Earth Observation and Computer Vision for Agricultural and Forest Monitoring

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Plan

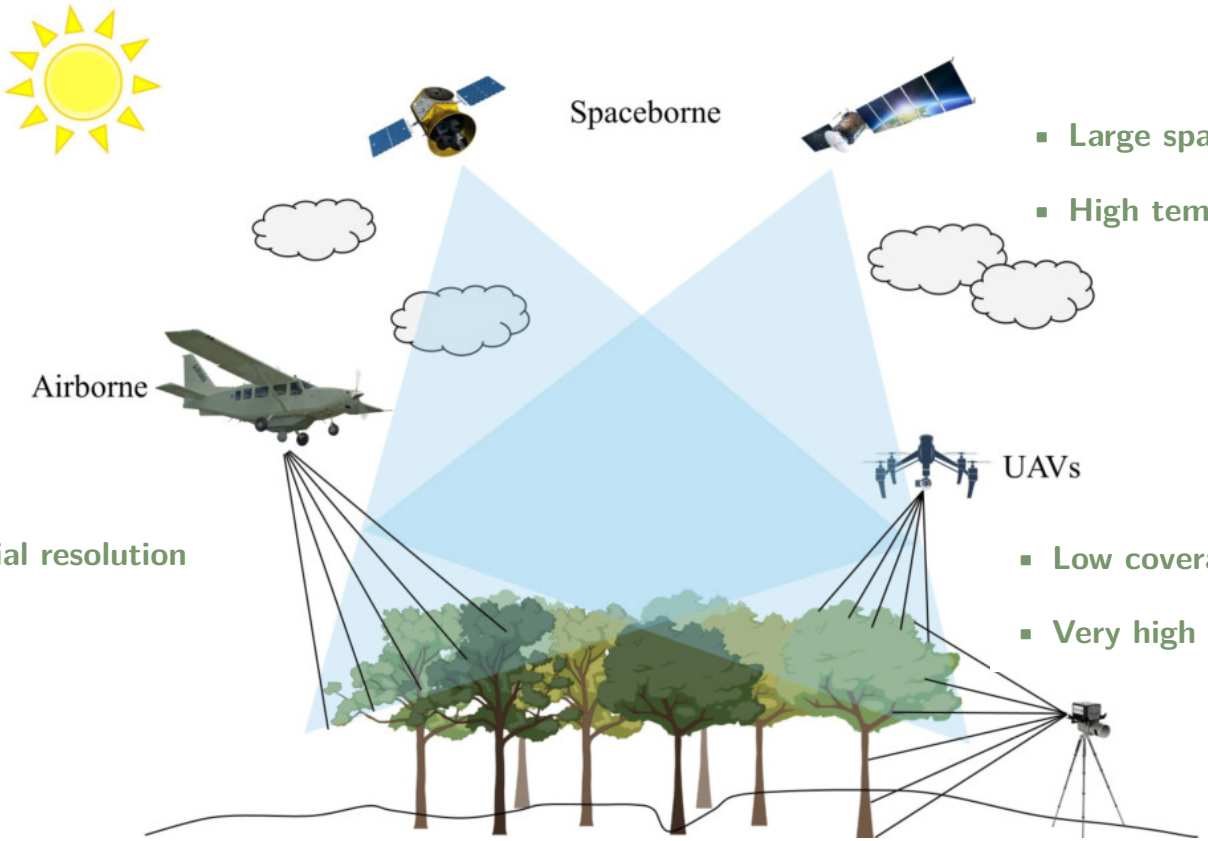
Course material

All course material is available online. Scan the QR code or click the link:

🔗 https://eo-computer-vision-course-9a2fe9.pages-forge.inrae.fr/cv-rs-index/

What is Earth Observation (Remote Sensing)?

- The science and art of acquiring information about the Earth's surface **without actually being in contact with it** using sensors onboard drones, aircraft, or satellites.



- Large spatial coverage
- High temporal revisit frequency
- Medium coverage
- High/very high spatial resolution
- Low coverage
- Very high spatial resolution

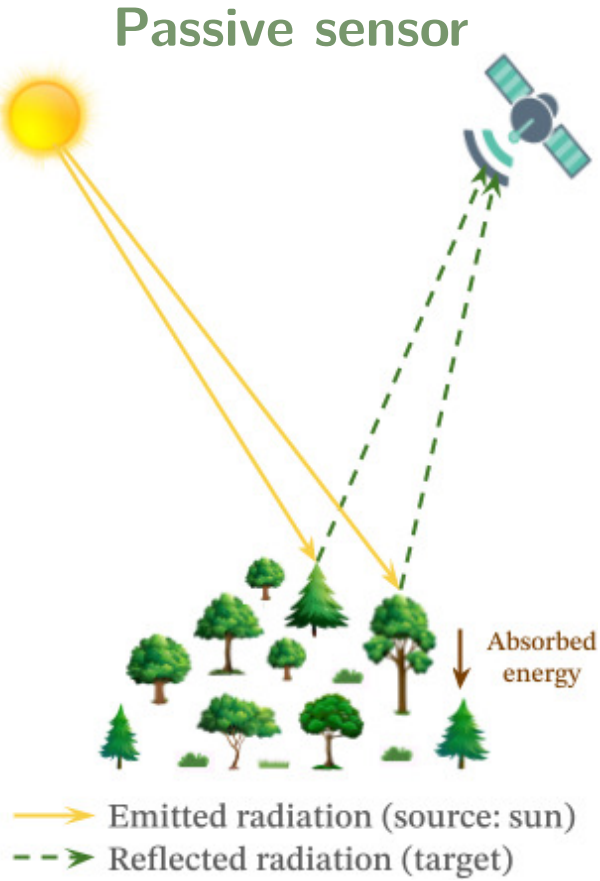
Source: adapted from Tian et al. (2023)

