LAND SURFACE PHENOLOGY AS INDICATOR OF GLOBAL TERRESTRIAL ECOSYSTEM DYNAMICS

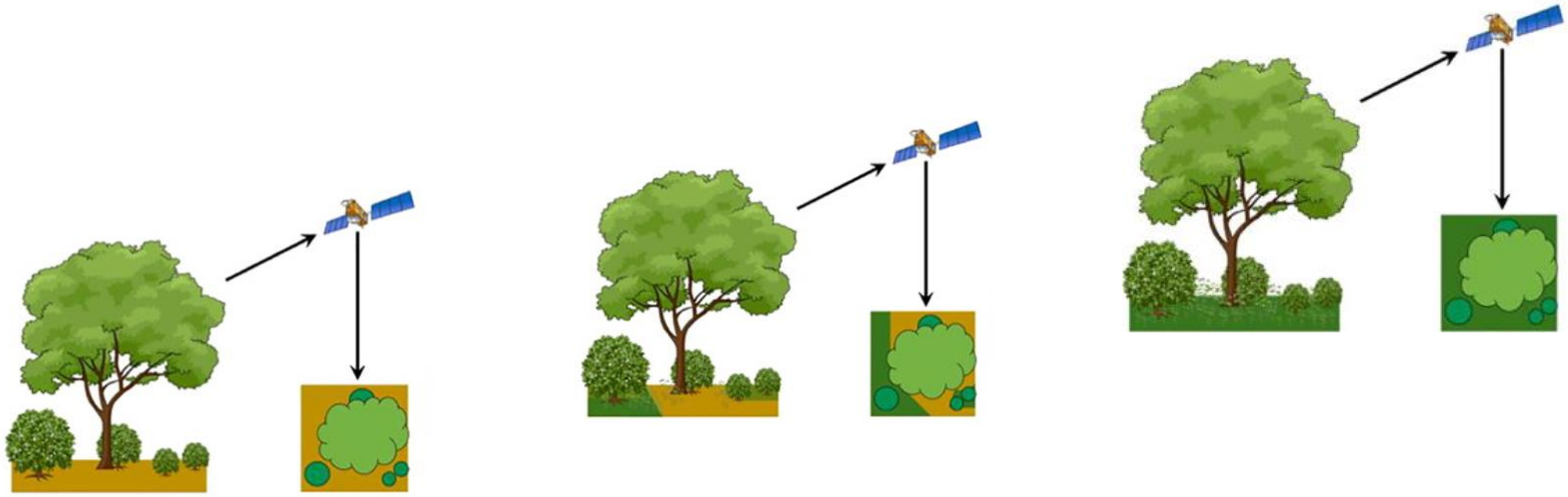
VICTOR RODRIGUEZ-GALIANO

DEPARTMENT OF PHYSICAL GEOGRAPHY AND REGIONAL GEOGRAPHIC ANALYSIS

UNIVERSITY OF SEVILLE

UNIVERSIDAD DE SEVILLA

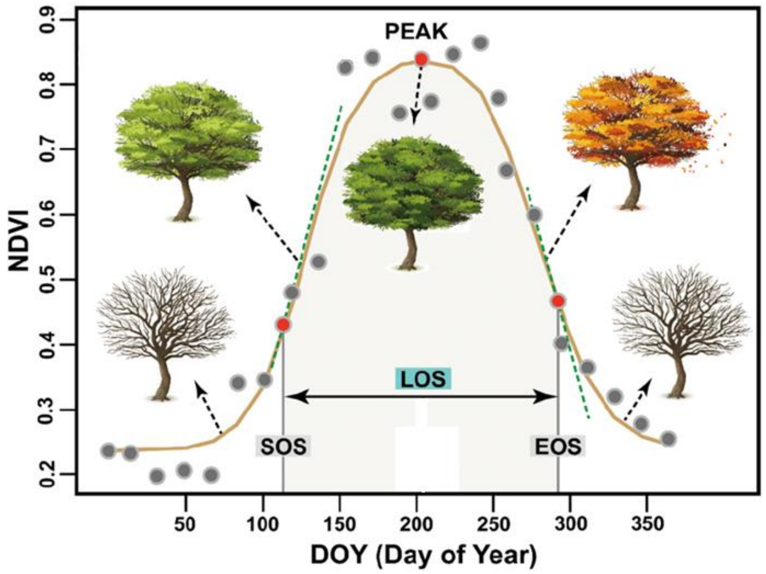
LAND SURFACE PHENOLOGY BASICS



I. INTRODUCTION: LAND SURFACE PHENOLOGY

- **Land surface phenology** (LSP) is defined as the study of the seasonal dynamics of the vegetated land surface observed from remotely sensed satellite imagery. LSP is estimated from **vegetation indices** (VI) or **biophysical variables** (BV) time-series, which can be used as proxy for vegetative vigour and amount.

- VI (or BV) can be used to obtain specific phenological metrics or **phenometrics**. These phenometrics are ecologically-meaningful metrics that may be considered as proxies of timing of spring and autumn phenophases. Phenometrics include the **start of the (growing) season (SOS)**, also referred in the literature as the green-up date (GUD), onset of greenness (OG) or spring phenology; the **end of the (growing) season (EOS)**, also called end of senescence (EOS), end of greenness, dormancy or autumn phenology; and the **length of the (growing) season (LOS).**



Phenometrics extracted from VI time series datasets.

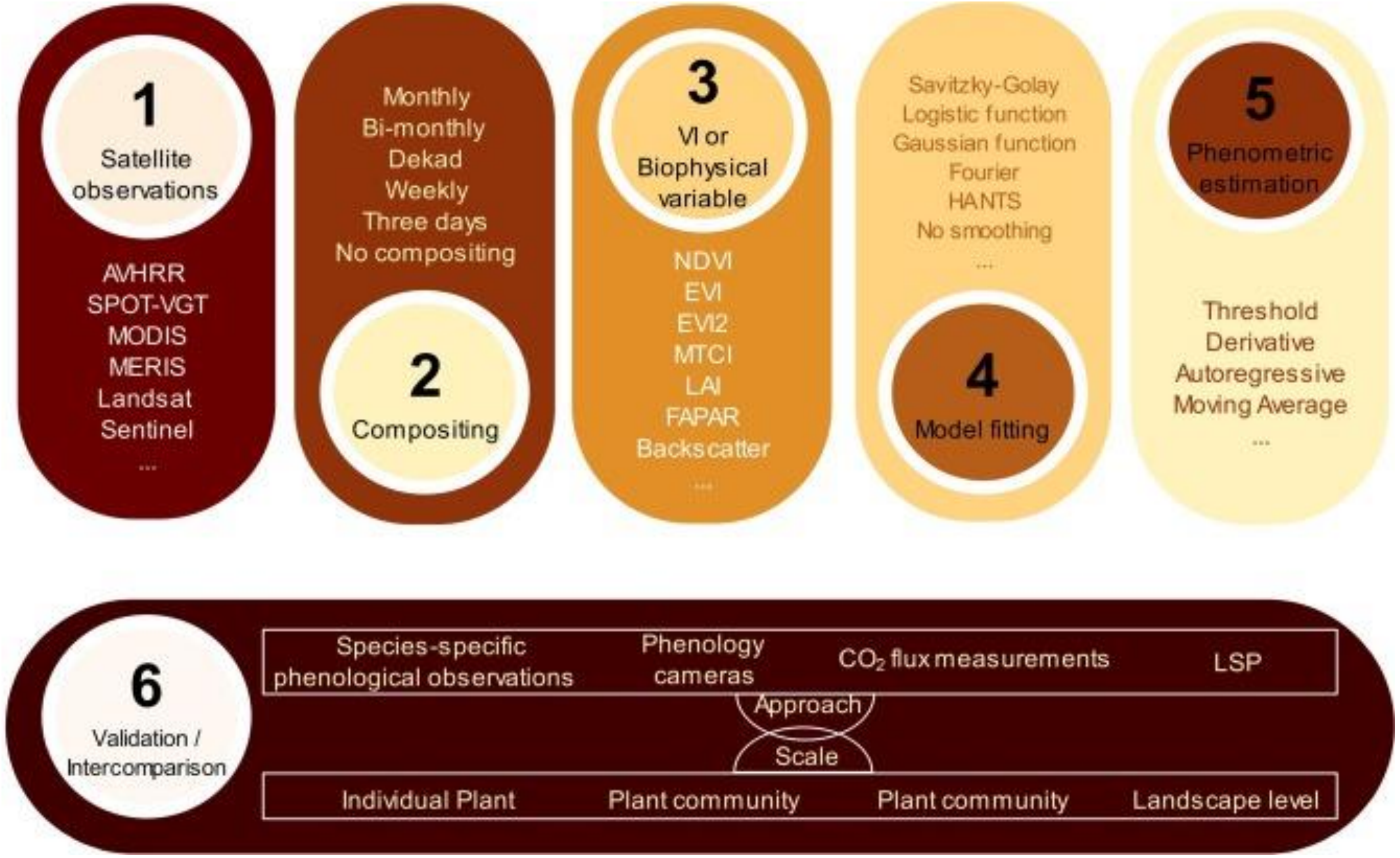
SOS: the point in time extracted from the ascending phase (pre-maximum phase) of the curve of the VI (or BV), which could be associated to timing of spring phenophases (e. g., **leaf unfolding** or **flowering**).

EOS: the point in time extracted from the descending phase (post-maximum phase) of the curve of the VI (or BV variable), which could be related to timing of autumn phenophases (e. g., **autumnal colouring of leaves** or **leaf fall**)

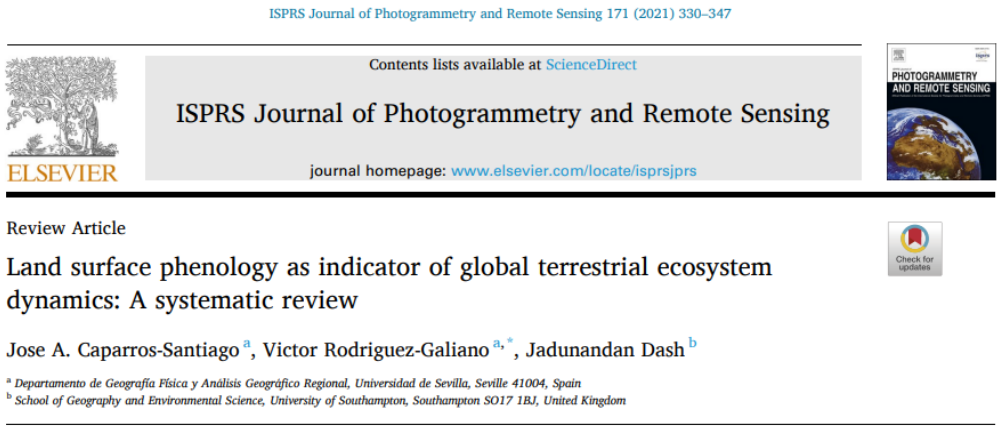
LOS: difference between SOS and EOS, which could be associated to the complete temporal extension of the period of vegetative development of plants.

Guo, J., et al. (2021). Specific Drivers and Responses to Land Surface Phenology of Different Vegetation Types in the Qinling Mountains, Central China. Remote Sensing, 13

II. LAND SURFACE PHENOLOGY ESTIMATION



Schematic diagram on the steps involved in LSP estimation from satellite data. Extracted from Caparros-Santiago et al. (2021).


ISPRS Journal of Photogrammetry and Remote Sensing 171 (2021) 330–347

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Review Article

Land surface phenology as indicator of global terrestrial ecosystem dynamics: A systematic review

Jose A. Caparros-Santiago [a], Victor Rodriguez-Galiano [a,*], Jadunandan Dash [b]

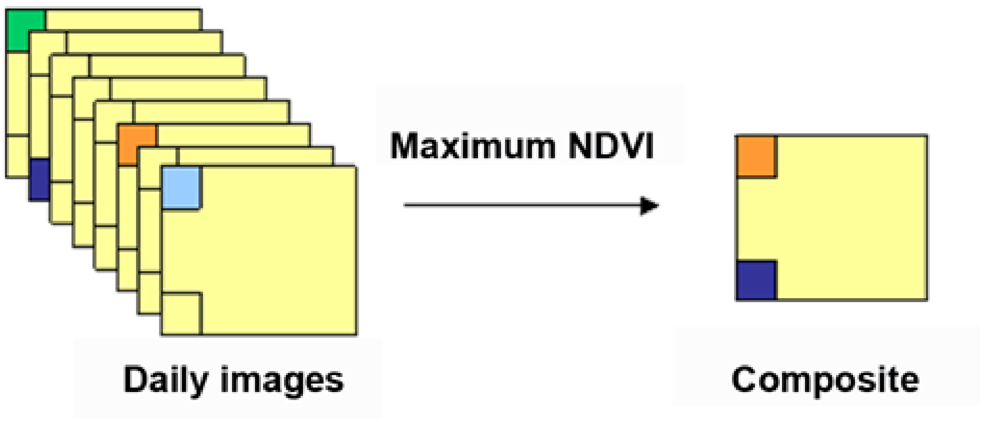
[a] Departamento de Geografía Física y Análisis Geográfico Regional, Universidad de Sevilla, Seville 41004, Spain
[b] School of Geography and Environmental Science, University of Southampton, Southampton SO17 1BJ, United Kingdom

Summary of some common satellite sensors.

