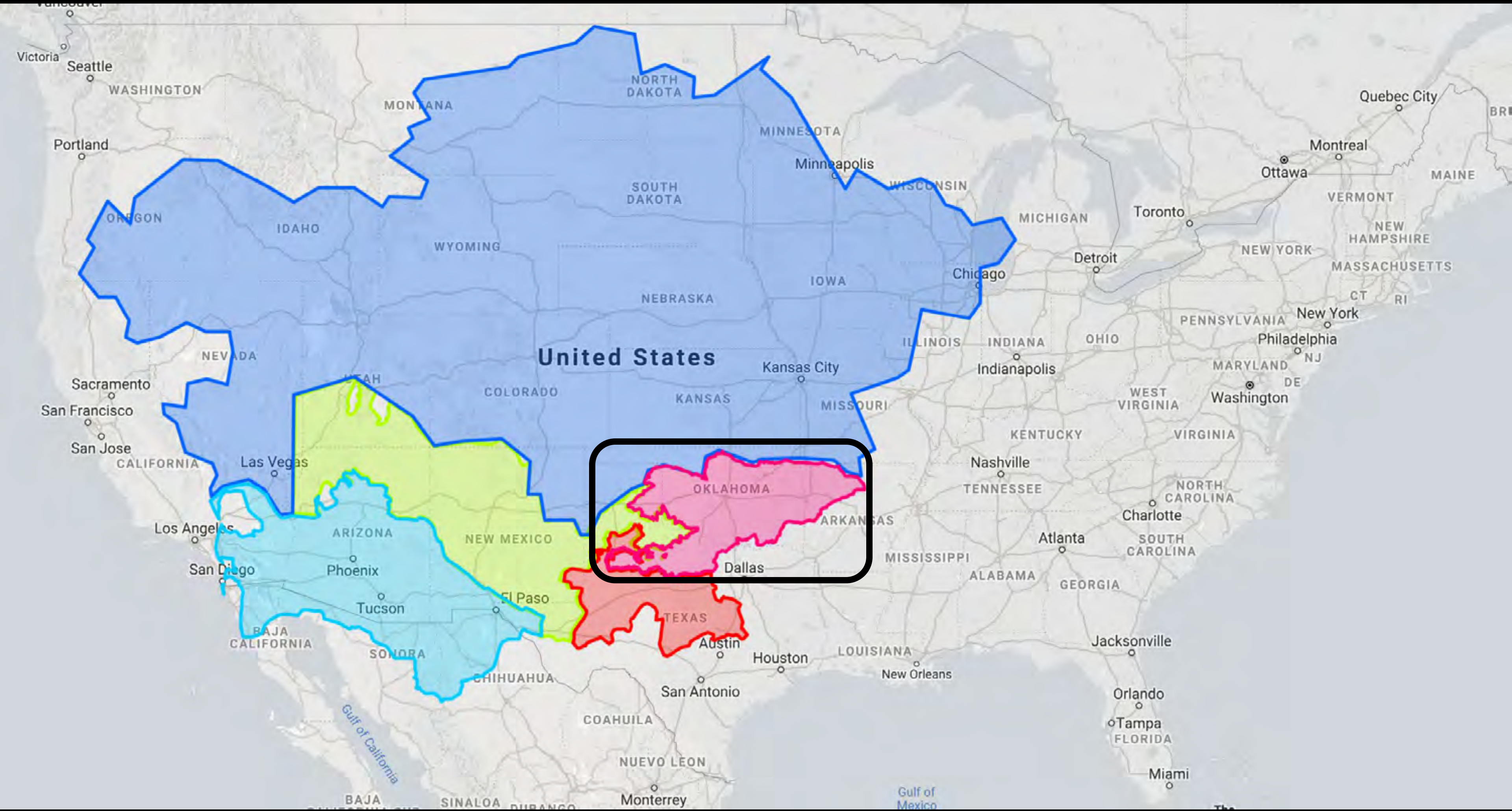


Figure 6. (Left) MOD12 land cover data at 1 km spatial resolution at the study area in Kazakhstan. The black outlines on the image indicate the negative trends found with the 500 m NDVI trend analysis. The two main classes are grasslands (orange) and croplands (yellow). (Right) Corresponding Landsat TM image from World Reference System 2 coordinates path 165 and row 25. Image was captured on 27th August, 2006 and displayed with bands 5, 4, 3 as r/g/b. The white outlines indicate the negative trends found with the 500 m NDVI trend analysis.

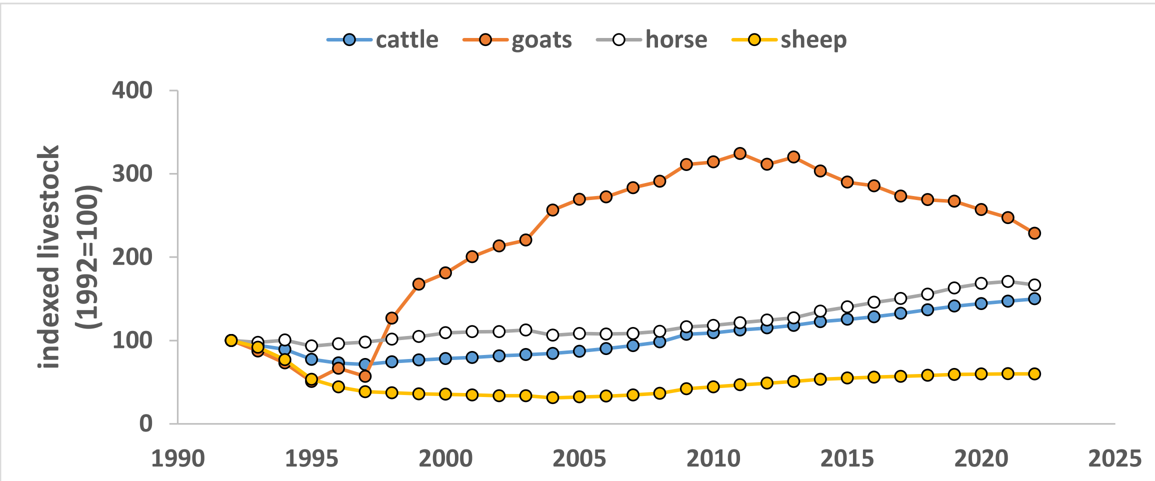
Central Asia is large in area and sparsely populated



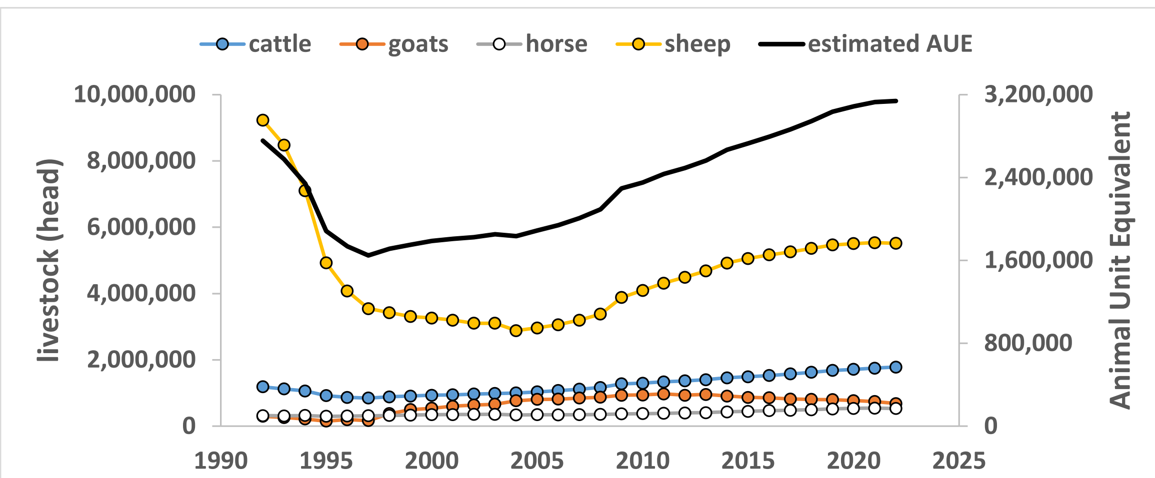
https://www.thetruesize.com

Kyrgyzstan is 94% mountainous!

Population is mostly rural. Agropastoralism is the foundation of the rural economy. Many herders rely on vertical transhumance.



Major readjustment of livestock on the landscape following the collapse of the USSR and the lean early years of independence.