How does EO works?

- **Physical principle:** interaction between electromagnetic waves and the Earth's surface

How does EO works: active *versus* passive

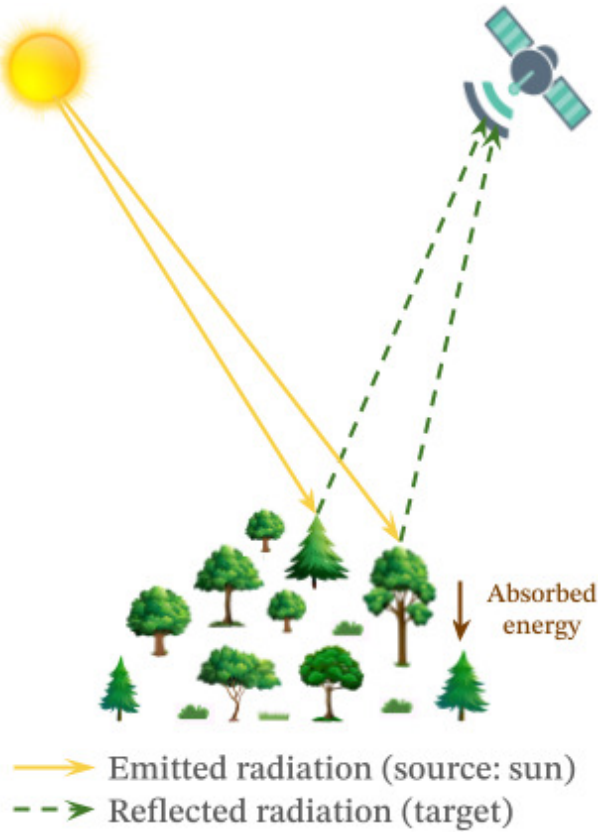
- **Two main acquisition modes**



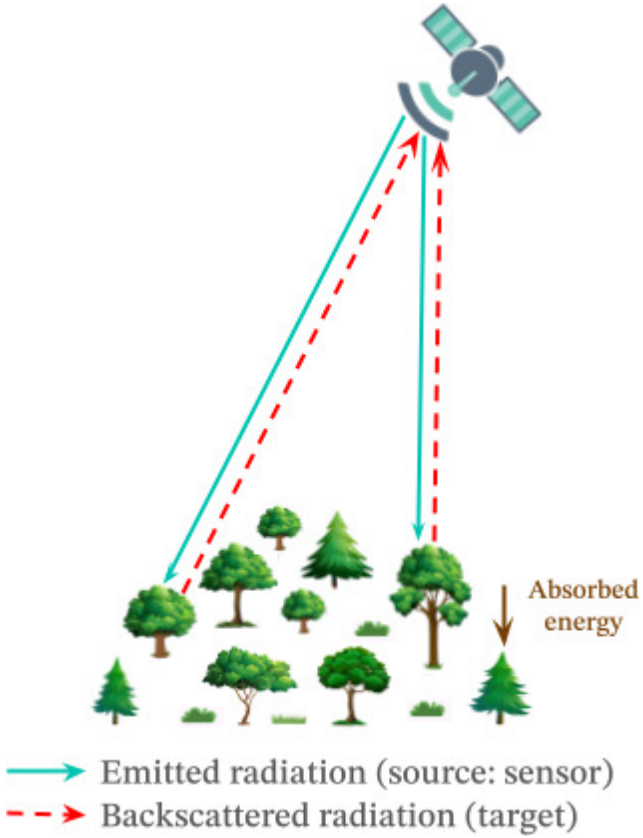
How does EO works: active *versus* passive