SENSORS	SPATIAL RESOLUTION	TEMPORAL RESOLUTION
AVHRR (NOAA)	1.1 km	Daily
MODIS (Terra and Aqua)	250 m (bands 1-2) 500 m (bands 3-7) 1000 m (bands 8-36)	1-2 days
SPOT-VGT	1.1 km	Daily
VIIRS	375 m (Bands I) and 750 m (Bands M)	Daily
IRS-WiFS	180 m	5 days
Landsat 4-5 TM	30 m (VIS-NIR); 120 m (TIR)	16 days
Landsat 7 ETM+	30 m (VIS-NIR); 60 m (TIR); 15 m (panchromatic band)	16 days
Landsat 8 OLI	30 m (VIS-NIR-TIR); 15 m (panchromatic band)	16 days
Sentinel 2 A/B MSI	10 m (bands 2 (B),3 (G),4 (R),8 (NIR), 20 m (bands 5, 6, 7, 8 A, 11, 12); 60 m (bands 1, 9, 10)	5 days
GeoEye-1	0.41 m panchromatic and 1.65 m 4-band multi-spectral data	1-4 days

II. LAND SURFACE PHENOLOGY ESTIMATION

2. COMPOSITING



- Satellite **composites** instead of daily or near-daily images allows to reduce the amount of data, optimising the computational cost, and minimising atmospheric effects (e. g., cloud cover).

❖ **Composite:** statistical aggregated value (e. g., maximum, median or mean value) at pixel level within a fixed temporal window.

Example of the temporal window of image composites of some satellite products

SATELLITE	SENSOR	TEMPORAL RESOLUTION	SATELLITE PRODUCT	TEMPORAL WINDOW OF COMPOSITE
NOAA	AVHRR (1981-current)	Daily	PAL AVHRR	**10 days**
			GIMMS AVHRR	**15 days**
Terra / Aqua	MODIS (1999-current)	1-2 days	MOD09A1	**8 days**
			MOD09Q1	**8 days**
			MOD13Q1	**16 days**
S-NPP	VIIRS (2011-current)	Daily	VNP09H1	**8 days**
			VNP13A1	**16 days**

Summary of common satellite-derived remote sensing VI. Adapted from Zeng et al. (2020)

VI	CALCULATION	CHARACTERISTICS
NDVI (Normalised Difference Vegetation Index)	$\frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$	Sensitive to chlorophyll, but saturated in areas with high biomass density.It minimises some types of noise (e. g., cloud shadows, topographic effects etc.)
EVI (Enhanced Vegetation Index)	$G \times \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + (C_1 \times \rho_{RED} - C_2 \times \rho_{BLUE}) + L}$	Introducing atmosphere-sensitive blue band to correct the red band for aerosol influences. Sensitivity in areas with high biomass density.
EVI2 (A two−band Enhanced Vegetation Index)	$G \times \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + C \times \rho_{RED} + L}$	Similar to EVI, retaining the soil-noise adjustment function and maintaining the improved sensitivity and linearity in high biomass regions, with the absence of a blue band.
MTCI (MERIS Terrestrial Chlorophyll Index) **OTCI** (Sentinel−3 OLCI Terrestrial Chlorophyll Index)	$\frac{\rho_{753.75} - \rho_{708.75}}{\rho_{708.75} - \rho_{681.25}}$	Sensitive to high chlorophyll content and limited sensitive to atmospheric effect or spatial resolution.
NDWI (Normalised Difference Water Index)	$\frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}}$	Sensitive to the water
PPI (Plant Phenology Index)	$-K \times \ln \frac{(M - DVI)}{(M - DVI_S)}$	It minimice the snow influence and increase the sensitivity to minor seasonal variation in dense canopy greenness of the boreal forests

Zeng, L. et al. (2020). A review of vegetation phenological metrics extraction using time-series, multispectral satellite data. Remote Sensing of Environment, 237, 111511

Summary of common satellite-derived remote sensing BV. Adapted from Zeng et al. (2020) and Caparros-Santiago et al. (2021)

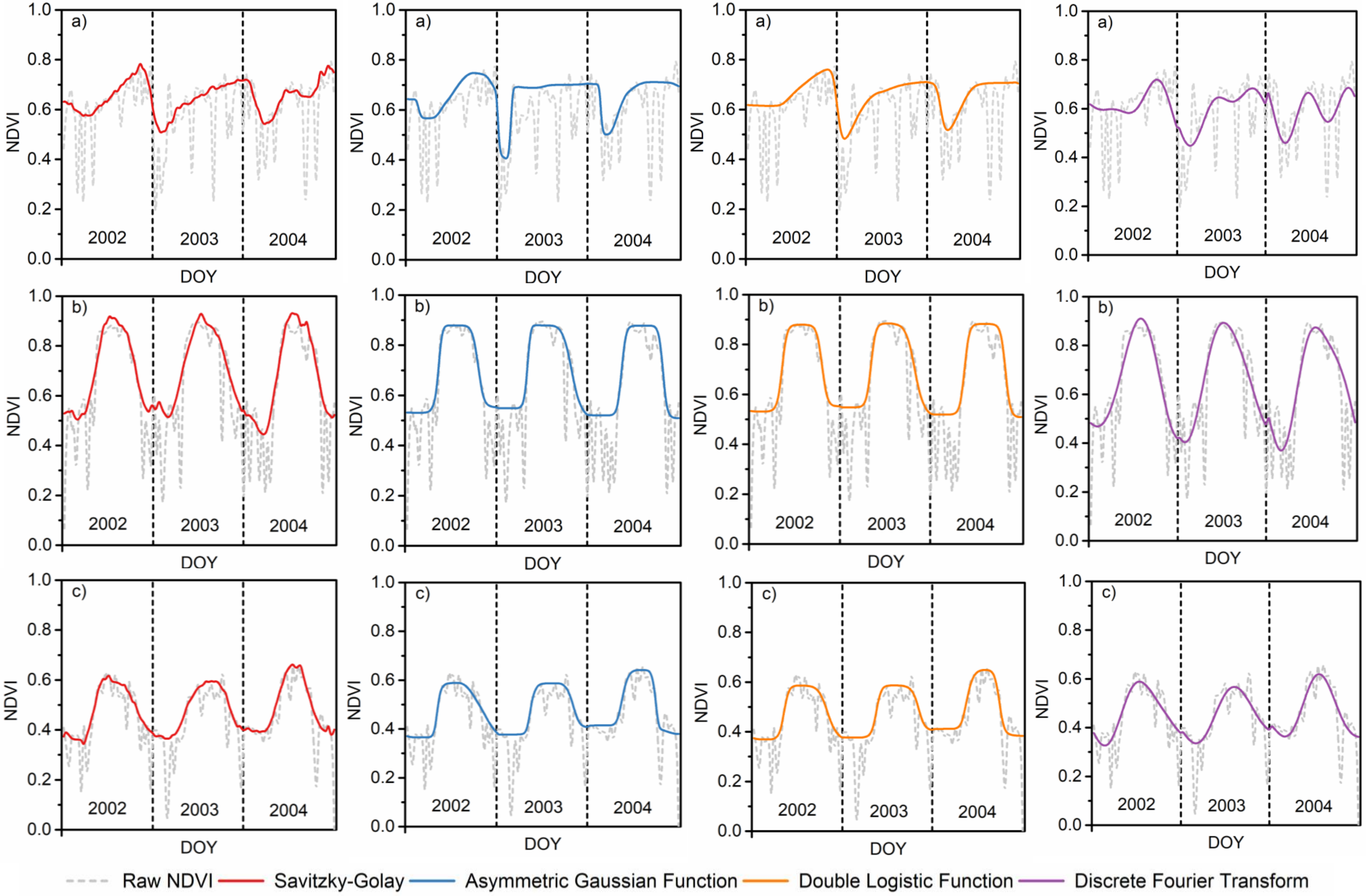
BV	Characteristics
LAI (Leaf Area Index)	Biophysical variable that measures the leaf area (m^2) per unit of ground surface area (m^2).
FAPAR (Fraction of Absorbed Photosynthetically Active Radiation)	Biophysical variable that measures the amount of solar radiation absorbed by the canopy during photosynthetic activity.
SIF (solar-induced chlorophyll fluorescence)	Biophysical variable that quantifies a small portion of solar energy absorbed by plants (1-2%), which is not used for photosynthesis and is therefore re-emitted at a longer wavelength.
AGB (Above-ground biomass)	Biophysical variable that is determined by the vegetation cover and its height.

Caparros-Santiago, J.A., Rodriguez-Galiano, V., & Dash, J. (2021). Land surface phenology as indicator of global terrestrial ecosystem dynamics: A systematic review. *ISPRS Journal of Photogrammetry and Remote Sensing, 171*, 330-347

Zeng, L., et al. (2020). A review of vegetation phenological metrics extraction using time-series, multispectral satellite data. Remote Sensing of Environment, 237, 111511

II. LAND SURFACE PHENOLOGY ESTIMATION

4. MODEL FITTING



Evergreen needleleaf forests
(41° 59′ 33.086″ N; 02° 47′43.125″ W)

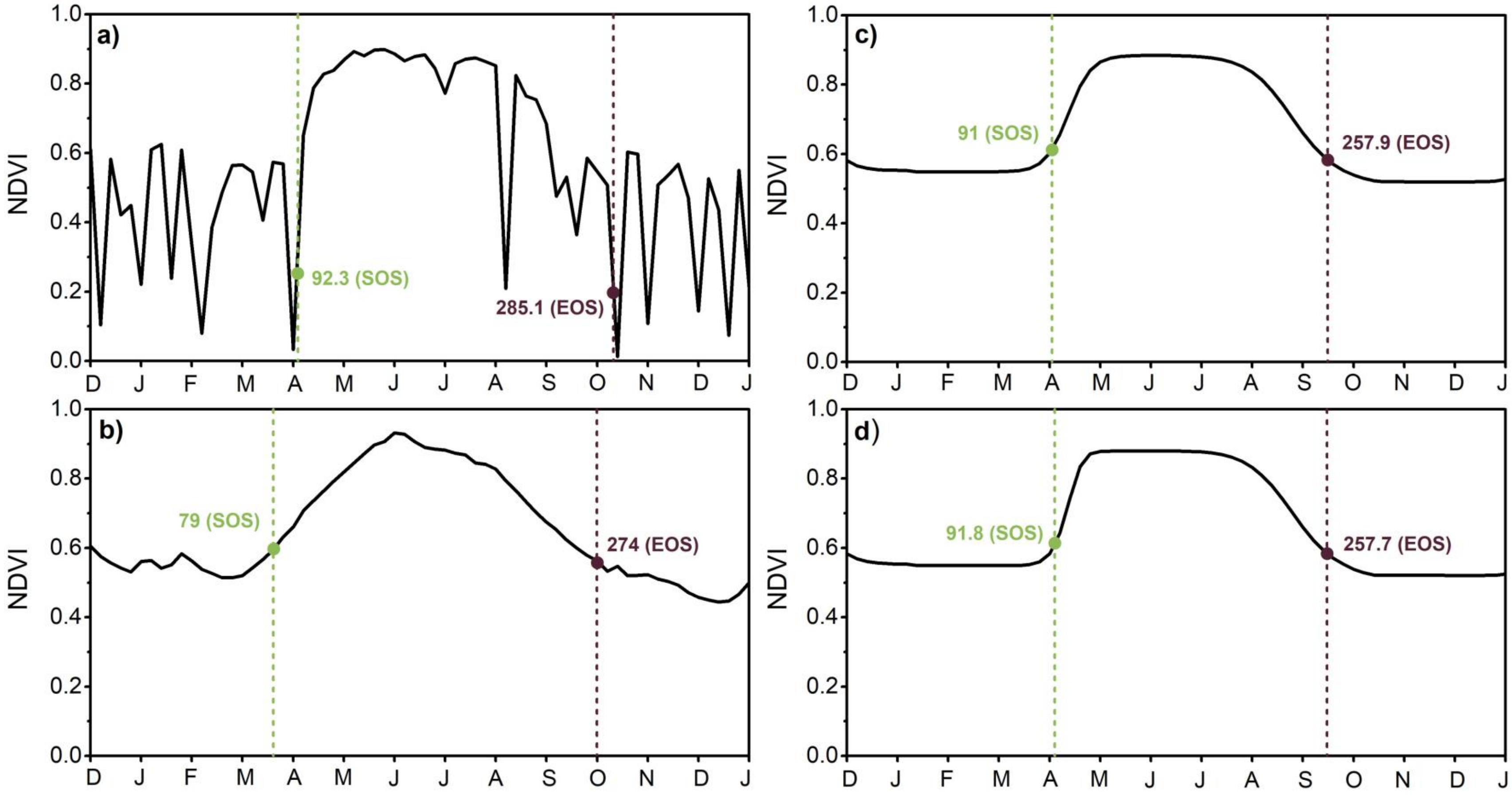
Deciduous broadleaf forests
(42° 22′ 13.207″ N; 02° 55′ 8.891″ W)

Grasslands
(42° 34′ 50.023″ N; 05° 09′ 48.131″ W)

Raw and smoothed MODIS-NDVI time series for different land covers. Adapted from Caparros-Santiago et al., (2021).