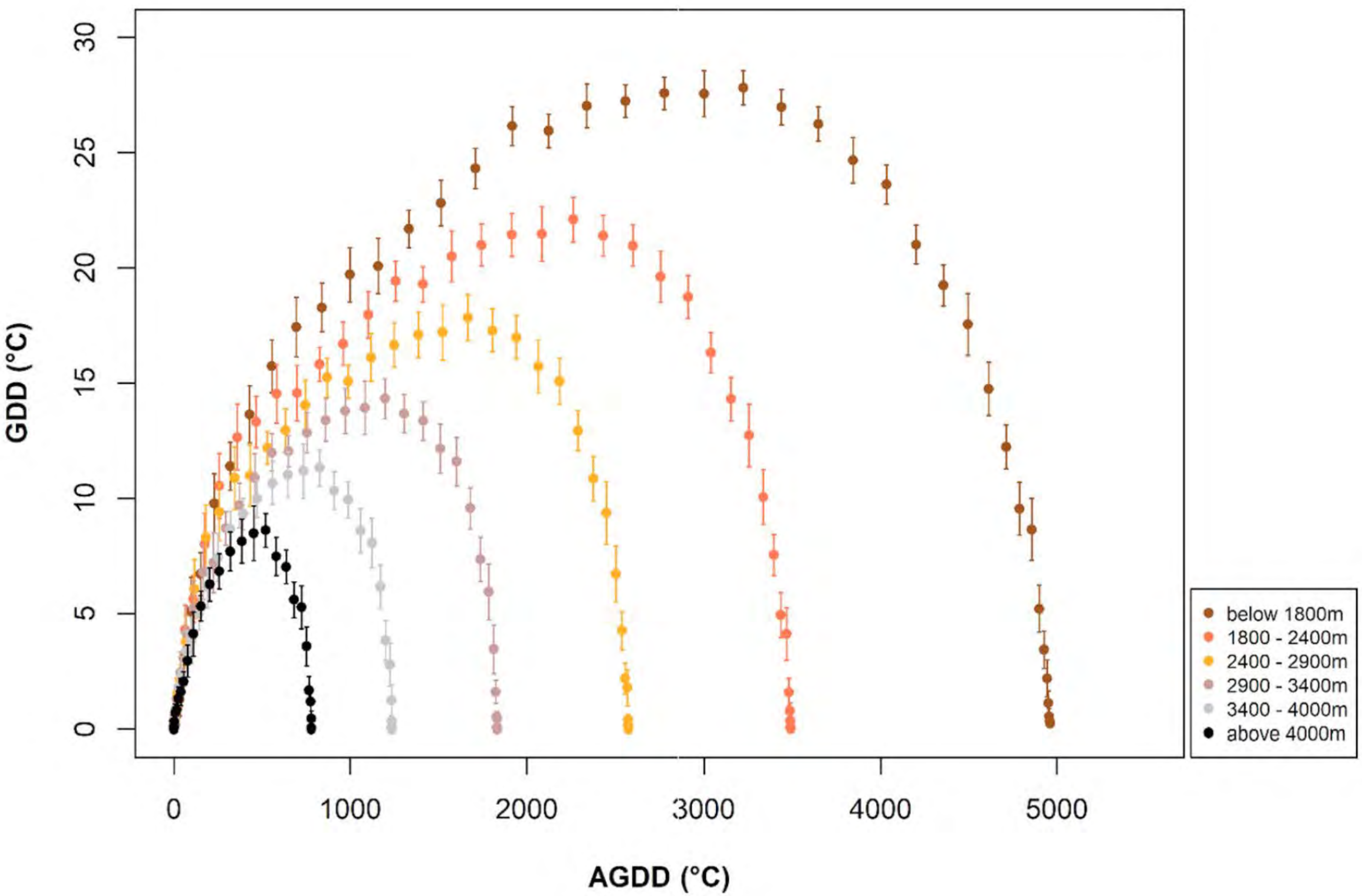


While sheep numbers are about half of the 1980s, increases in cattle, horses, and goats have steadily increased pressure on pastures.

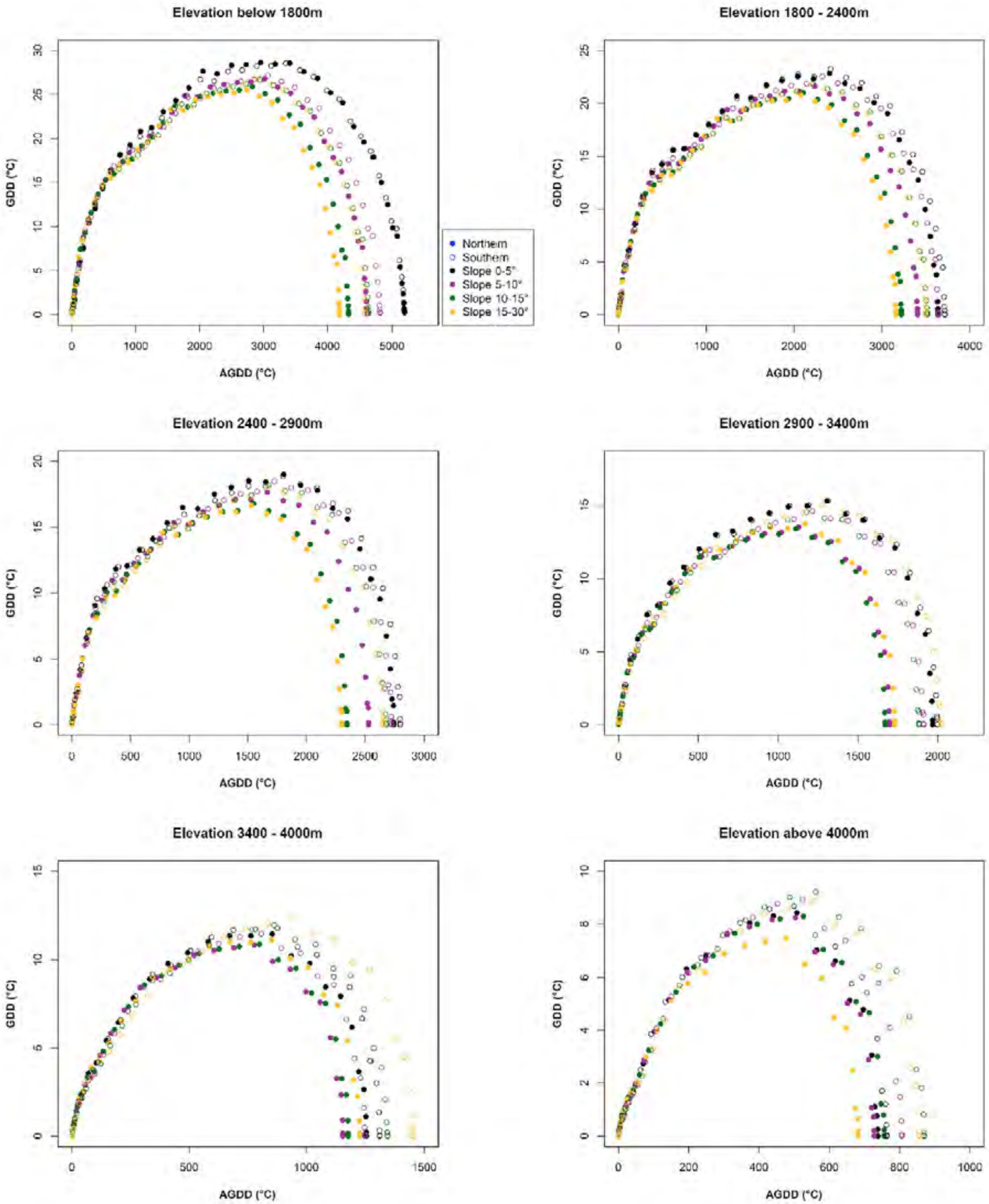
Estimated animal unit equivalents is now ~20% higher than during USSR and herd mobility is lower.

Source: FAOSTAT 2024

Thermal seasonality by elevational stratum



Tomaszewska MA, LH Nguyen, GM Henebry. 2020. Land surface phenology in the highland pastures of montane Central Asia: Interactions with snow cover seasonality and terrain characteristics. *Remote Sensing of Environment* 240:111675.