- **Two main acquisition modes**

Passive sensor

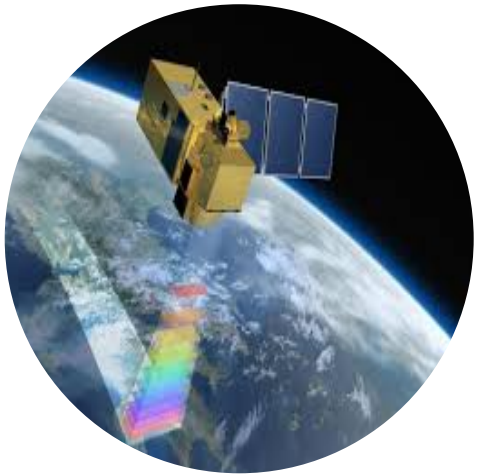


Active sensor

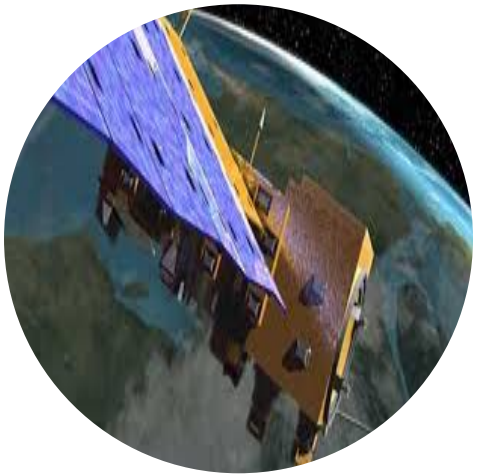


How does EO works: active *versus* passive

- Example of passive sensors:

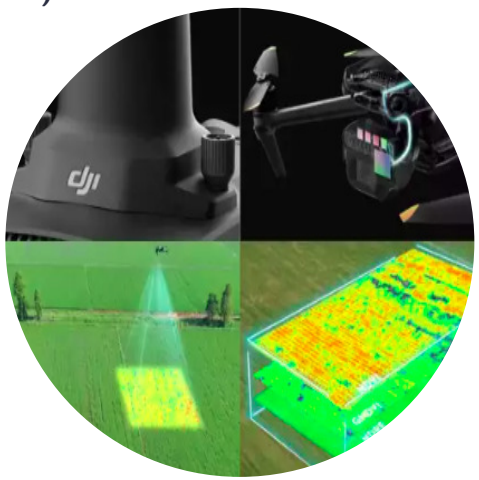


Sentinel-2 (MSI)

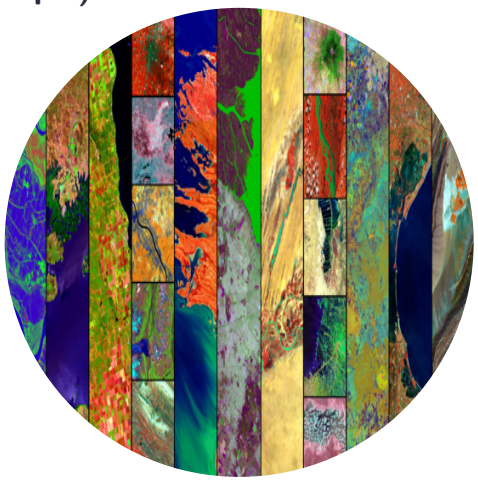


MODIS (Terra/Aqua)

Landsat 8/9 (OLI/TIRS)



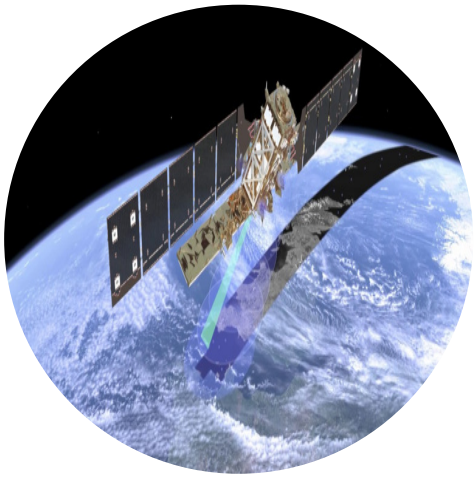
Multispectral camera onboard UAV



EnMAP hyperspectral sensor

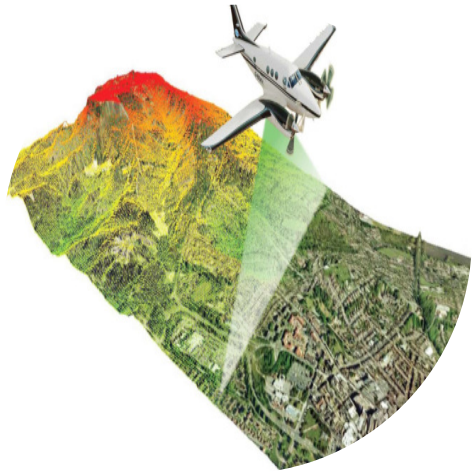
How does EO works: active *versus* passive

- Example of active sensors:



Sentinel-1 (Synthetic Aperture Radar)

GEDI (LiDAR)



Airborne LiDAR

How does EO works: the electromagnetic spectrum

🤔 Did you know?

Radar systems can see through clouds!