II. LAND SURFACE PHENOLOGY ESTIMATION

5. PHENOMETRIC EXTRACTION

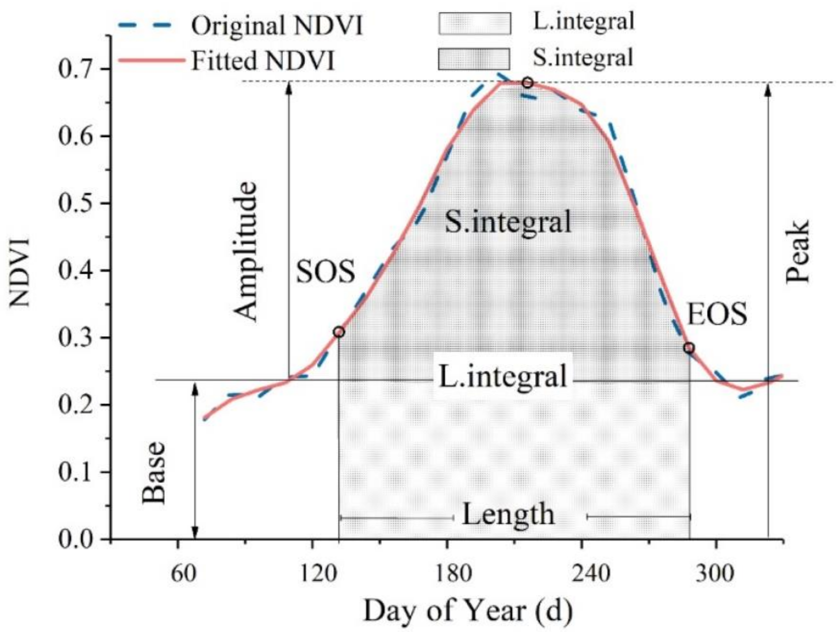


Phenometrics derived from **a) raw NDVI**; **b)** smoothed NDVI using a **Savitzky-Golay** filter; **c)** smoothed NDVI using a **double logistic function**; and **d)** smoothed NDVI using an **asymmetric Gaussian function**. A **20% threshold-based method** was used to extract SOS and EOS. These phenometrics are expressed in Julian days. The selected pixel is representative of a deciduous broadleaf forest (42° 22′ 13.207″ N; 02° 55′8.891″ W). Adapted from Caparros-Santiago et al., (2021).

THRESHOLD-BASED TECHNIQUE

SOS is defined as the date (e. g., day of the year; DOY) on which the pre-processed VI reaches a specific upward threshold before maximum, whilst the **EOS** date is defined as the point at which the adjusted curve crosses a specific downward threshold after maximum. These thresholds can be:

- **Relative thresholds:** **SOS** and **EOS** are defined as the moment when the smoothed VI trajectory reaches a percentage of the amplitude between a specific minimum level (e. g., base level; given as the average of the left and right minimum values) and the maximum value (Jönsson and Eklundh, 2002).
- **Absolute thresholds:** **SOS** and **EOS** are defined as the timing when the smoothed VI curve reached a specific absolute VI value (e. g., SOS = 0.52, EOS = 0.56) (Du et al., 2014)).
- **Thresholds based on VI ratio**: **SOS** and **EOS** are defined as the time when the smoothed VI curve reached a VI ratio. This threshold is based on a relationship between maximum and minimum VI values (Piao et al., 2006).

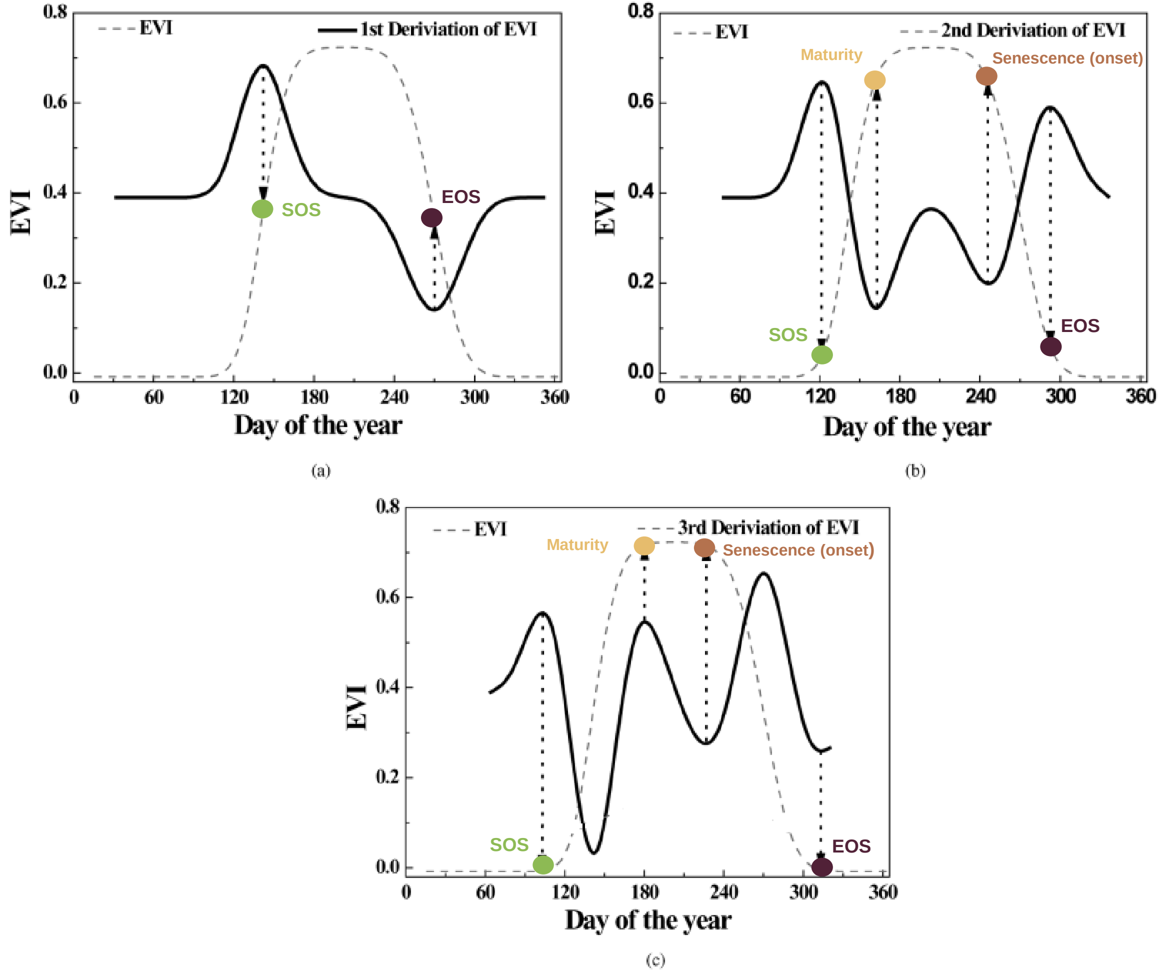


Example of the extraction of phenometrics from a **relative threshold-based technique**. **SOS** was defined as the timing (DOY) when the smoothed NDVI curve reached the 25% of its amplitude in upward direction before maximum, while the **EOS** was defined as the date (DOY) at which the smoothed NDVI curve fell to 25% of the amplitude after maximum. Extracted from Ma et al. (2020).

Ma, J., Zhang, C., Guo, H., Chen, W., Yun, W., Gao, L., & Wang, H. (2020). Analyzing ecological vulnerability and vegetation phenology response using NDVI time series data and the BFAST algorithm. Remote Sensing, 12, 1-21

II. LAND SURFACE PHENOLOGY ESTIMATION

5. PHENOMETRIC EXTRACTION



Example of the extraction of phenometrics from a **first (a), second (b) and third (c) derivative-based technique.**

DERIVATIVE-BASED TECHNIQUES

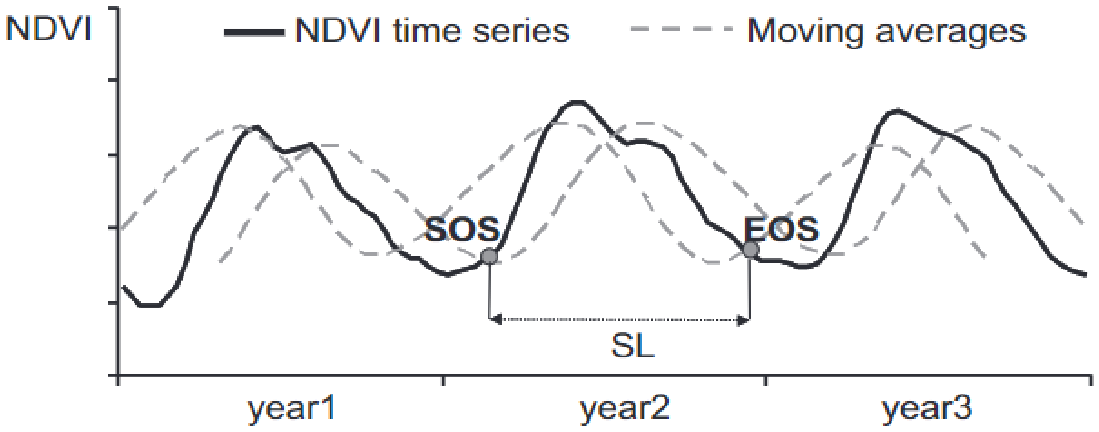
- The local maximum and minimum of the **FIRST DERIVATIVE** curve corresponds to the maximum rate of increase and decrease of the corresponding **greenup** (**SOS**) and **browndown** (**EOS**) processes.

- The local maximums of the **SECOND DERIVATIVE** curve correspond to the **beginning of the greenup** (**SOS**) (before maximum value of the VI) and the **end of browndown** (**EOS** or dormancy) (after maximum value of the VI)**.** The local minimums of the second derivative curve correspond to the **end of greenup** (maturity) (before maximum value of the VI) and the **beginning of the browndown** (onset of senescence) (after maximum value of the VI)**.**

- The local maximums of the **THIRD DERIVATIVE** curve before maximum VI value corresponds to the **beginning of greenup** (**SOS**) and the **end of greenup** (maturity). The local minimums of the third derivative curve after maximum VI value correspond to the **beginning of the browndown** (onset of senescence), and the **end of browndown** (**EOS** or dormancy).