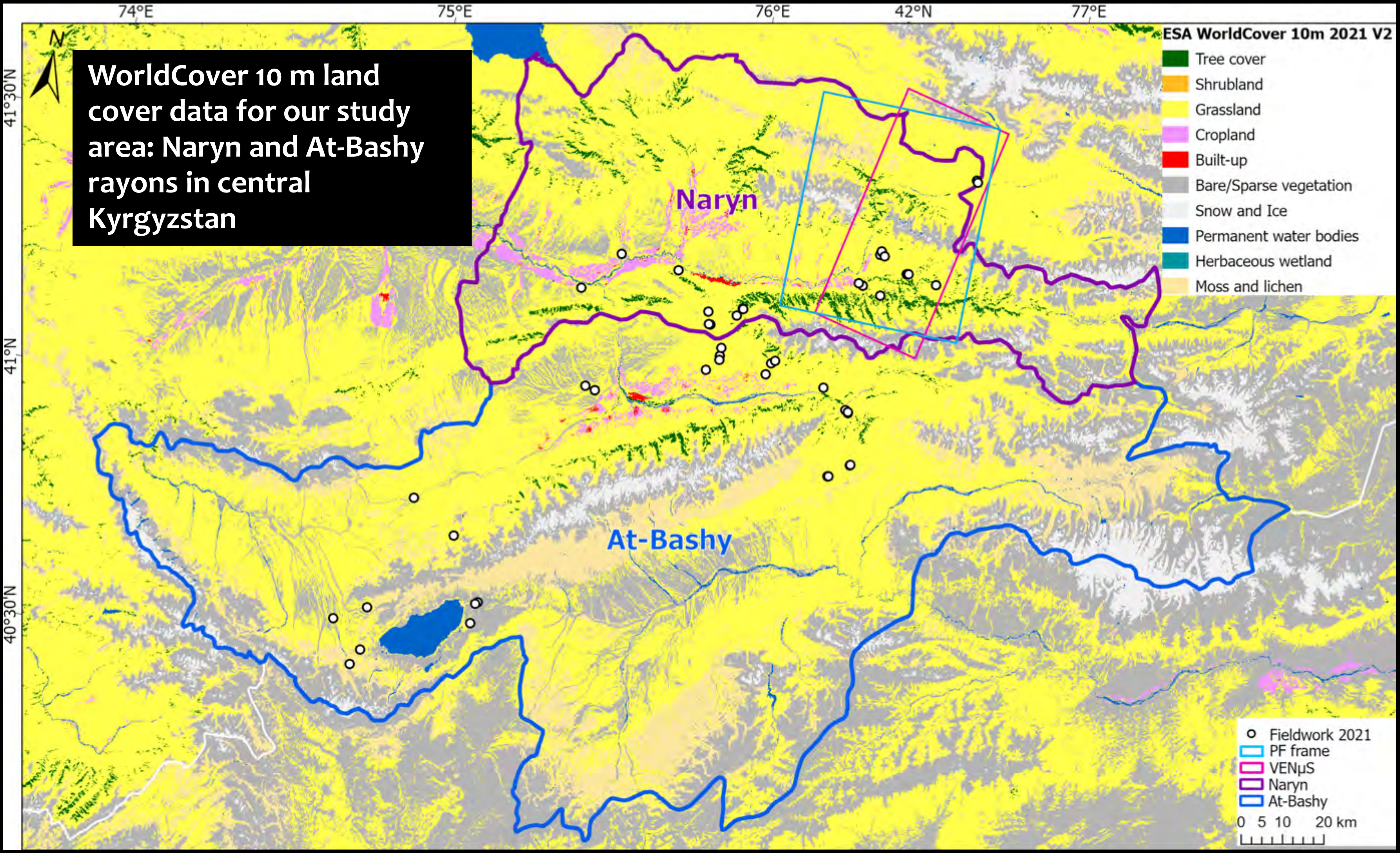


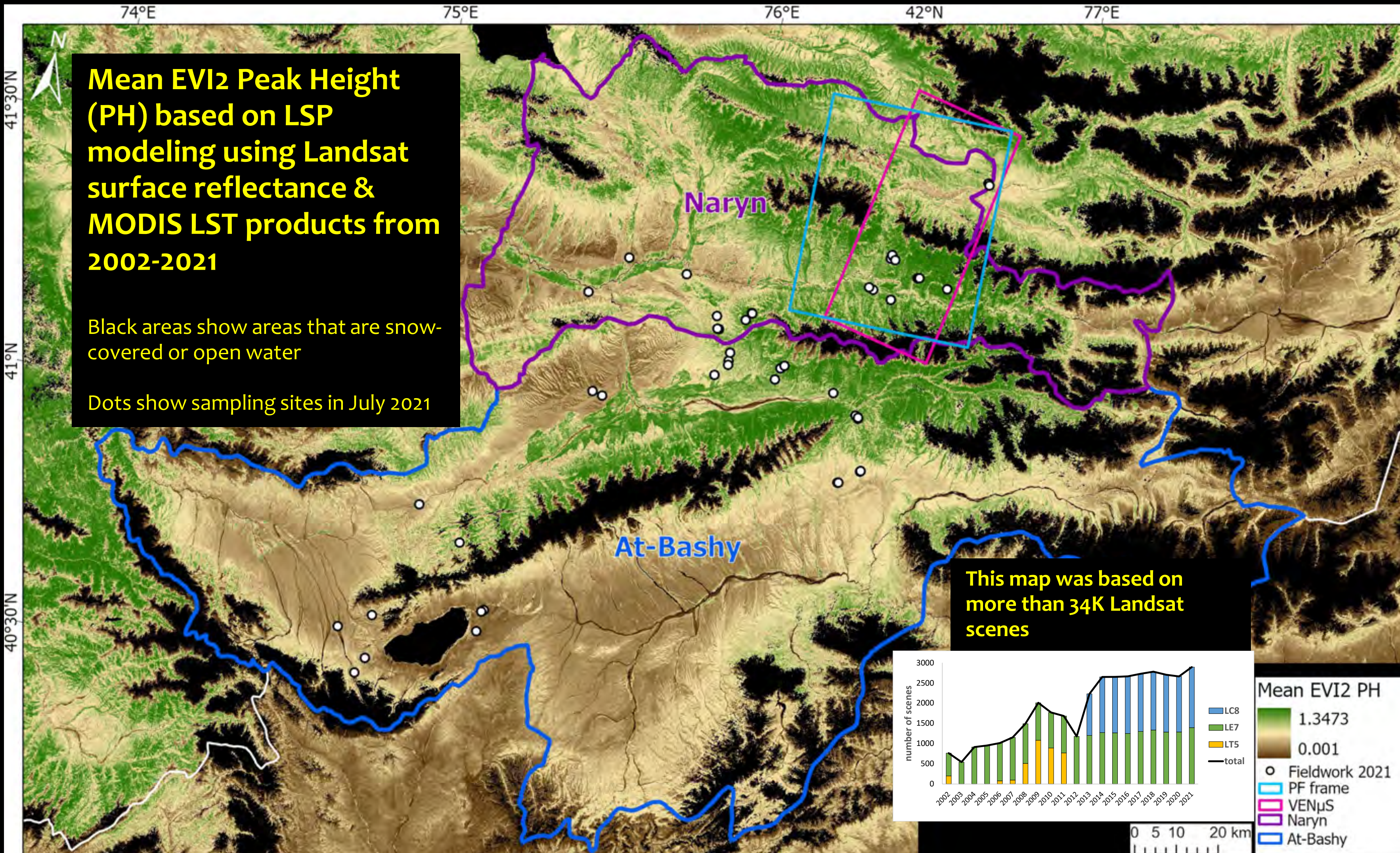
In mountains, the local thermal environment is modulated by terrain features.

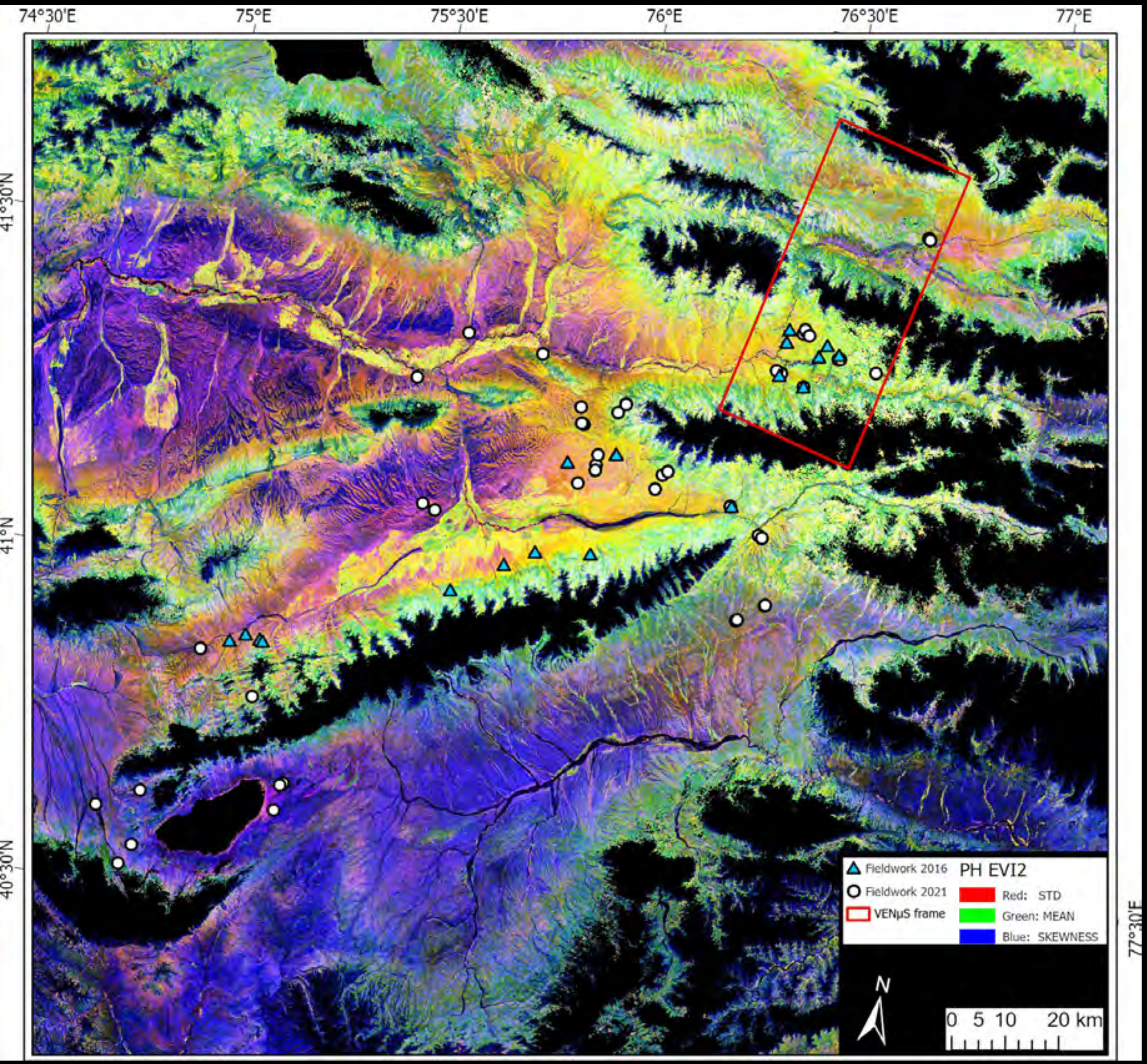
Slope-aspect interactions generate microclimates that are more different at higher elevations.

Tomaszewska MA, LH Nguyen, GM Henebry. 2020. Land surface phenology in the highland pastures of montane Central Asia: Interactions with snow cover seasonality and terrain characteristics. *Remote Sensing of Environment* 240:111675.