How does EO works: the electromagnetic spectrum

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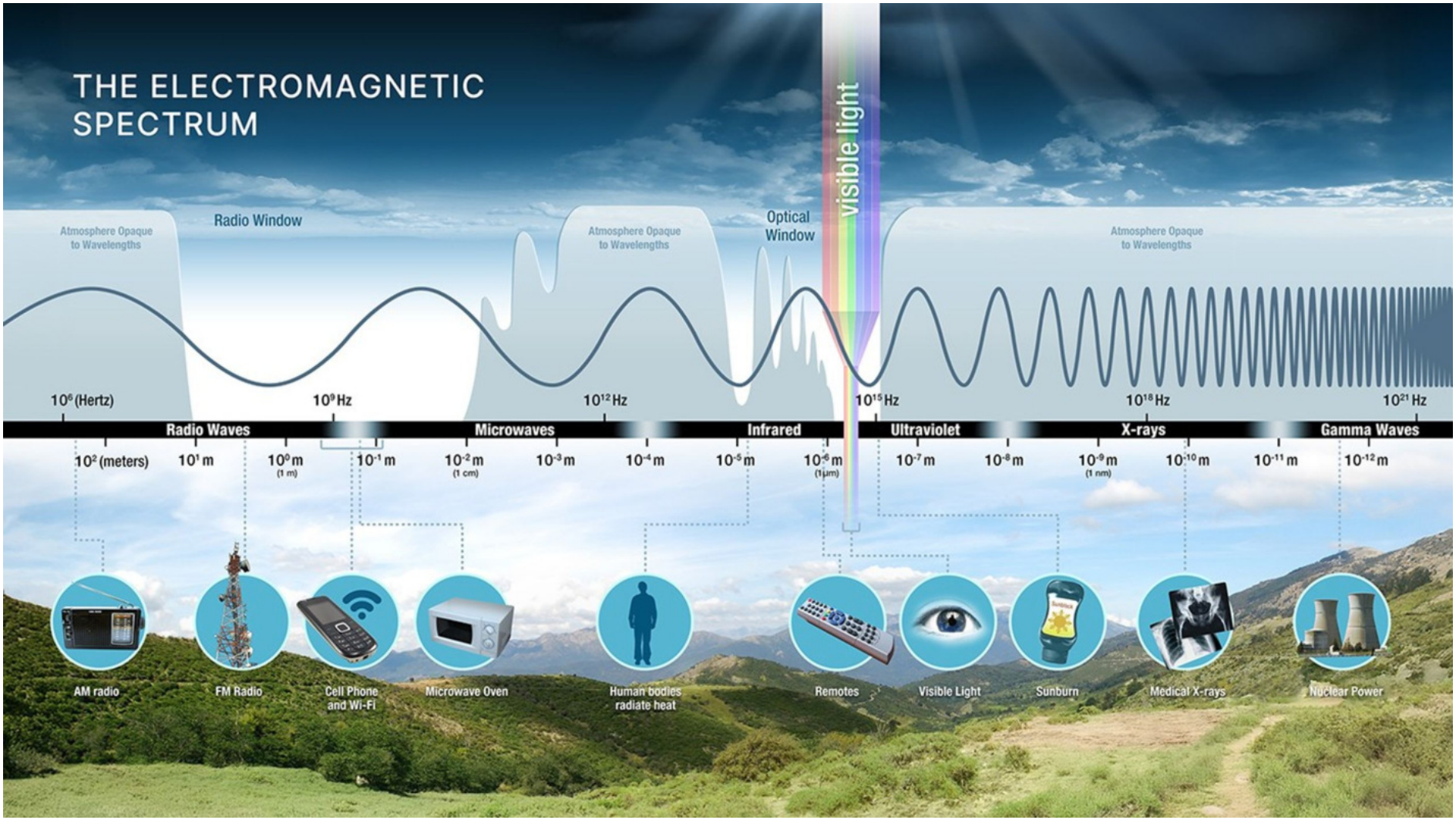
Radar systems can see through clouds!

It's all about the atmosphere
and the electromagnetic spectrum!

How does EO works: the electromagnetic spectrum



Source: NASA

🤔 Did you know?

Radar systems can see through clouds!

It's all about the atmosphere and the electromagnetic spectrum!

> The electromagnetic spectrum is the complete range of wavelengths (or frequencies) of electromagnetic radiation (EMR), subdivided into seven regions according to wavelength.

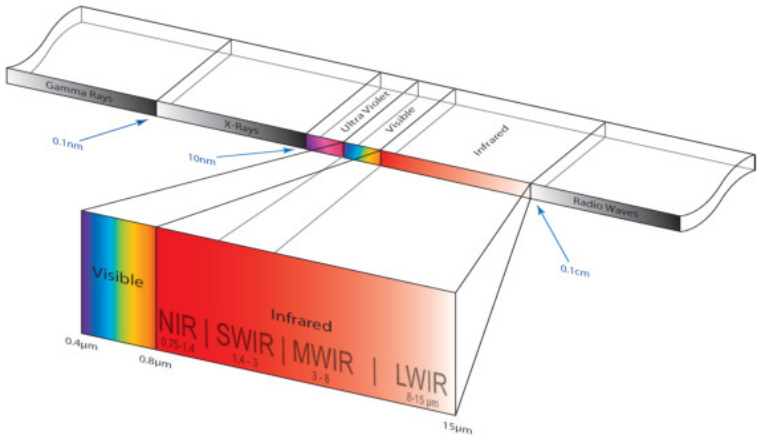
How does EO works: optical *versus* Radar