Tan, B., et al. (2011). An Enhanced TIMESAT Algorithm for Estimating Vegetation Phenology Metrics From MODIS Data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 4, 361-371

AUTOREGRESSIVE MOVING AVERAGE TECHNIQUE

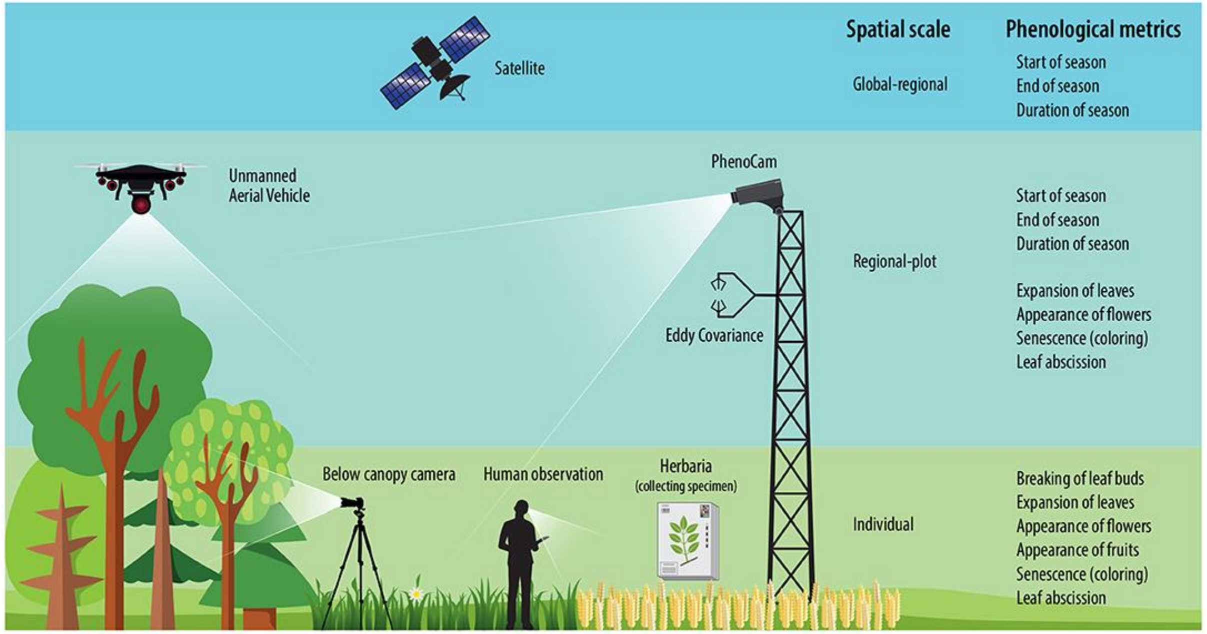


Example of the extraction of phenometrics from **autoregressive moving average technique**.

- **SOS** and **EOS** are determined for each pixel as the intersections of the reference time-series and the forward and backward lagged moving average curves respectively.

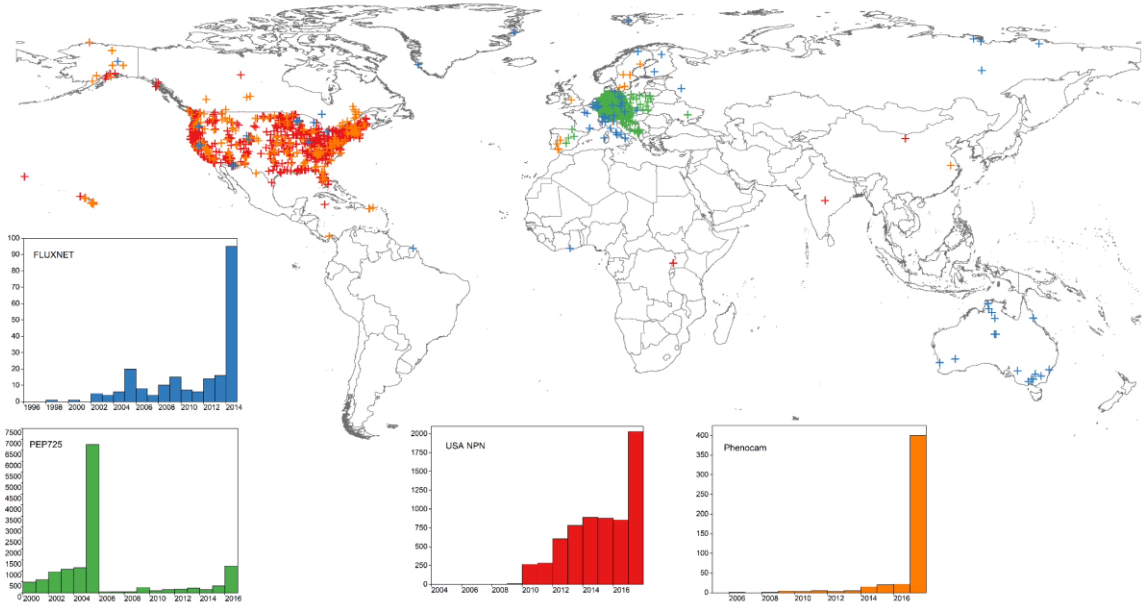
Ivits, E., et a. (2012). Combining satellite derived phenology with climate data for climate change impact assessment. Global and Planetary Change, 88-89, 85-97

6. VALIDATION / INTERCOMPARISON



Overview of phenological approaches.

Katal, N., Rzanny, M., Mäder, P., & Wäldchen, J. (2022). Deep Learning in Plant Phenological Research: A Systematic Literature Review. Frontiers in Plant Science, 13



Spatial distribution of phenological observation stations.

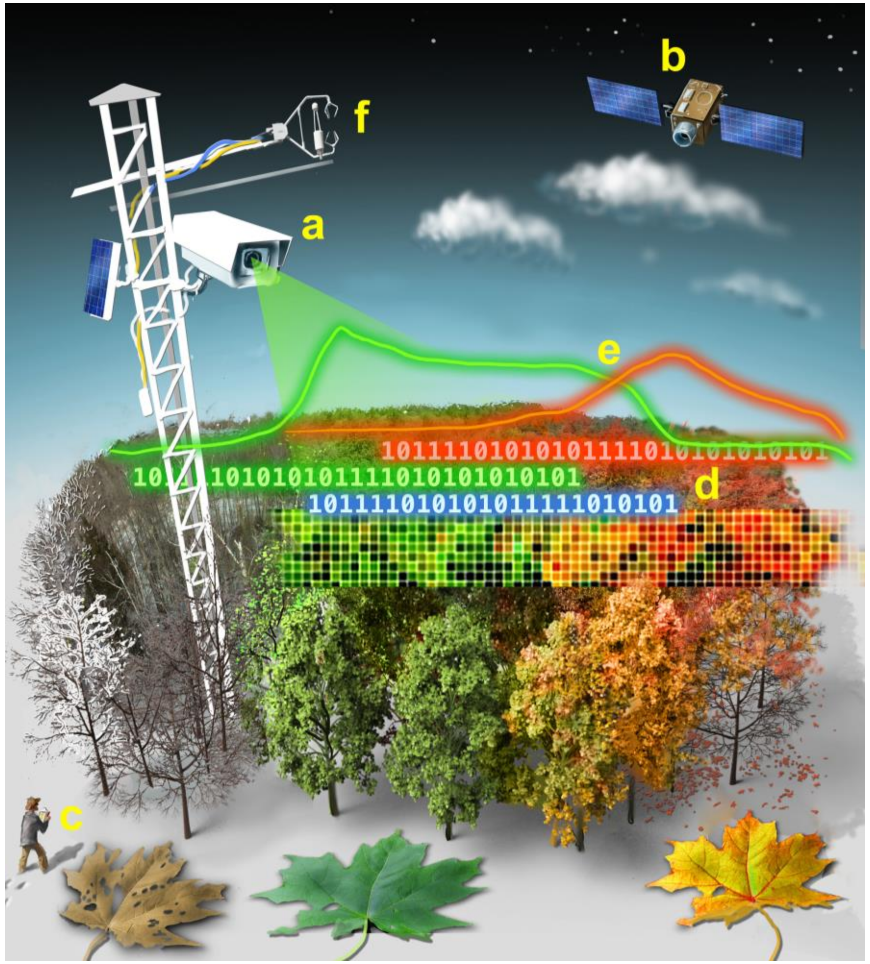
In situ human observations	Phenology cameras	CO_2 flux measurements	LSP

Approach

Scale

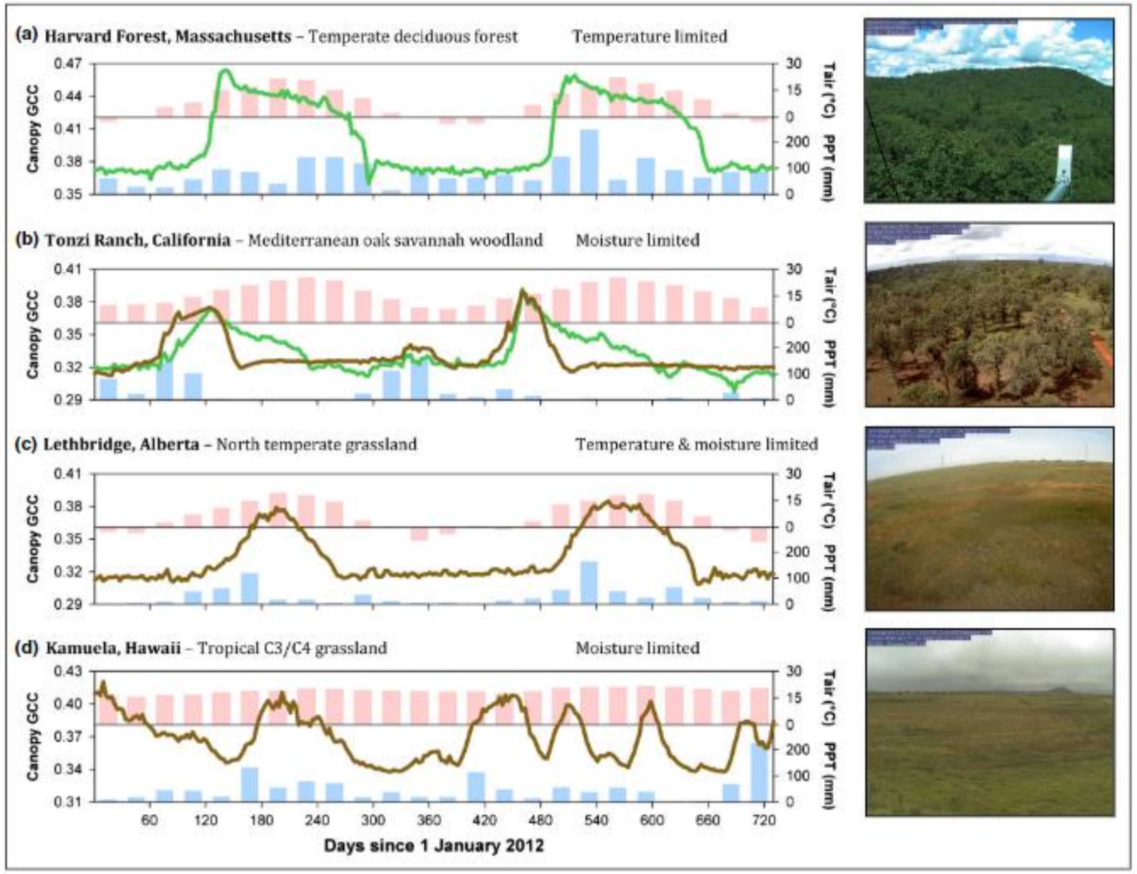
Individual Plant	Plant community	Plant community	Landscape level

Phenological approaches. Adapted from Caparros-Santiago et al. (2021).



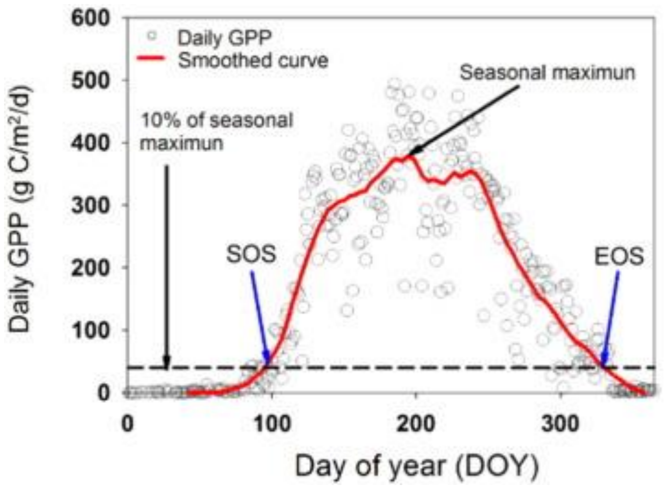
Overview of phenocam.