WorldCover 10 m land cover data for our study area: Naryn and At-Bashy rayons in central Kyrgyzstan




Mean EVI2 Peak Height (PH) based on LSP modeling using Landsat surface reflectance & MODIS LST products from 2002-2021
Black areas show areas that are snow-covered or open water
Dots show sampling sites in July 2021
This map was based on more than 34K Landsat scenes
74°E
75°E
76°E
42°N
77°E
41°30'N
41°N
40°30'N
N
Naryn
At-Bashy
number of scenes
3000
2500
2000
1500
1000
500
0
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
LC8
LE7
LT5
total
0 5 10 20 km
Mean EVI2 PH
1.3473
0.001
Fieldwork 2021
PF frame
VENμS
Naryn
At-Bashy



Sampling locations during the field campaigns of 2016 and 2021 in Naryn and At-Bashy rayons, Naryn oblast, KG

Image shows false color composite of the first three statistical moments (std – mean – skew) of the LSP time series (2002-2021)

Areas in black are either open water or snow covered; thus, no modeled peak height

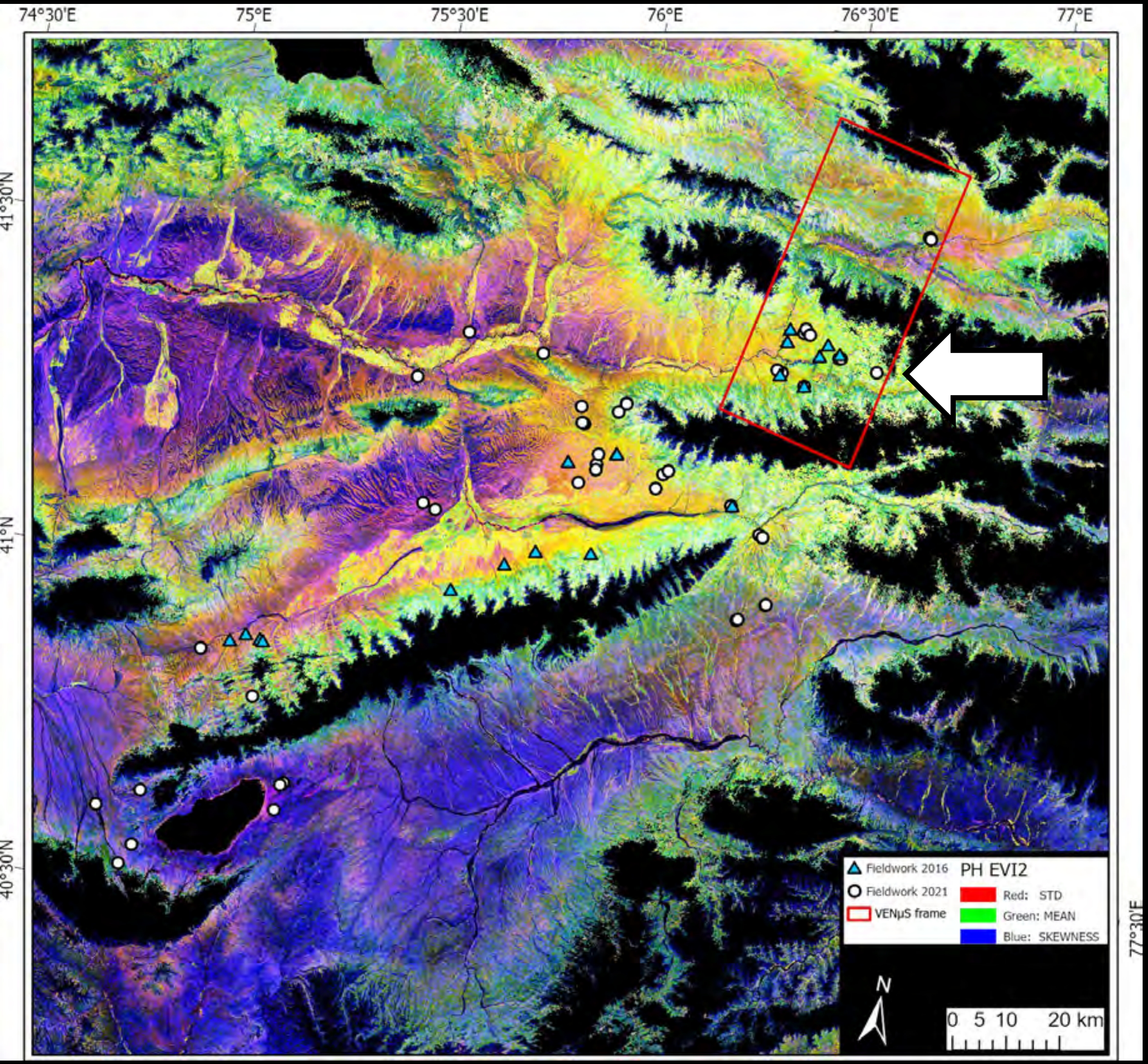
The Problem of Pasture Degradation in Montane Central Asia

Pastoralists practice vertical transhumance: moving livestock from lower elevation winter pastures to spring pastures at higher elevation and then to even higher, more distant summer pastures before descending to overwinter

Degradation of Central Asian pastures has been widely reported & disputed

Many studies have used remote sensing data to evaluate the degradation

However, the "not degraded" baselines are often unclear or rely on a Soviet-era understanding of vegetation community dynamics formulated ***prior to*** the widespread recognition of a changing climate and its implications



Sampling locations during the field campaigns of 2016 and 2021 in Naryn and At-Bashy rayons, Naryn oblast, KG

Image shows false color composite of the first three statistical moments (std – mean – skew) of the LSP time series (2002-2021)

Areas in black are either open water or snow covered; thus, no modeled peak height


12/7/2021 12:18


12/7/2021 12:19


Landscape engineers at work!
12/7/2021 15:58

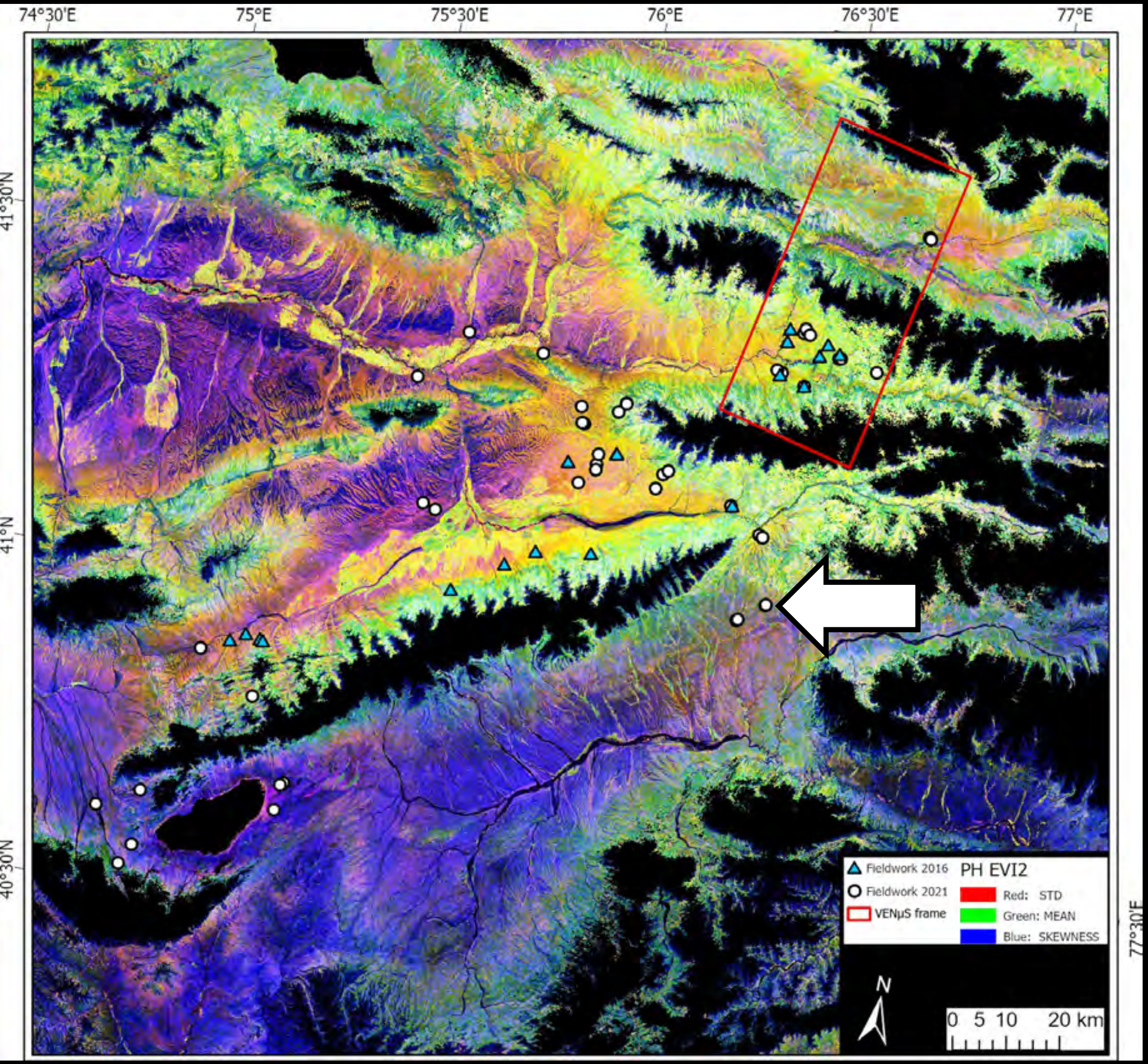

12/7/2021 12:40


217 AAT
12/7/2021 16:23


12/7/2021 15:12


P100
S100
12/7/2021 15:46


4K digital photos enable species identification and cover estimation by vegetation scientists