Optical: uses visible and infrared

Radar: uses microwaves

How does EO works: focus on the optical domain

- The **optical domain** refers to a part of the electromagnetic spectrum including:
  - Visible (VIS)
  - Near-Infrared (NIR)
  - Short-Wave Infrared (SWIR)



Source: AMETEK Land (2021)

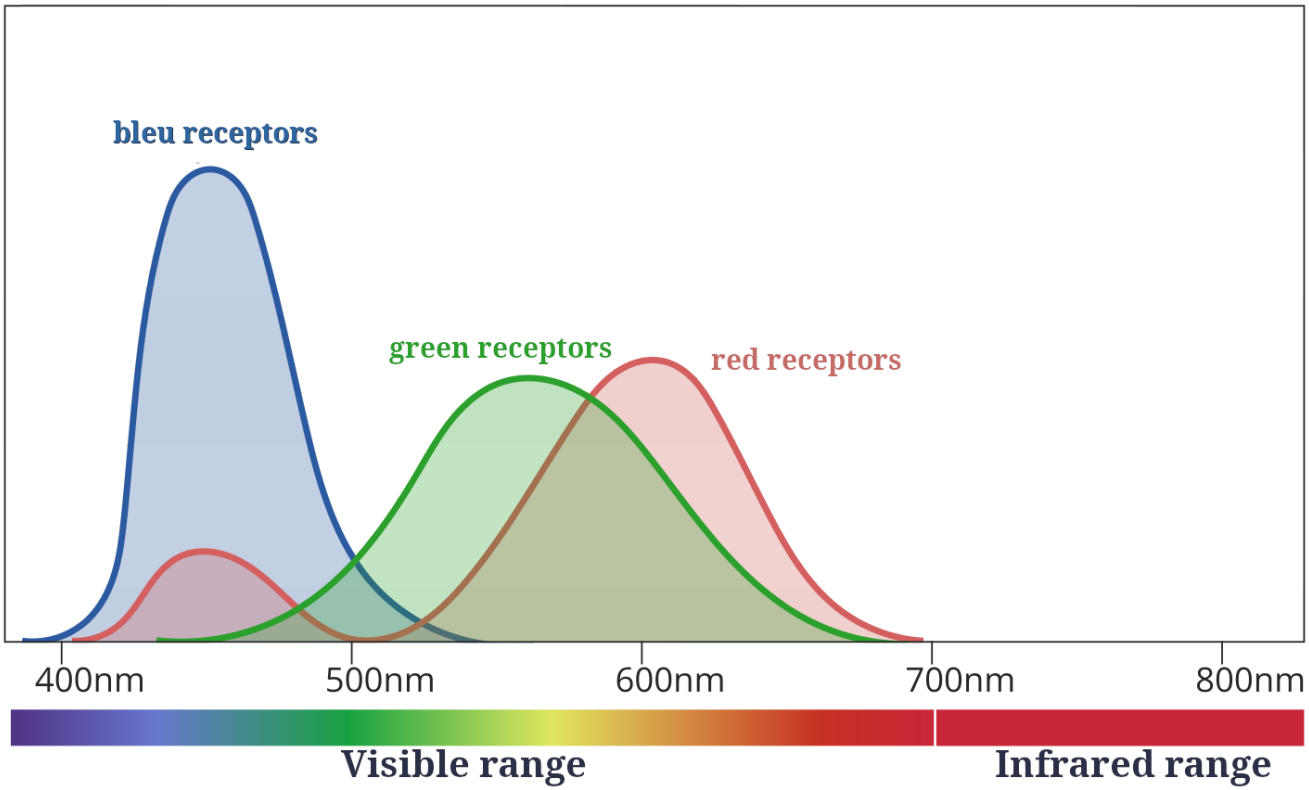
- Optical measurements can be either:
  - **passive** (reflected solar radiation, thermal emission)
  - or **active** (e.g. laser-based systems such as LiDAR)
- It provide key information on surface composition and vegetation properties

⚠ Optical ≠ passive

Optical sensing does not necessarily mean **passive** sensing. The optical domain refers to wavelengths, whereas passive sensing refers to the acquisition mode!