Richardson, A.D. (2019). Tracking seasonal rhythms of plants in diverse ecosystems with digital camera imagery. New Phytologist, 222, 1742-1750



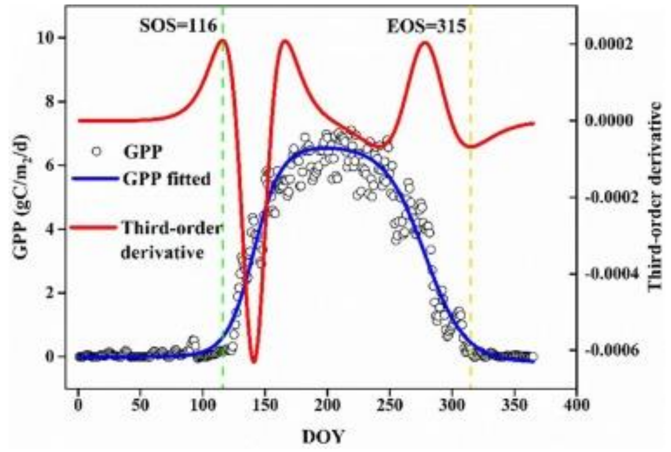
Vegetation canopy greenness, as quantified by green chromatic coordinate (GCC) using PhenoCam imagery, in relation to seasonal patterns of monthly precipitation (blue bars) and air temperature (red bars). Lines correspond to GCC for trees (green) and grasses (brown) in camera field of view (FOV)..

Brown, T.B., et al. (2016). Using phenocams to monitor our changing earth: Toward a global phenocam network. *Frontiers in Ecology and the Environment, 14*, 84-93



The schematic representation for calculating land surface phenology (SOS and EOS) from daily gross primary productivity (GPP) at SK-OBS in 2005. Phenometrics are extracted using a threshold-based method.

Liu, Y., et a. (2016). Improved modeling of land surface phenology using MODIS land surface reflectance and temperature at evergreen needleleaf forests of central North America. Remote Sensing of Environment, 176, 152-162



An example for determining the phenology based on daily GPP time series using double logistic growth model. The daily GPP and fitted GPP time series were plotted by black circles and the solid blue line. The curvature represented the third derivative of the fitted GPP time series (red line-right axis). SOS and EOS were plotted with horizontal lines. Phenometrics are extracted using a third derivative-based method.

Zhou, L., et al. (2022). Land surface phenology detections from multi-source remote sensing indices capturing canopy photosynthesis phenology across major land cover types in the Northern Hemisphere. Ecological Indicators, 135, 108579

	BBCH	Description			
	61	Beginning of flowering: about 10% of flowers open	Début de la floraison : environ 10% des fleurs sont ouvertes	Comienzo de la floración: aproximadamente el 10% de las flores están abiertas	Blühbe-ginn; 10% der Blüten offen
	65	Full flowering: at least 50% of flowers open, first petals falling	Pleine floraison: au minimum 50% des fleurs épanouies, les premiers pétales tombent	Plena floración: por lo menos 50% de las flores están abiertas, los primeros pétalos caen	Vollblüte; 50% der Blüten offen
	67	Flowers fading: majority of petals fallen	La floraison s'achève, la plupart des pétales sont tombés	Se termina la floración, la mayoría de los pétalos han caído	Abgehende Blüte, mei-sten Blü-tenblätter abgefallen
	69	End of flowering: all petals fallen	Fin de floraison: tous les pétales sont tombés	Final de floración: todos los pétalos se han caído	Blühende, alle Blü-tenblätter abgefallen
	72	Green ovary surrounded by dying sepal crown, sepals beginning to fall	Ovaire vert entouré de sépales fanés, les premiers sépales tombent	Ovario verde rodeado de una corona de sépalos marchitos, los primeros sépalos caen	Grüner Fru-chtknoten von abster-benden Kel-chblattkranz umgeben
	85	Maturity base on colouring	Maturité évaluée par la couleur	Maduración basada en el color del fruto	Fortgeschritt ene Frucht-ausfärbung
	92	Senescence: Leaves begin to discolour, at least 10% of yellow leaves	Sénescence : début de décoloration des feuilles, au moins 10% de feuilles jaunes	Senescencia: Inicio de la decoloración de las hojas, por lo menos 10% de hojas amarillas	Beginn der Laubblatt-verfärbung

Developmental stages for cherry.

Wenden, B., et al (2017). Harmonisation of phenology stages and selected cherry cultivars as bioindicators for climate change. In, Acta Horticulturae (pp. 9-12)

A = dormant bud.
B = leaf bud swelling.
C = first leaves separating.
D = first leaves unfolded.
E = more leaves unfolded.
F = all leaves unfolded.
G = beginning of shoot growth.
H = shoots reached 90% of final length.
I = leaves start to fade color.
J = beginning of senescence.
K = 50% of leaves are fallen.
L = leaves fall ending.

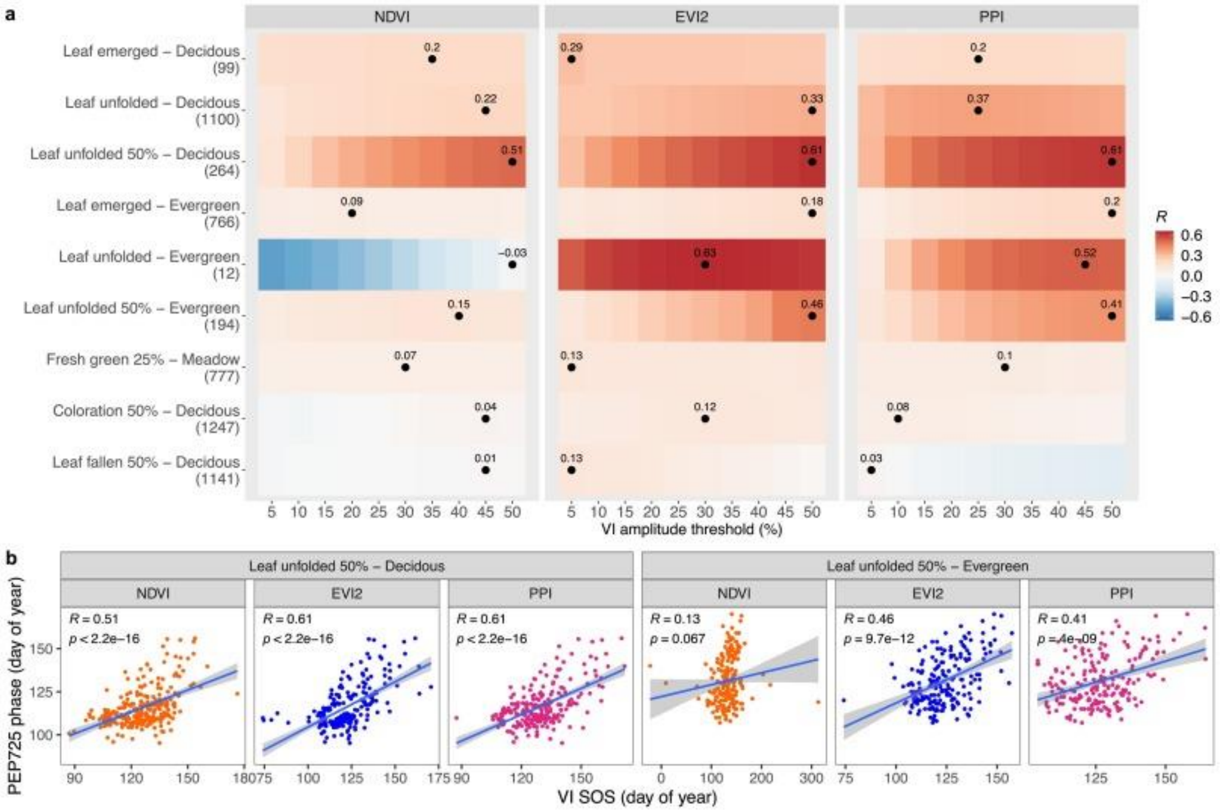
Credit: Brian Powell

Sakar, E.H., El Yamani, M., Boussakouran, A., & Rharrabti, Y. (2019). Codification and description of almond (Prunus dulcis) vegetative and reproductive phenology according to the extended BBCH scale. Scientia Horticulturae, 247, 224-234

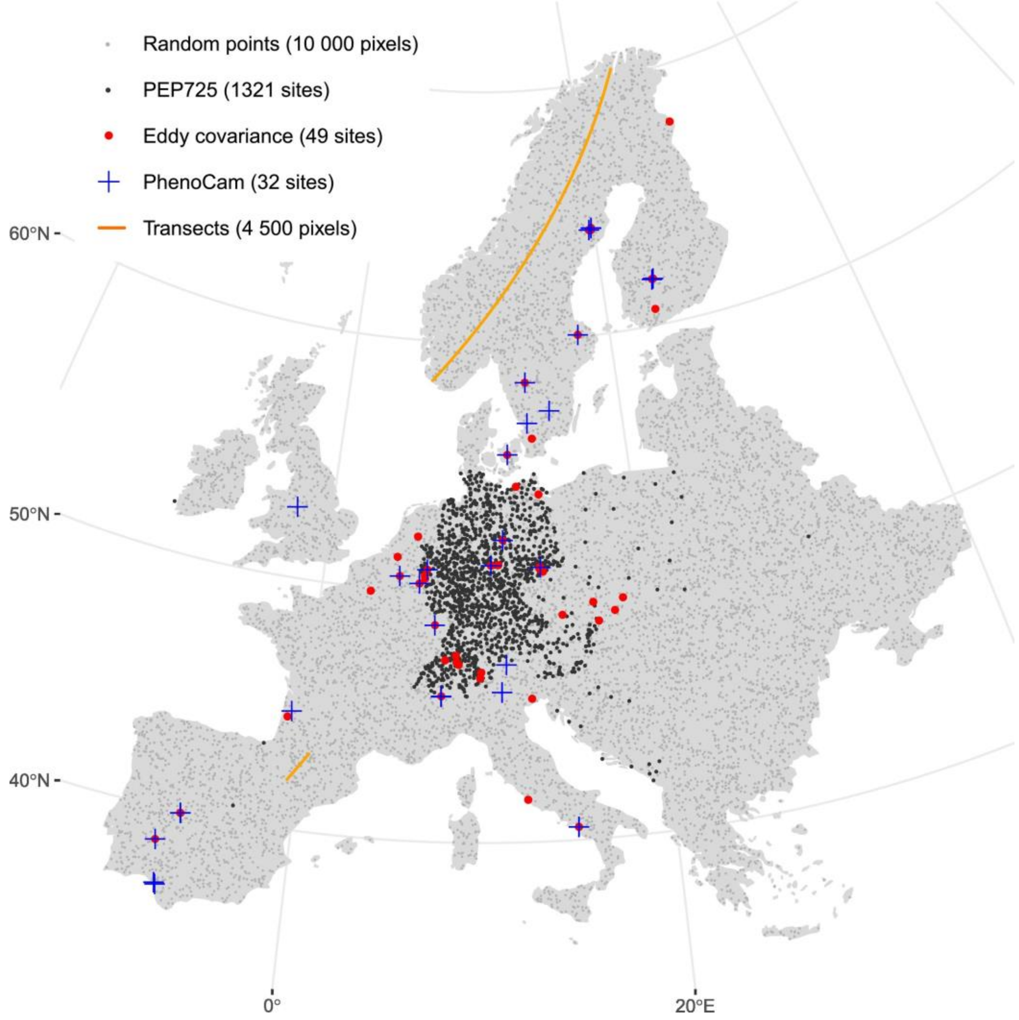
Illustrations of vegetative phenology of almond (*Prunus dulcis*) according to BBCH scale.