Sampling locations during the field campaigns of 2016 and 2022 in Naryn and At-Bashy rayons, Naryn oblast, KG

Image shows false color composite of the first three statistical moments (std – mean – skew) of the LSP time series (2002-2021)

Areas in black are either open water or snow covered; thus, no modeled peak height


24/7/2021 11:32

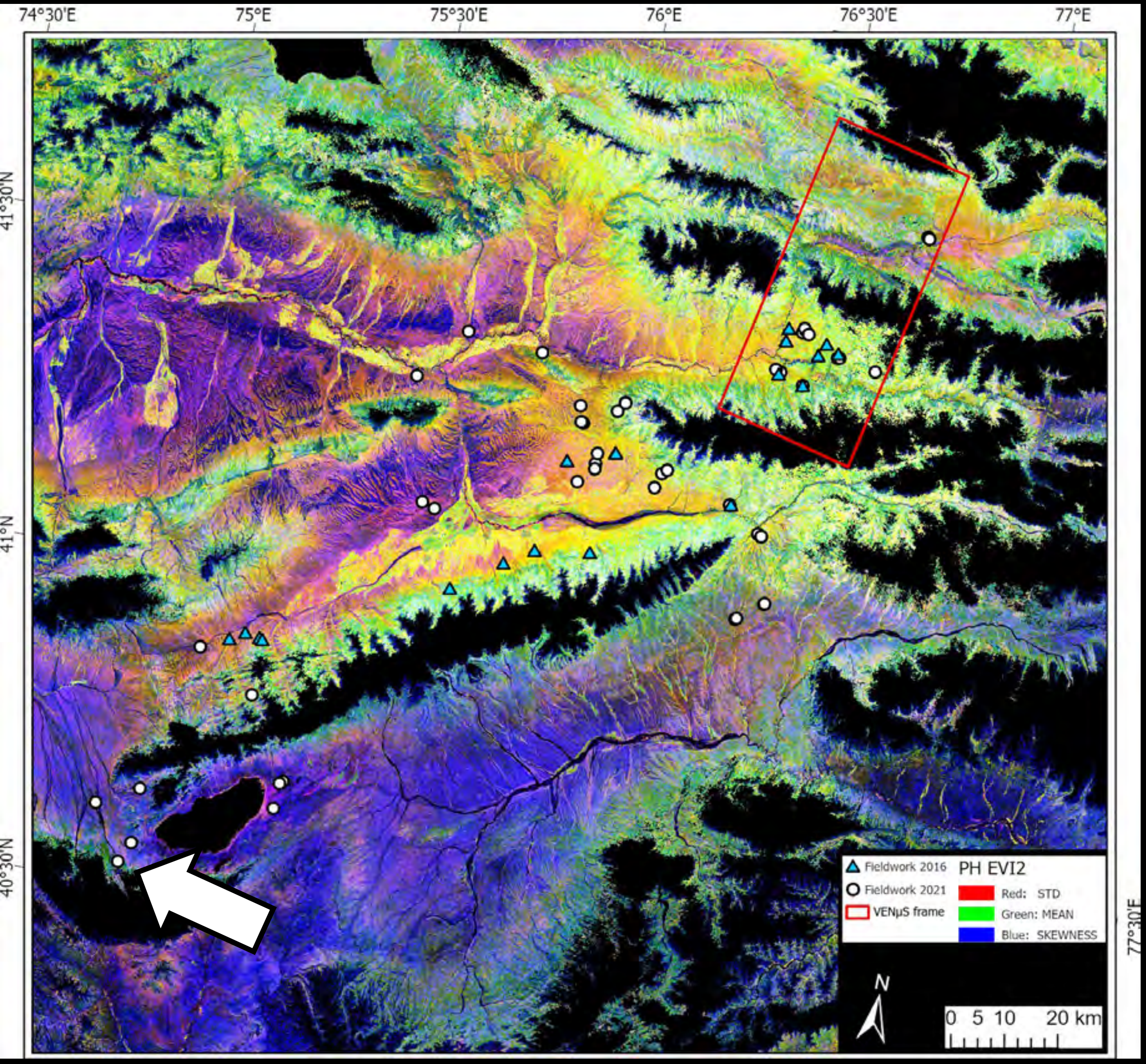

24/7/2021 12:49


24/7/2021 13:39


24/7/2021 13:41


24/7/2021 13:55


S49
24/7/2021 13:54



Sampling locations during the field campaigns of 2016 and 2022 in Naryn and At-Bashy rayons, Naryn oblast, KG

Image shows false color composite of the first three statistical moments (std – mean – skew) of the LSP time series (2002-2021)

Areas in black are either open water or snow covered; thus, no modeled peak height


28/7/2021 15:36


28/7/2021 16:30

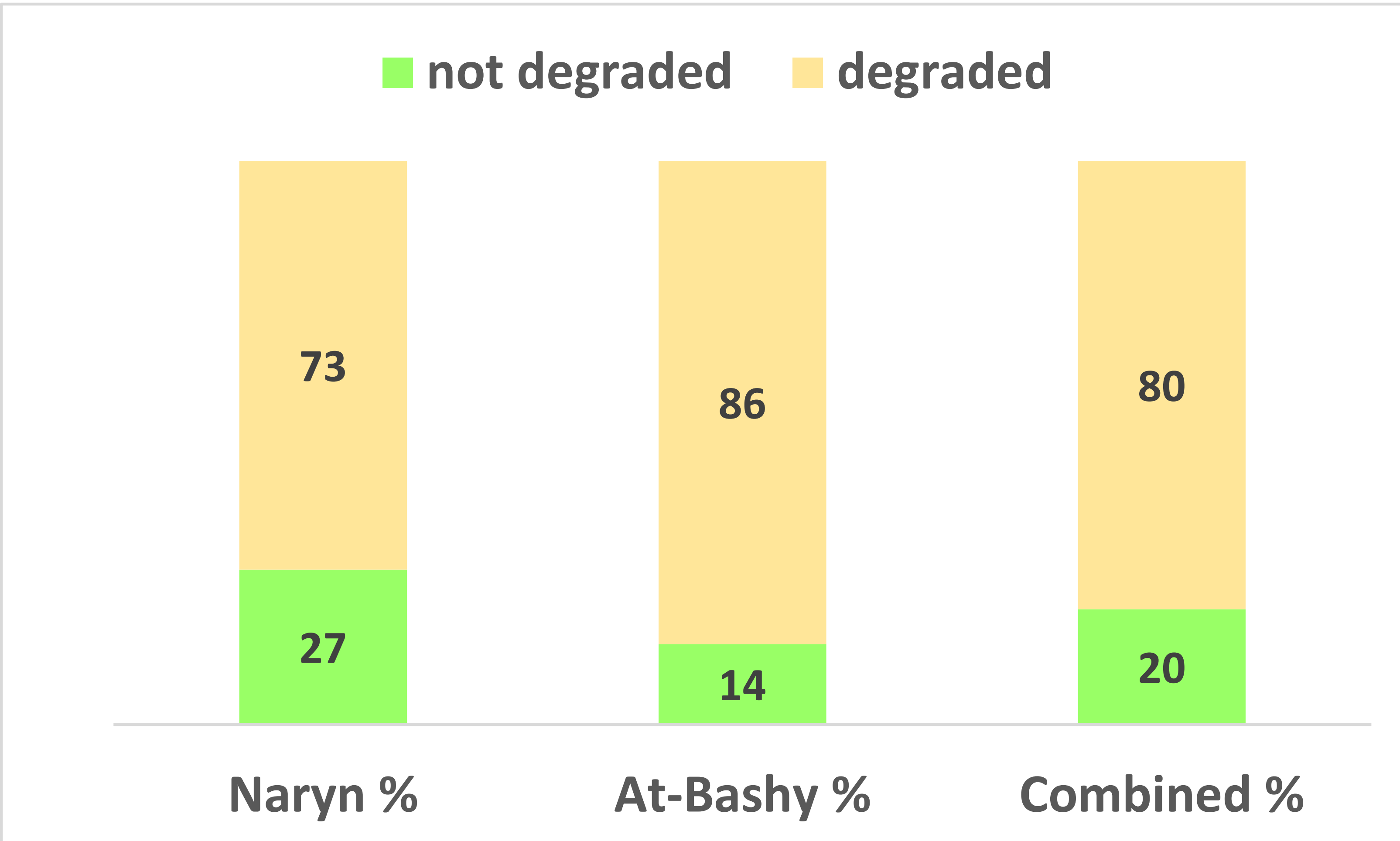

28/7/2021 16:08

28/7/2021 16:18

28/7/2021 16:30


S49
28/7/2021 16:29

80% of our sample sites were degraded, with more in drier At-Bashy than in Naryn (but site selection was not random)