How does EO works: focus on the optical domain

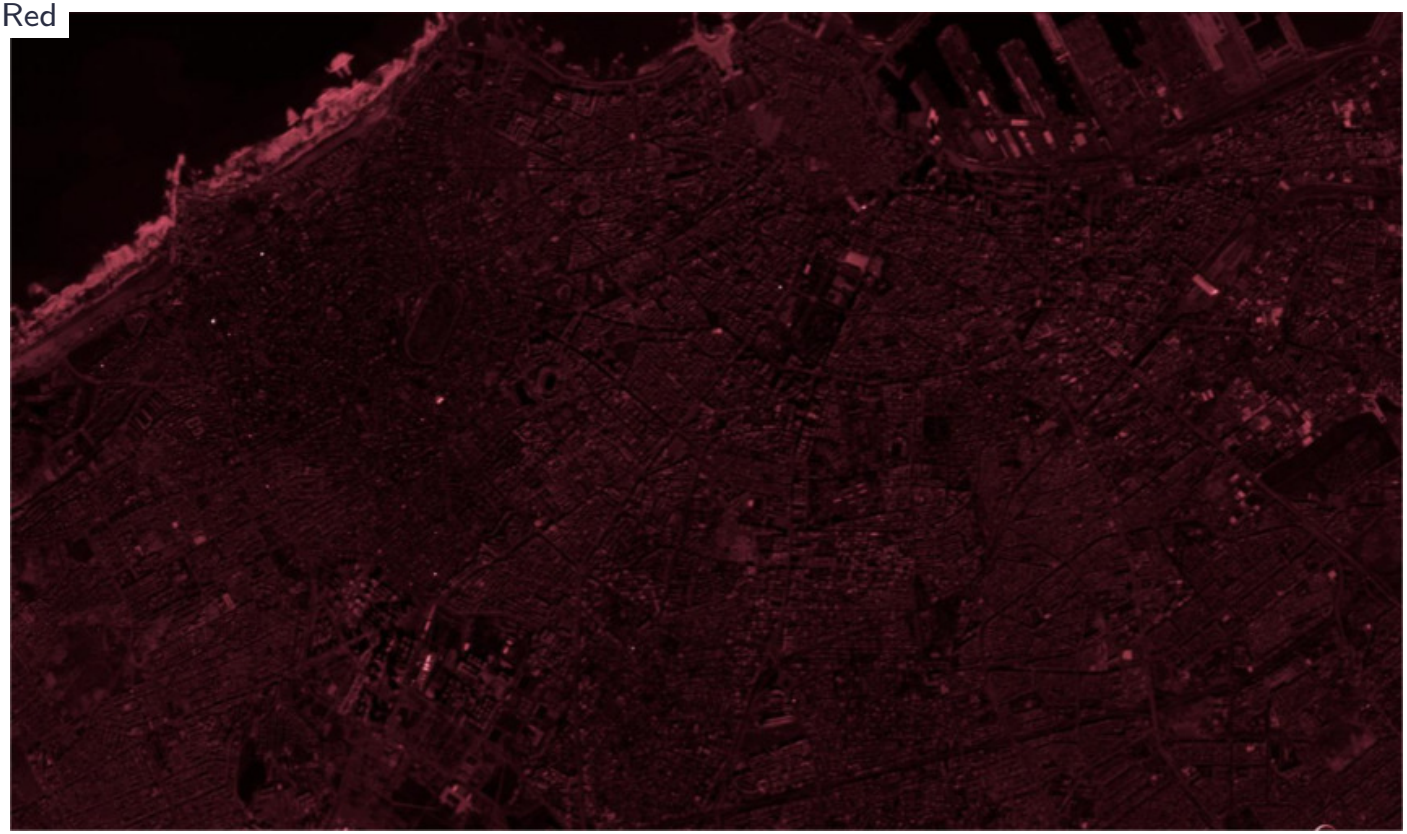
- The human eye is sensitive to the **visible spectrum**.
- Color perception results from the **combination** of the responses in the three wavelengths (red, green and blue)