II. LAND SURFACE PHENOLOGY ESTIMATION

6. VALIDATION / INTERCOMPARISON

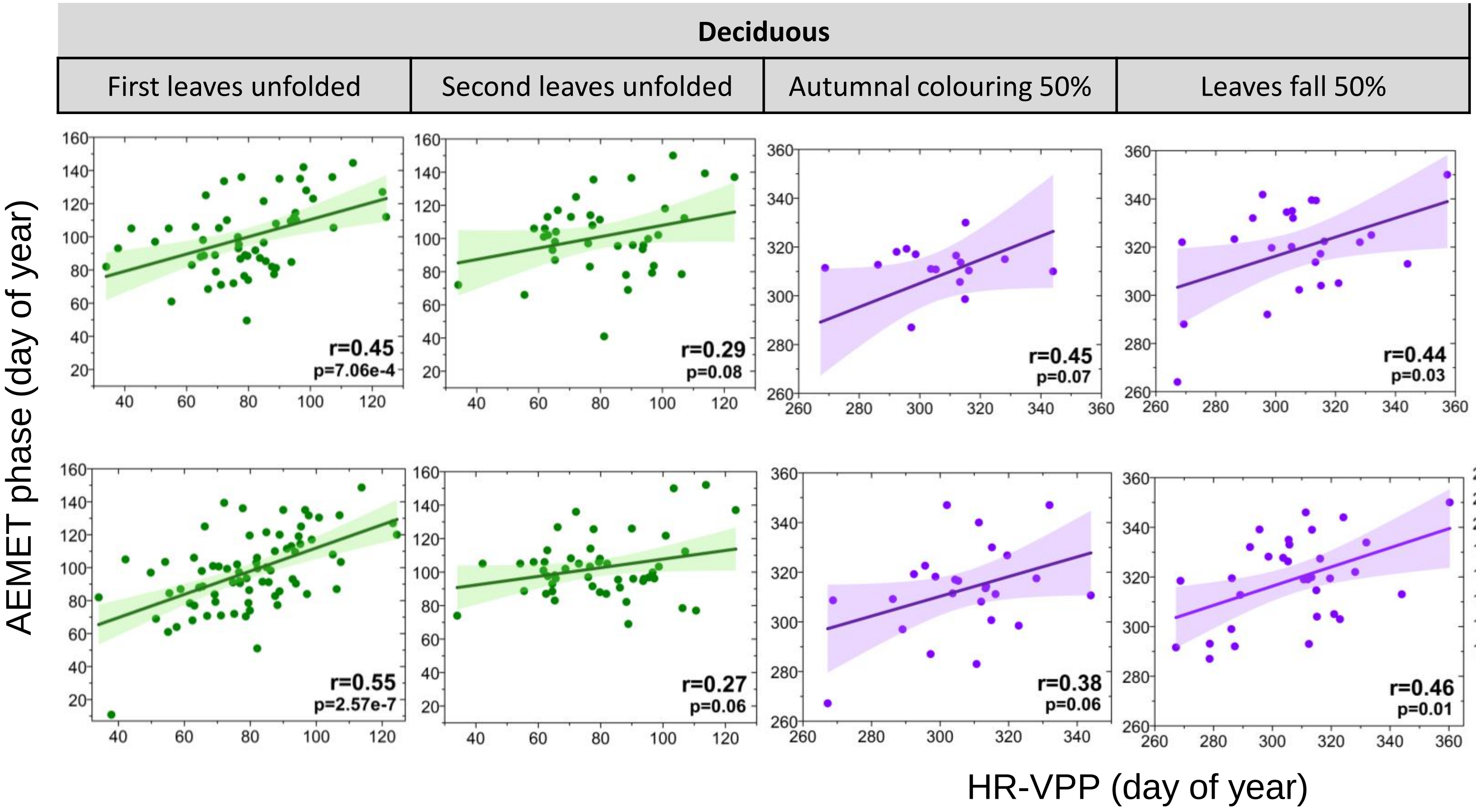


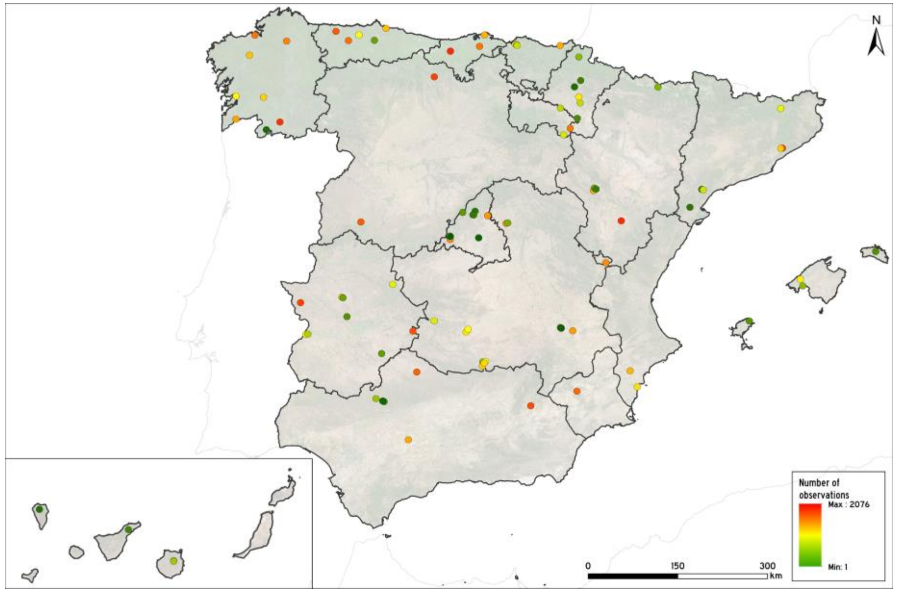
Spatial correlation between paired PEP725 and VI phases. (a) Heatmap matrix showing the R values at varying VI thresholds. The number of sites containing each paired **PEP725** and **Sentinel-2** phase is labeled on the y-axis. (b) Scatterplots with linear regression lines of the leaf unfolded 50% phase for deciduous broad-leaved trees and evergreen coniferous trees at VI threshold 50% (for illustration purpose)

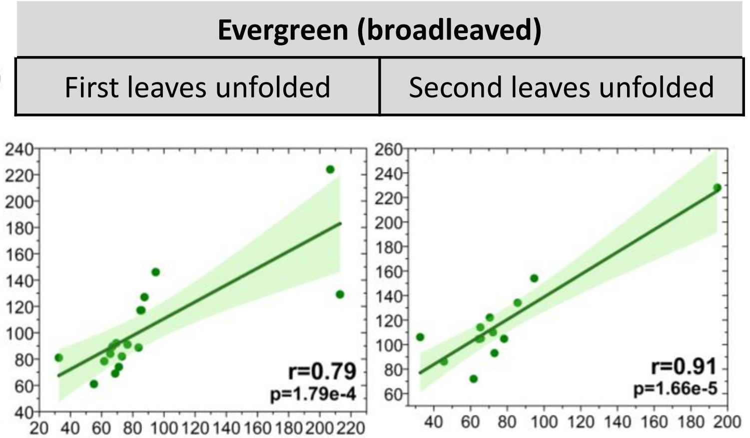


Tian, F., et al. (2021). Calibrating vegetation phenology from Sentinel-2 using eddy covariance, PhenoCam, and PEP725 networks across Europe. Remote Sensing of Environment, 260

Rodriguez-Galiano et al. (in prep)

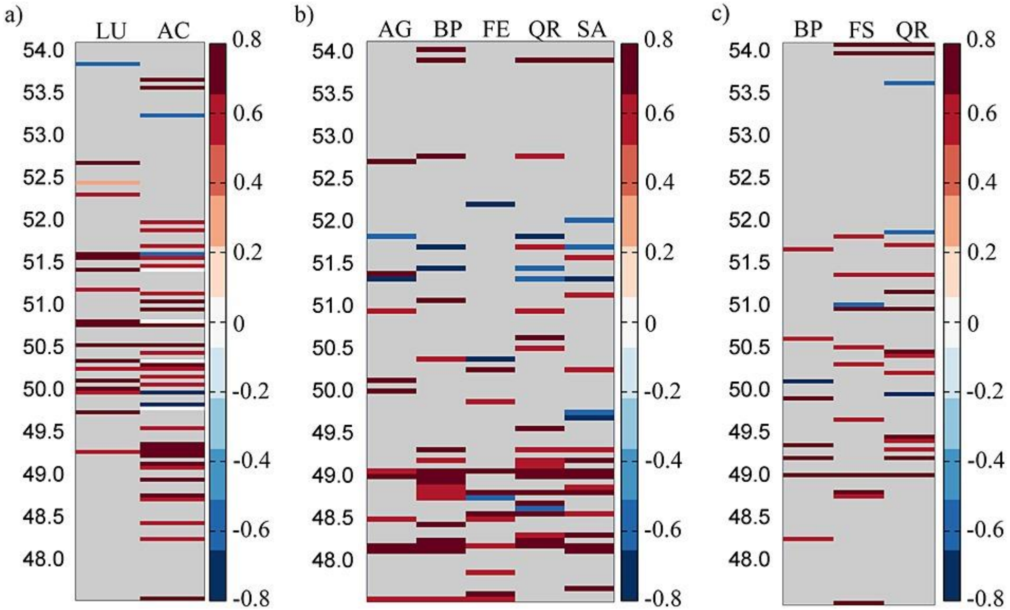






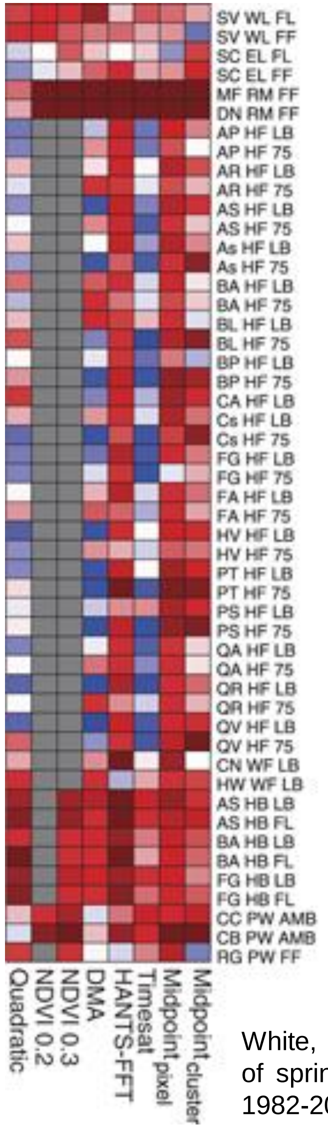
II. LAND SURFACE PHENOLOGY ESTIMATION

6. VALIDATION / INTERCOMPARISON



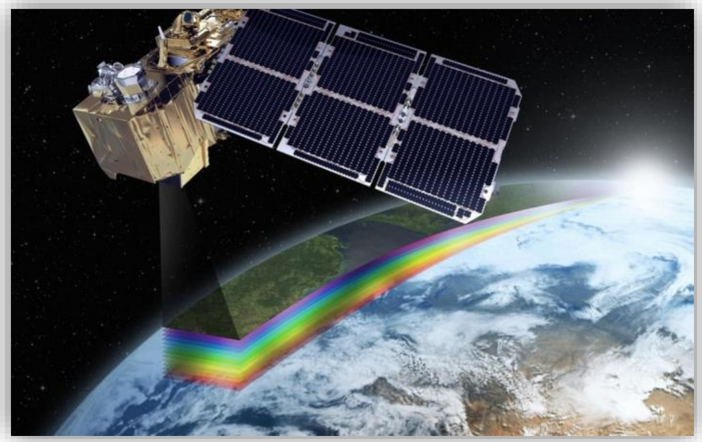
Averaged Pearson's product-moment correlation coefficients between GP (in situ human observation) and LSP estimates at every 0.5 of latitude. (a) First column shows the results of regressions between OG (SOS) LSP and leaf unfolding (LU) of a species mixture; second column shows the results of regressions between EOS LSP and autumnal coloring (AC) of species mixture. (b) Correlation coefficients between OG LSP and LU of different deciduous tree species: AG, *Alnus Glutinosa*; BP, *Betula Pendula*; FE, *Fraxinus Excelsior*; QR, *Quercus Robur*; and SA, *Sorbus Aucuparia*. (c) Correlation coefficients between EOS LSP and AC of different deciduous tree species: BP, *Betula Pendula*; FS*, Fagus Sylvatica*; and QR, *Quercus Robur*.