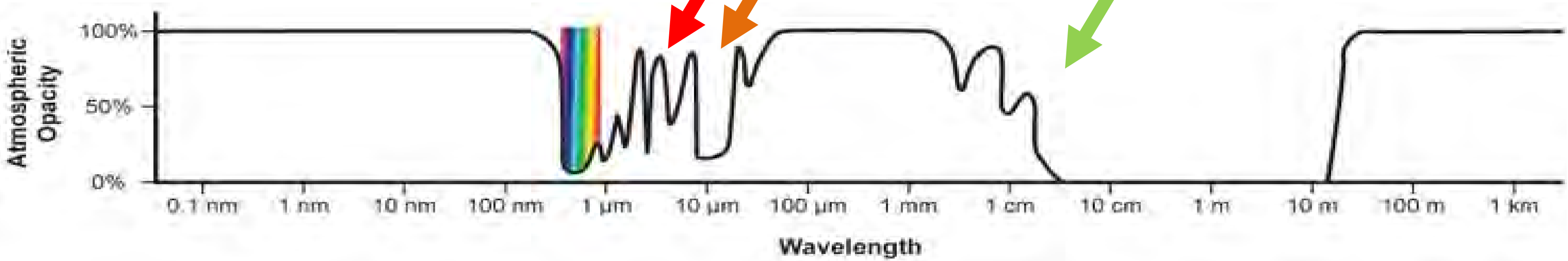
5. LSPs in Cool Earthlight

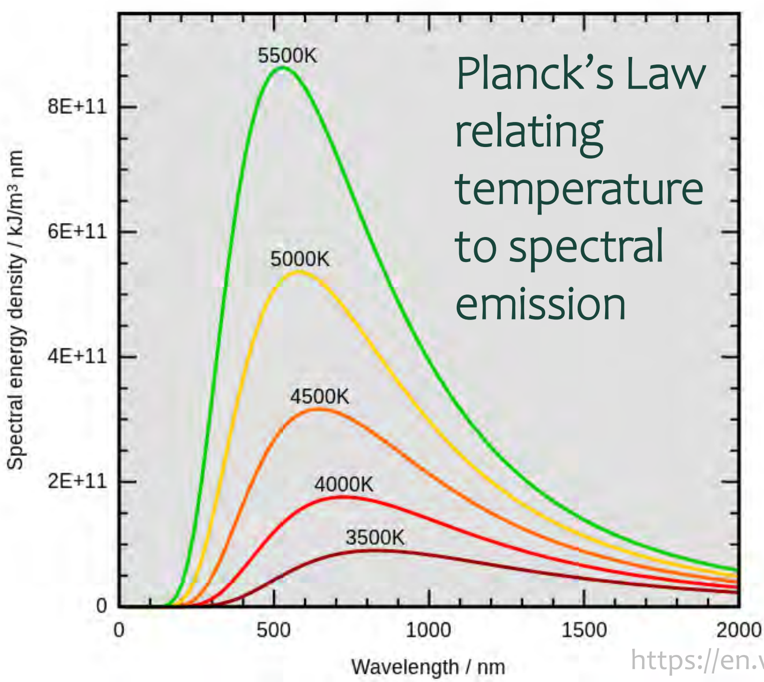
What are the Types of Earthlight?

T at peak wavelength→ **Hot: 800 °F**
Hot: 700 K
MIR: 3-5 μm

Warm: 98 °F
Warm: 310 K
TIR: 8-15 μm

Cool: < 50 °F
Cool: < 283 K
Microwaves: 1-25 cm



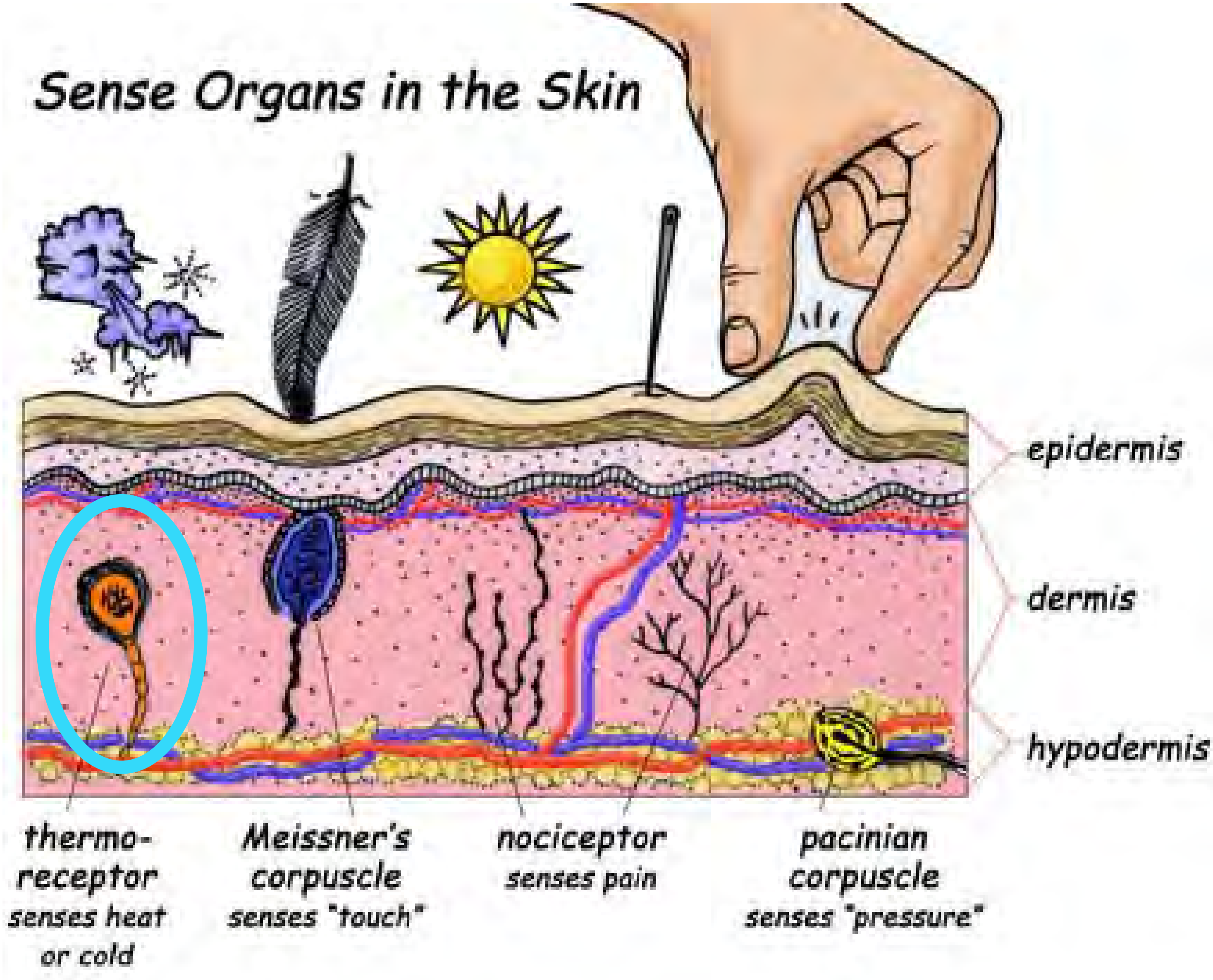


Earth mostly emits **"warm earthlight"** – the realm of the living, but it also faintly emits microwaves **"cool earthlight"** that can tell us about moisture, temperature & vegetation.

https://en.wikipedia.org/wiki/Wien%27s_displacement_law#/media/File:Wiens_law.svg
https://en.wikipedia.org/wiki/Visible_spectrum#/media/File:Atmospheric_electromagnetic_opacity.svg

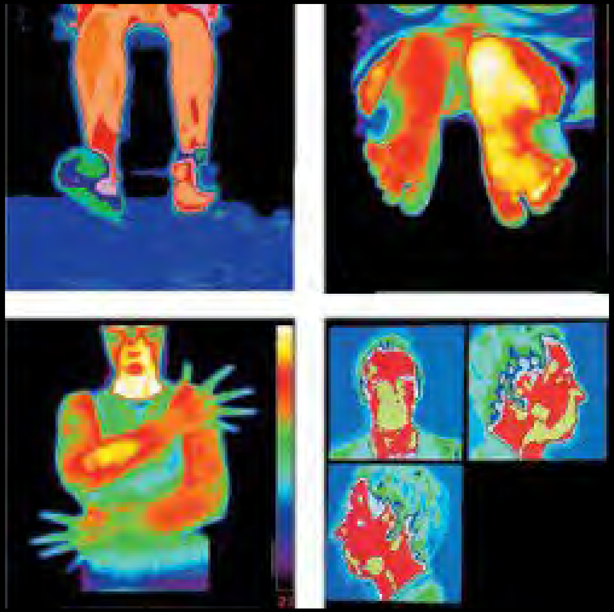
We sense heat & cold primarily through our skin.

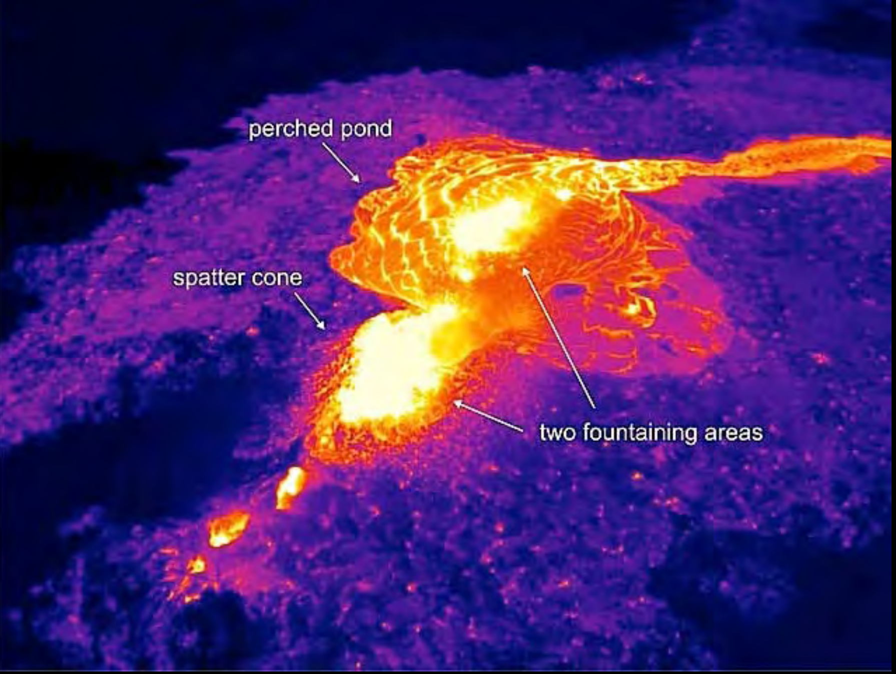
Some parts of the body are more sensitive than others.