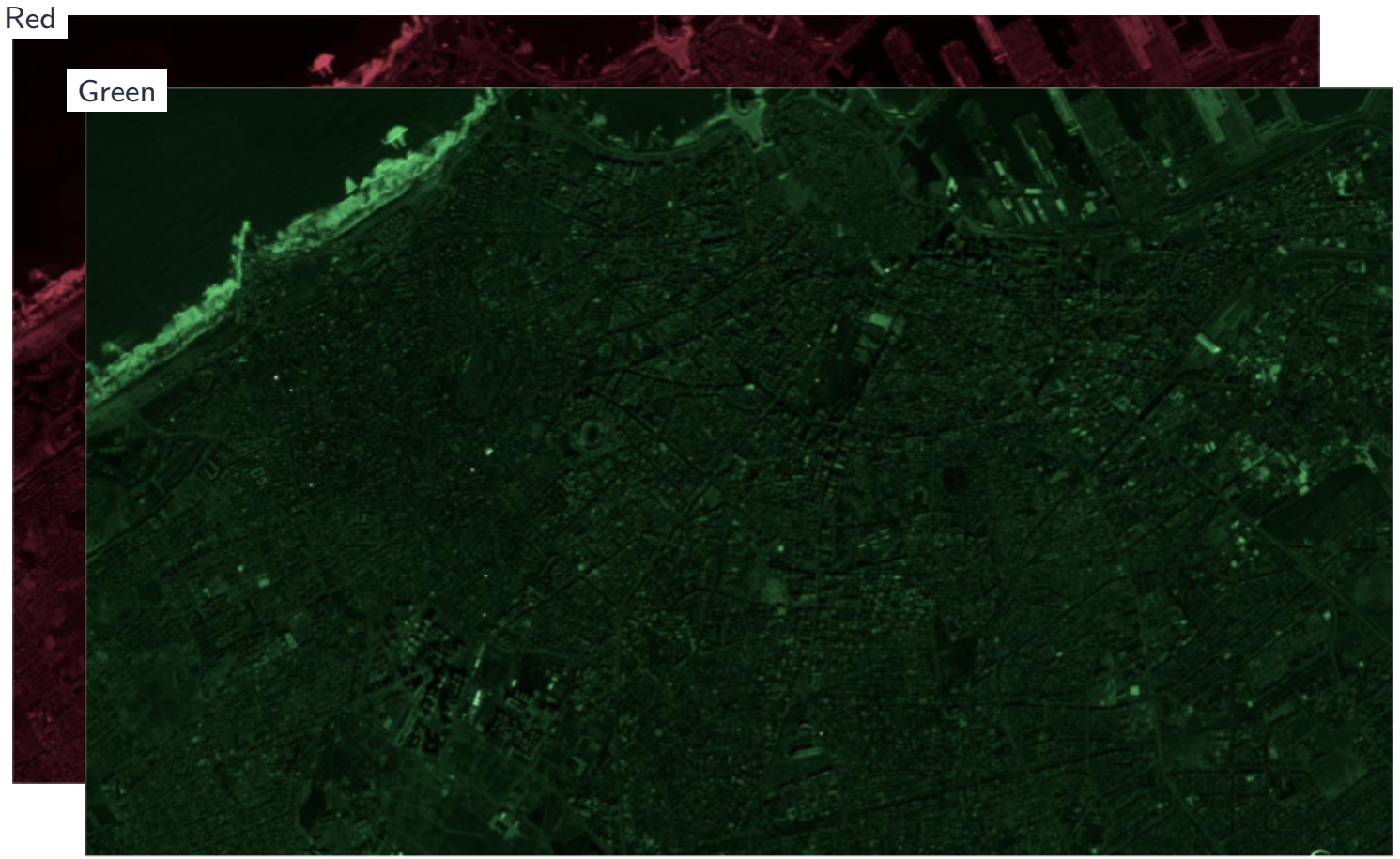
Color sensitivity of the human eye

How does EO work: focus on the optical domain

Red



How does EO work: focus on the optical domain



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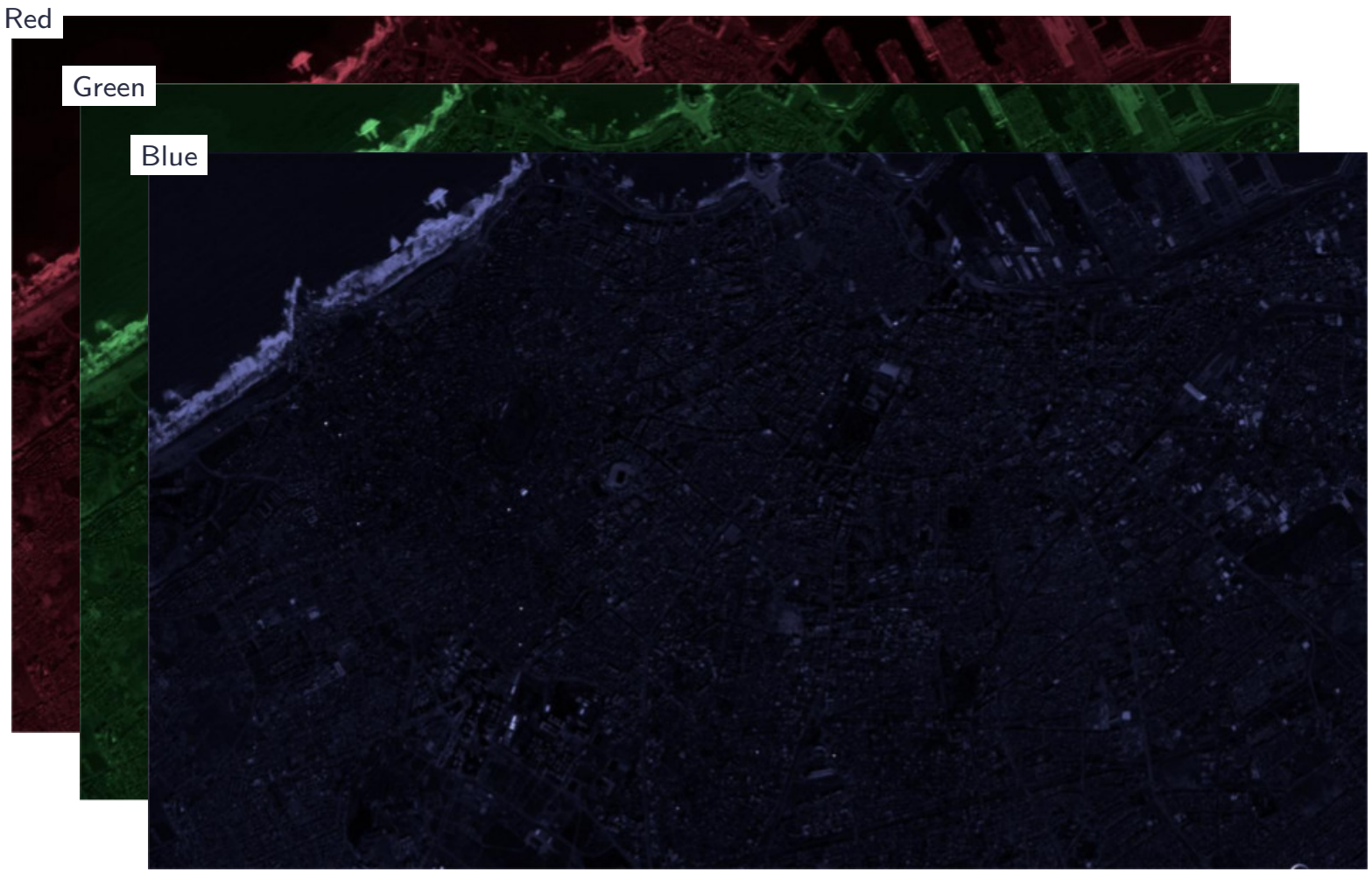
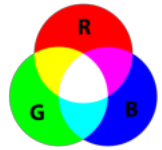