Rodriguez-Galiano, et al.. (2015). Intercomparison of satellite sensor land surface phenology and ground phenology in Europe. GRL 42(7), pp. 2253-2260



White, M.A., et al. (2009). Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982-2006. GCB, 15, 2335-2359

II. LAND SURFACE PHENOLOGY: A LITERATURE REVIEW



ISPRS Journal of Photogrammetry and Remote Sensing 171 (2021) 330–347

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

ELSEVIER

Review Article

Land surface phenology as indicator of global terrestrial ecosystem dynamics: A systematic review

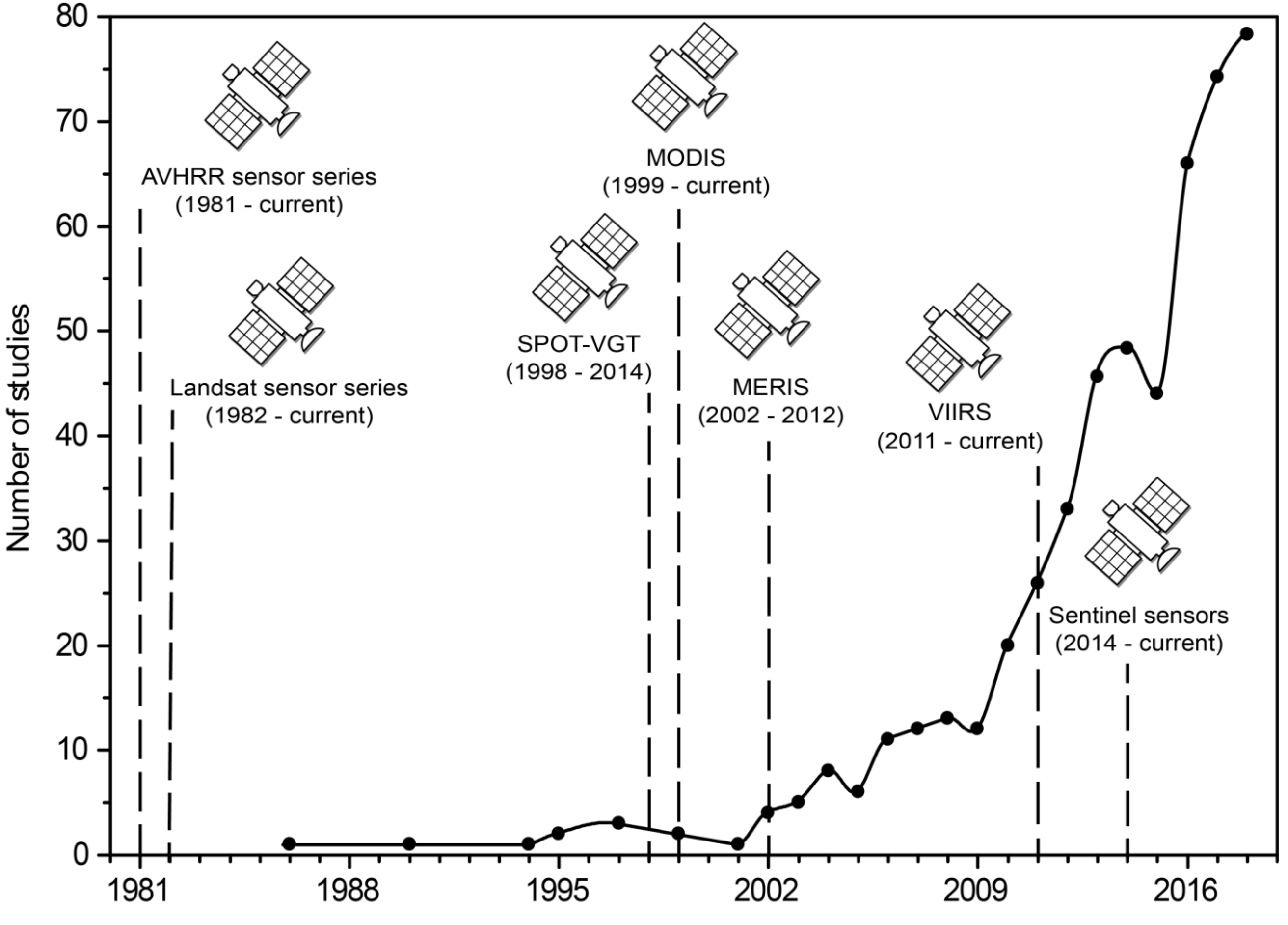
Jose A. Caparros-Santiago [a], Victor Rodriguez-Galiano [a,*], Jadunandan Dash [b]

[a] Departamento de Geografía Física y Análisis Geográfico Regional, Universidad de Sevilla, Seville 41004, Spain
[b] School of Geography and Environmental Science, University of Southampton, Southampton SO17 1BJ, United Kingdom

I. NUMBER AND SPATIAL DISTRIBUTION OF LAND SURFACE PHENOLOGY STUDIES

- Before 2000's: 10 studies
- Between 2000-2010: 72
- Between 2010-2019: 435

- Reasons for this:
  - 40 years of data from AVHRR
  - 20 years of data from MODIS
  - Improved temporal resolution of Sentinel-2 (5 days)



Number of LSP studies from 1980 onwards and timeline of the primary satellite sensors used by said studies. Only sensors used in more than 5 publications are represented.