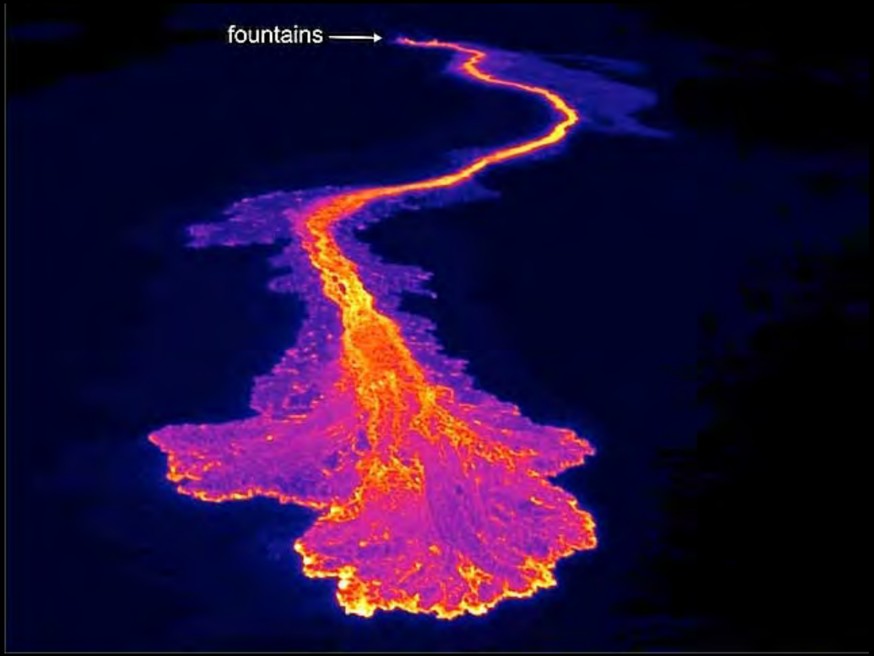
http://www.exploringnature.org/db/view/1569

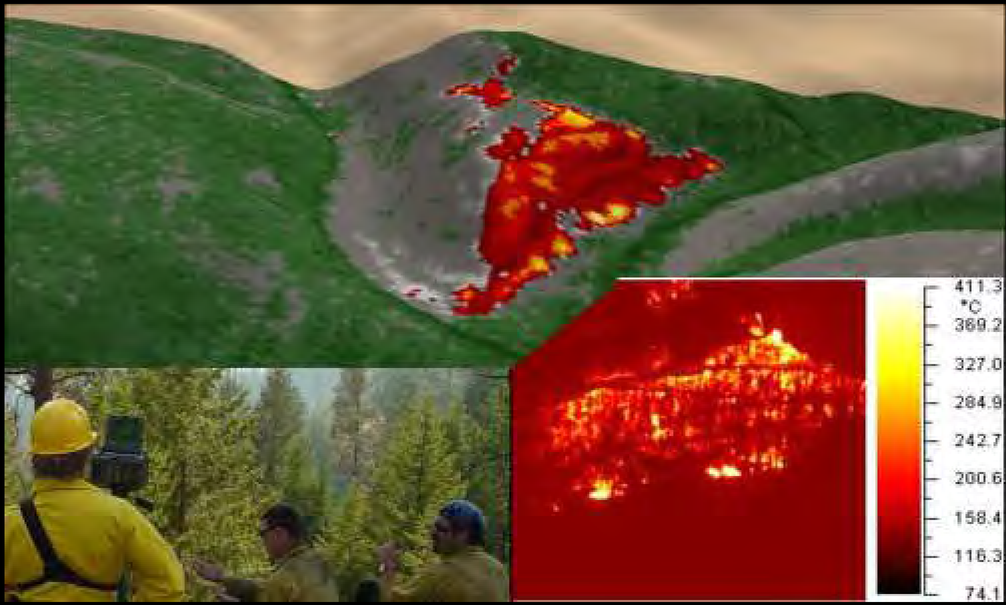
Forward Looking Infrared (FLIR) cameras reveal the warm earthlight of human bodies for diagnosis & survelliance.





FLIR cameras can also reveal hot earthlight of volcanoes, wildfires, and other very hot things.





http://www.firelab.org/resource/thermal-imaging

http://www.x20.org/product/m1-d-micro-ptz-infrared-camera/

Passive microwave radiometers track “cool earthlight” at night and through clouds, but not over frozen surfaces or open water, to retrieve:

ta: **surface air temperature at 2 meters.** Daily temperature is considered minimum on descending overpass (~ 0130) and maximum on ascending overpass (~1330).

tc: canopy transmittance at specific frequencies

V: vertically integrated atmospheric water vapor

vsm: volumetric soil moisture

fw: open water fraction

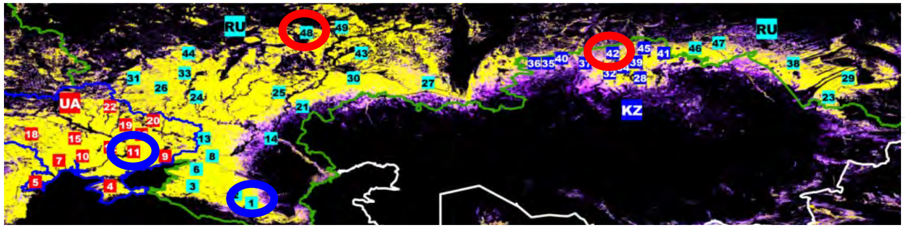
vod: vegetation optical depth

Few photons → coarse spatial resolution: 25 km

NASA Aqua AMSR-E

JAXA GCOM-W1 AMSR2

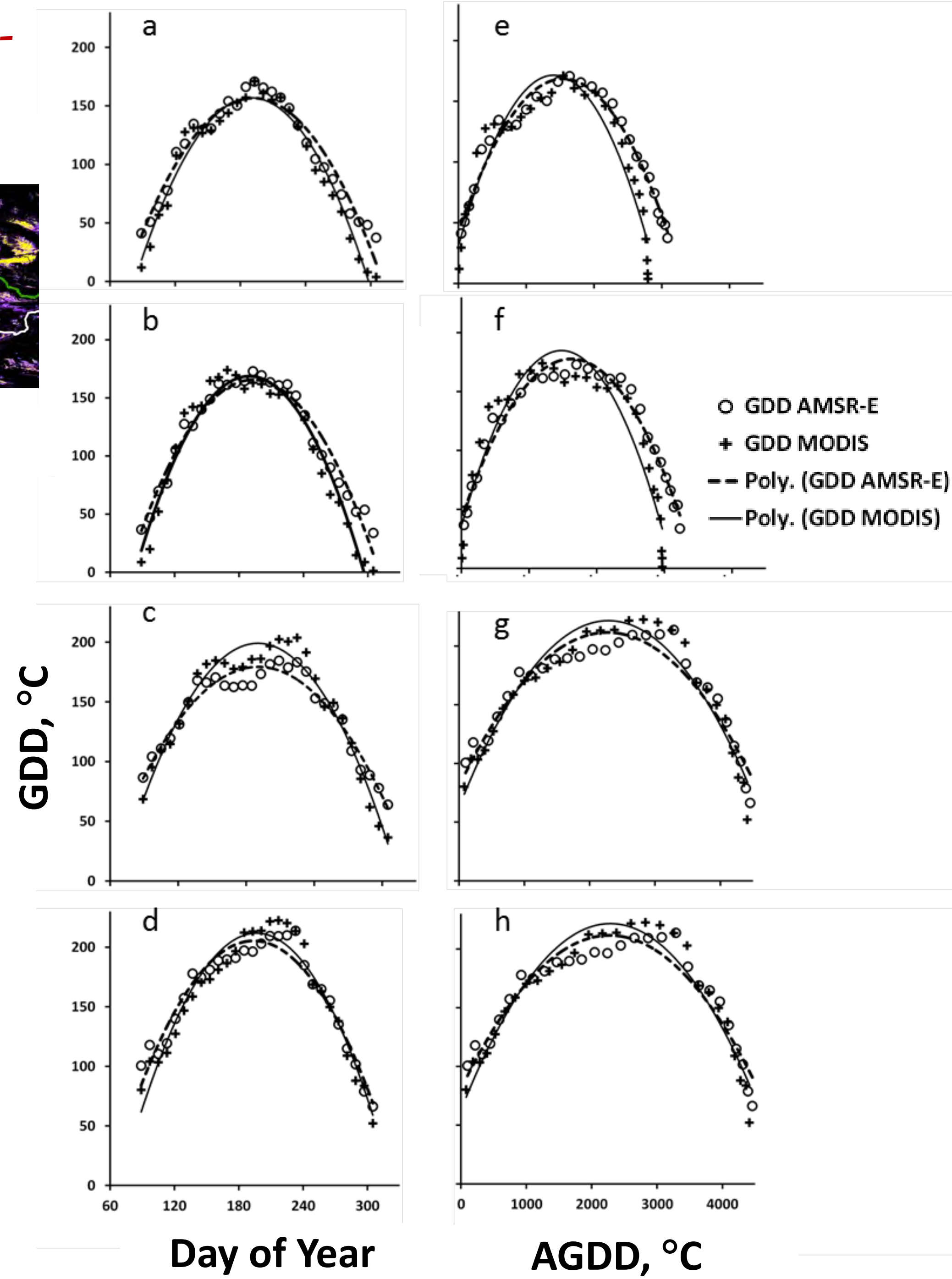
Seasonality of Growing Degree-Days (base 0 °C) in Northern Eurasia



A parabola well describes average GDD as a function of either DOY or AGDD.