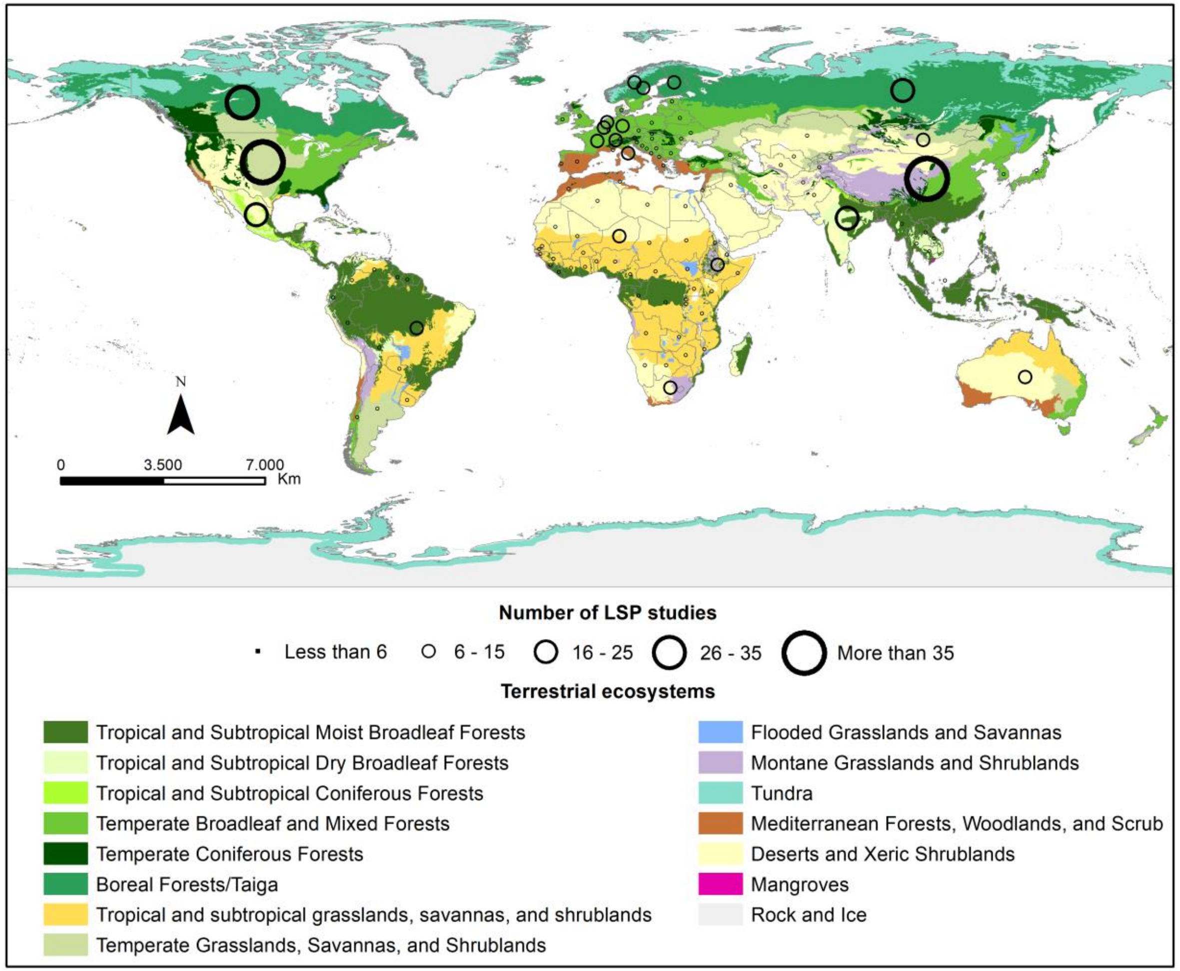
I. NUMBER AND SPATIAL DISTRIBUTION OF LAND SURFACE PHENOLOGY STUDIES

AVIGNON
20-24 JUNE
2022



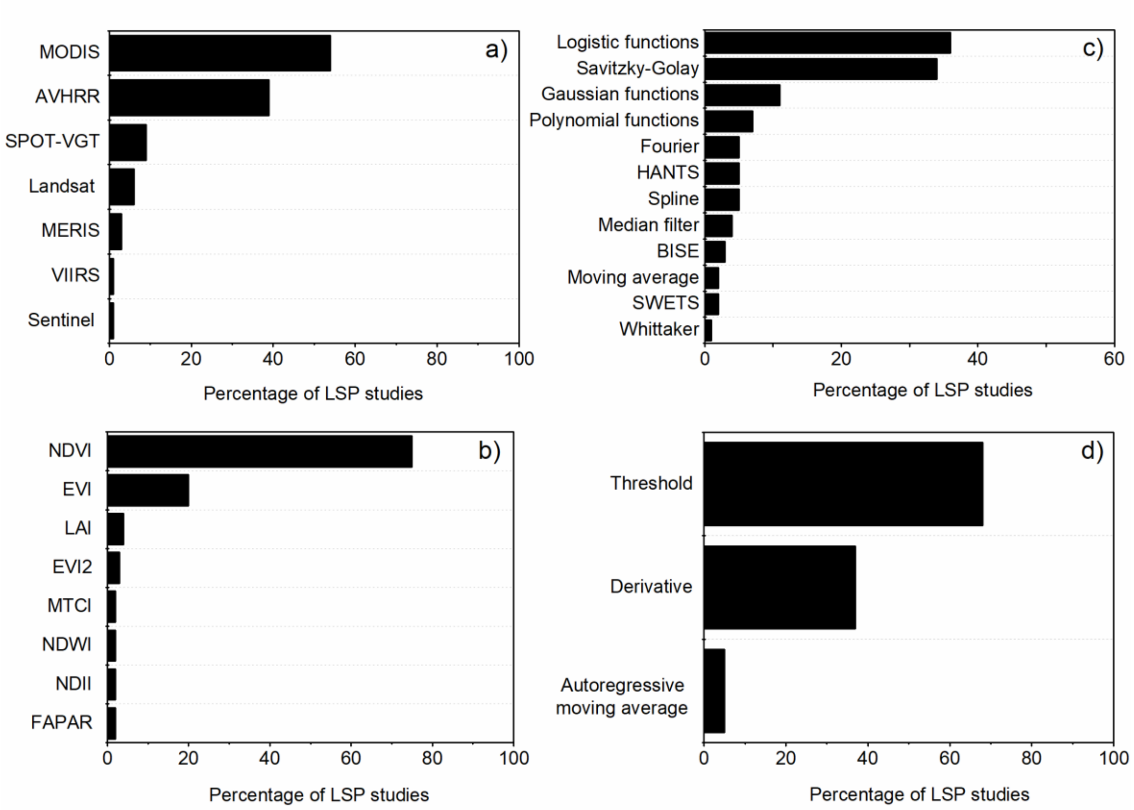




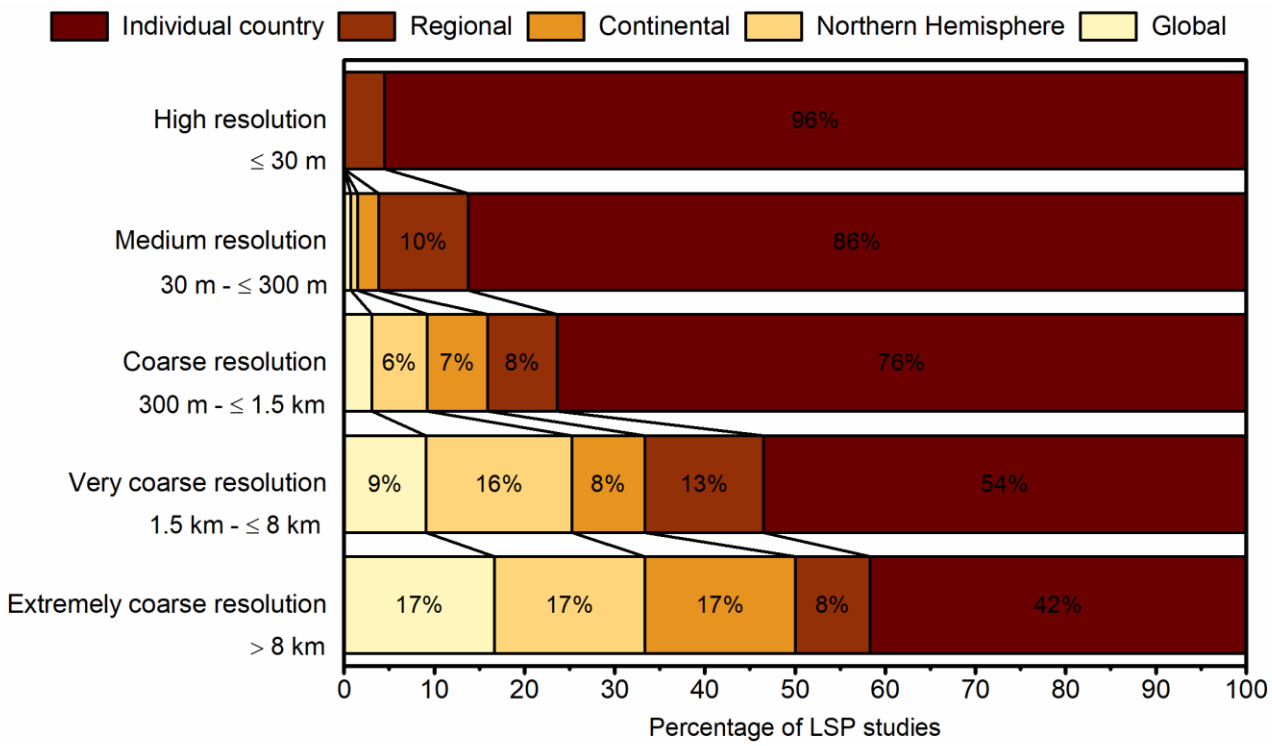


Spatial distribution of LSP studies. This maps is based on the ecosystem classification proposed by Olson et al. (2001).

- Boreal and temperate ecosystems are well documented
- Some mid latitude ecosystems highly susceptible to the effect of climate (increasing heat waves and droughts) change are not studied in great detail such as the Mediterranean ecosystems.
- Knowledge of LSP dynamics in a significant portion of tropical ecosystems also remains limited (tropical rainforest: Central and South America, Central Africa or Southeast Asia.
- Tropical or subtropical dry forests, savannahs and croplands were the most-studied tropical ecosystems due to their better-defined vegetation seasonality.

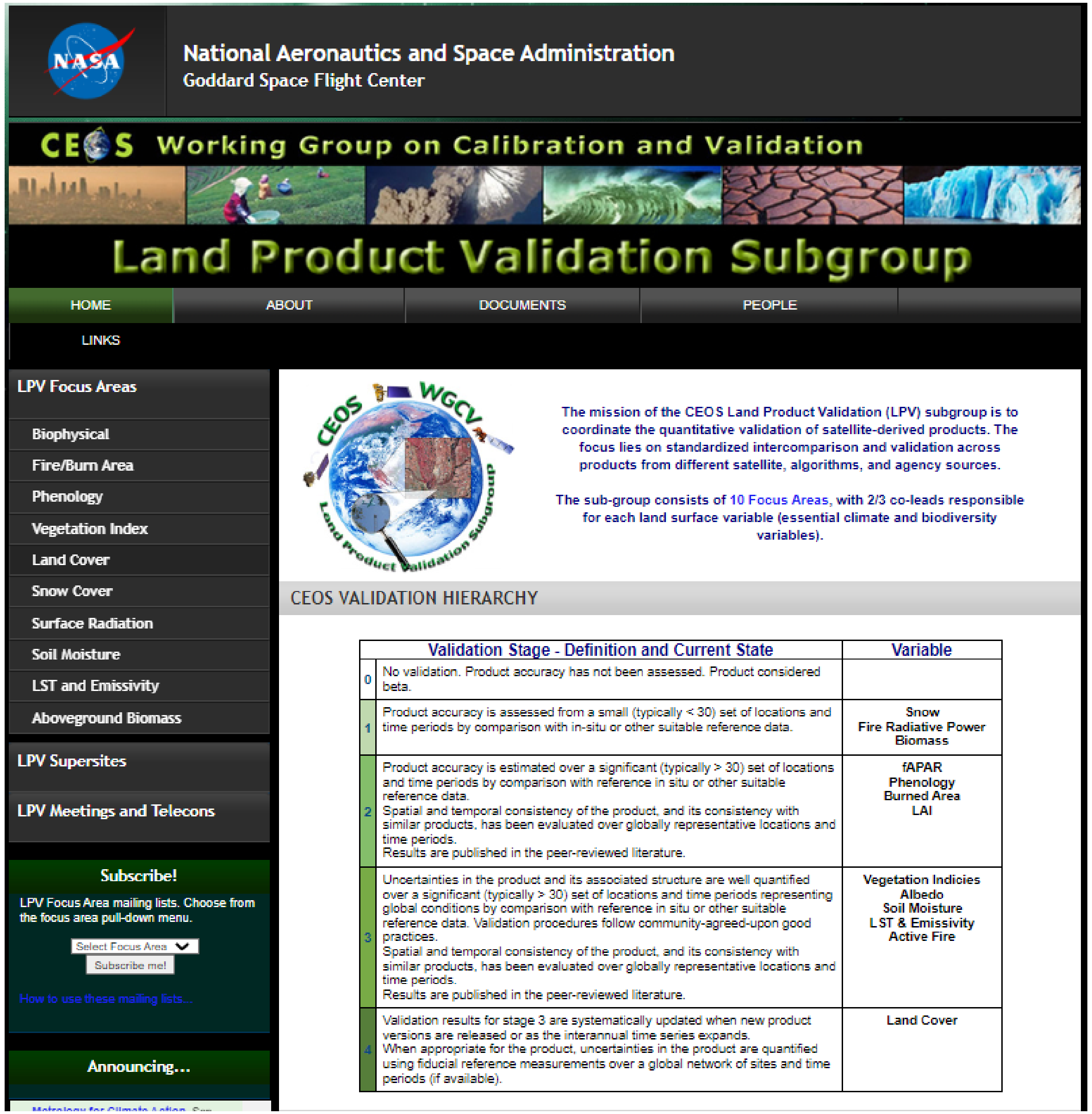


Percentage of LSP studies using: a) sensors; b) VI or biophysical variables; c) smoothing techniques; d) phenometric extraction methods..



Relationship between spatial resolution and the geographic coverage of study areas for different LSP studies..

III. CEOS LPV phenology subgroup



	Validation Stage - Definition and Current State	Variable
0	No validation. Product accuracy has not been assessed. Product considered beta.	
1	Product accuracy is assessed from a small (typically < 30) set of locations and time periods by comparison with in-situ or other suitable reference data.	Snow Fire Radiative Power Biomass
2	Product accuracy is estimated over a significant (typically > 30) set of locations and time periods by comparison with reference in situ or other suitable reference data. Spatial and temporal consistency of the product, and its consistency with similar products, has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature.	fAPAR Phenology Burned Area LAI
3	Uncertainties in the product and its associated structure are well quantified over a significant (typically > 30) set of locations and time periods representing global conditions by comparison with reference in situ or other suitable reference data. Validation procedures follow community-agreed-upon good practices. Spatial and temporal consistency of the product, and its consistency with similar products, has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature.	Vegetation Indicies Albedo Soil Moisture LST & Emissivity Active Fire
4	Validation results for stage 3 are systematically updated when new product versions are released or as the interannual time series expands. When appropriate for the product, uncertainties in the product are quantified using fiducial reference measurements over a global network of sites and time periods (if available).	Land Cover

- The mission of LPV is to coordinate the quantitative validation of satellite-derived products.
- The focus lies on standardized intercomparison and validation across products from different satellite, algorithms, and agency sources.
- The sub-group consists of 10 Focus Areas, with 2/3 co-leads responsible for each land surface variable (essential climate and biodiversity variables).
- The objectives of the Phenology LPV area are:
  - 1. To foster and coordinate quantitative validation of higher level (> Level 2) global land products derived from remotely sensed data.
  - 2. To increase the quality and efficiency of global satellite product validation by developing and promoting international standards and **protocols** for: field sampling, scaling techniques, accuracy reporting, and data and information exchange

Annual Phenology Metrics

MuSLI Land Surface Phenology, derived from Landsat-8/Sentinel-2 **Contact:** Mark Friedl **Institution:** Boston University	**Spatial Coverage:** North America **Temporal Coverage:** 2016-2019 **Spatial Scale:** 30 m **Temporal Scale:** Annual
Land Surface Phenology, derived from VIIRS **Contact:** Xiaoyang Zhang **Institution:** NASA GSFC *Link to validation information*	**Spatial Coverage:** Global **Temporal Coverage:** 2012-2018 **Spatial Scale:** 0.05 deg **Temporal Scale:** Annual
Land Surface Phenology, derived from VIIRS **Contact:** Xiaoyang Zhang **Institution:** NASA GSFC *Link to validation information*	**Spatial Coverage:** Global **Temporal Coverage:** 2012-2018 **Spatial Scale:** 500 m **Temporal Scale:** Annual
MODIS Land Cover Dynamics, derived from MODIS **Contact:** Josh Gray **Institution:** Boston University/NASA	**Spatial Coverage:** Global **Temporal Coverage:** 2001-2017 **Spatial Scale:** 500 m **Temporal Scale:** Annual
eMODIS Remote Sensing Phenology, derived from MODIS **Contact:** Jesslyn Brown **Institution:** USGS EROS	**Spatial Coverage:** Conterminous US **Temporal Coverage:** 2001-2017 **Spatial Scale:** 250 m **Temporal Scale:** Annual
Plant Phenology Index SOS & GSL, derived from MODIS **Contact:** Lars Eklundh **Institution:** EEA	**Spatial Coverage:** Europe & N. Africa **Temporal Coverage:** 2000-2016 **Spatial Scale:** 500 m **Temporal Scale:** Annual
Land Surface Phenology, derived from MODIS **Contact:** Alfredo Huete **Institution:** TERN	**Spatial Coverage:** Australia **Temporal Coverage:** 2000-2015 **Spatial Scale:** 0.05 deg **Temporal Scale:** Annual
ForWarn Land Surface Phenology, derived from MODIS **Contact:** William Hargrove **Institution:** USFS	**Spatial Coverage:** Conterminous US **Temporal Coverage:** 2000-2014 **Spatial Scale:** 500 m **Temporal Scale:** Annual
Land Surface Phenology, derived from AVHRR **Contact:** Jesslyn Brown **Institution:** USGS EROS	**Spatial Coverage:** Conterminous US **Temporal Coverage:** 1989-2014 **Spatial Scale:** 1000 m **Temporal Scale:** Annual
MEASURES VIP Phenology, derived from AVHRR & MODIS **Contact:** Kamel Didan **Institution:** University of Arizona	**Spatial Coverage:** Global **Temporal Coverage:** 1981-2014 **Spatial Scale:** 0.05 deg **Temporal Scale:** Annual

Phenology Focus Area Contributions to International Structures

Intergovernmental Platform on Biodiversity & Ecosystem Services (IPBES)

Land Surface Phenology is an Essential Biodiversity Variable (EBV), (Pereira, 2013).

Links to In Situ Phenology Measurement Networks

Best currently available in situ reference data for satellite-derived land surface phenology product validation are provided by networks based on the following measurements:

1. Species-specific phenological observations of bud-burst, flowering, etc.:
   - USA National Phenology Network
   - Pan European Phenology Project
   - Nature's Calendar (UK)
   - National Ecological Observatory Network (USA)
   - Nature Canada PlantWatch
   - ClimateWatch (Australia)
   - Swedish National Phenology Network
   - Project Budburst (USA)
2. Ground-based imaging/ continuous spectral measurements
   - USA Phenocam Network
   - European Phenology Camera Network
   - Phenologial Eyes Network
   - National Ecological Observatory Network (USA)
   - GeoPhoto Library at the University of Oklahoma
   - SPECNET - Lund University
   - NordSpec

Thanks for your attention!

vrgaliano@us.es