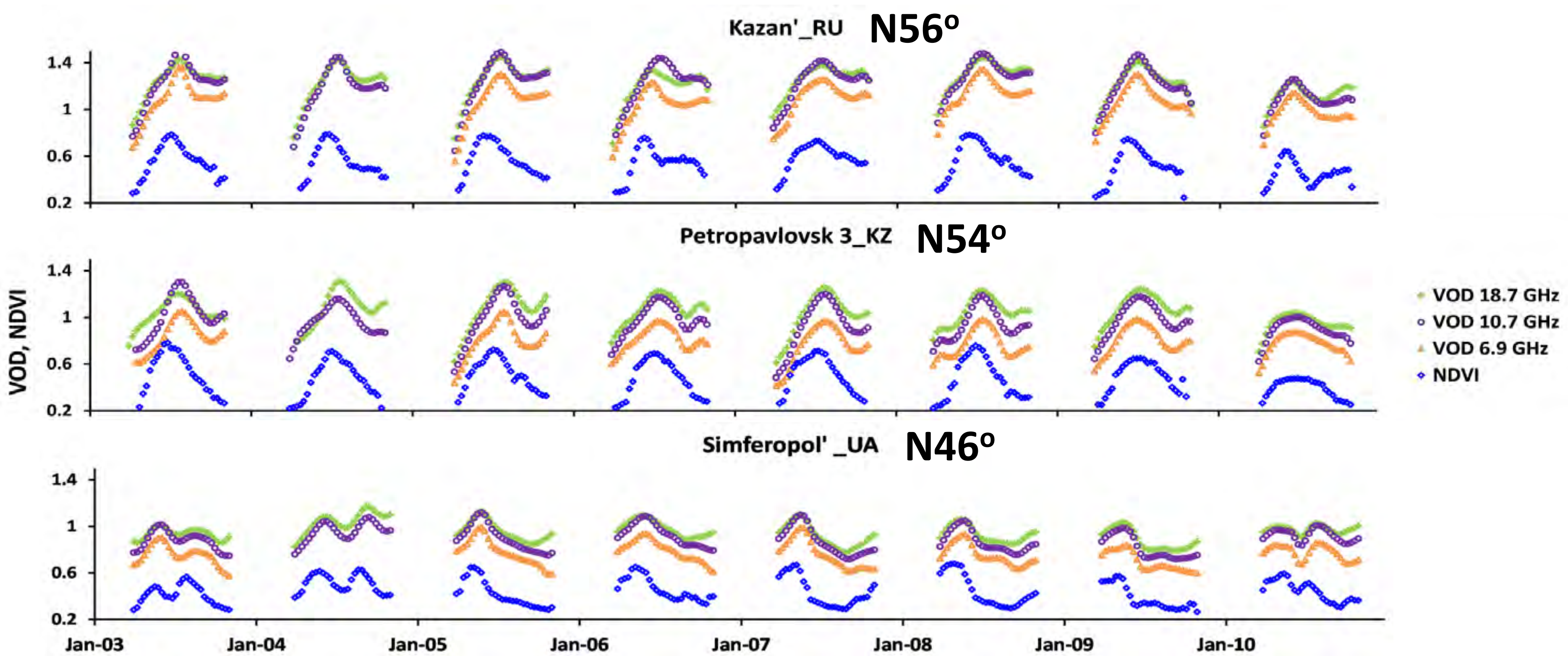
Excellent fits for both MODIS skin temperature (1 km) & AMSR-E air temperature (25 km), but AMSR-E fits are consistently better for AGDD.

Alemu WG and GM Henebry. 2016. Characterizing cropland phenology in major grain production areas of Russia, Ukraine, and Kazakhstan by the synergistic use of passive microwave and visible to near infrared data. *Remote Sensing* 8(12):1016.



Cool earthlight can enable monitoring of croplands, such as in North America, Northern Eurasia, East Africa, and more.

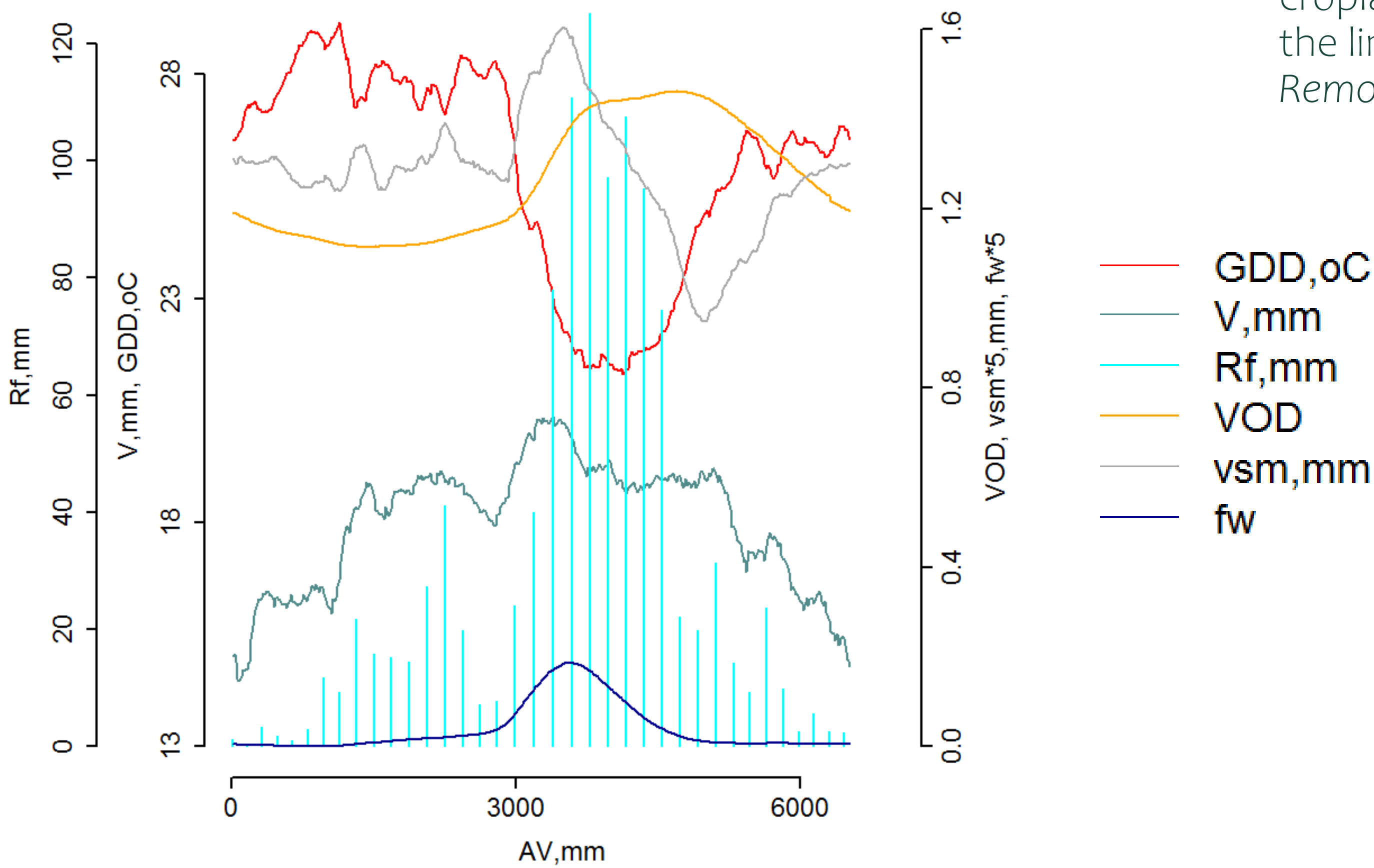
VOD = vegetation optical depth at microwave frequency
NDVI = normalized difference vegetation index



Alemu WG and GM Henebry. 2017. Comparing passive microwave with visible-to-near-infrared phenometrics in croplands of northern Eurasia. *Remote Sensing* 9(6):613.

Ethiopia: 2003-2014

Alemu WG and GM Henebry. 2017. Land surface phenology and seasonality using cool earthlight in croplands of eastern Africa and the linkages to crop production. *Remote Sensing* 9(9):914.



Tracking seasonal progression with accumulated water vapor (AV)

Lower GDD in July, August despite the overhead sun → ***cloud cover***

Peak VOD (vegetation) in October after the main rainy season

Take Home Points…

- Phenology—the study of timing of biological events—links climate, plants, animals, and humanity.
- Land Surface Phenologies characterize seasonality in the *vegetated land surface* [not organisms or vegetation].
- LSPs are linked to the timing & magnitude of energy and water exchanges between the vegetated land surface and the atmospheric boundary layer.
- Some LSPs can be captured by simple models.
- Phenologies are fundamental phenomena that can facilitate interdisciplinary research.

Thank you for your attention!

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*deceased 9/2022