How does EO work: focus on the optical domain

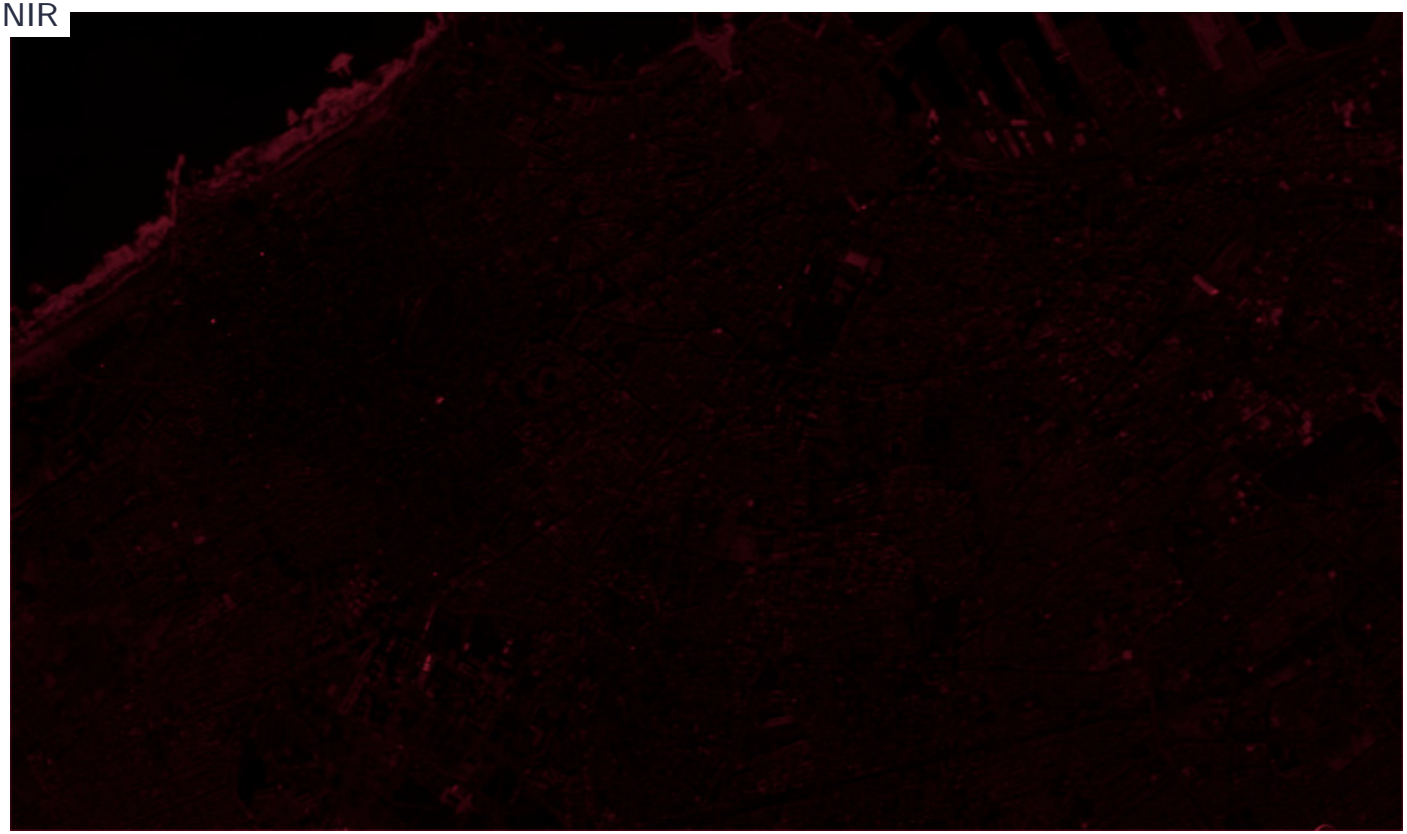


Additive color synthesis

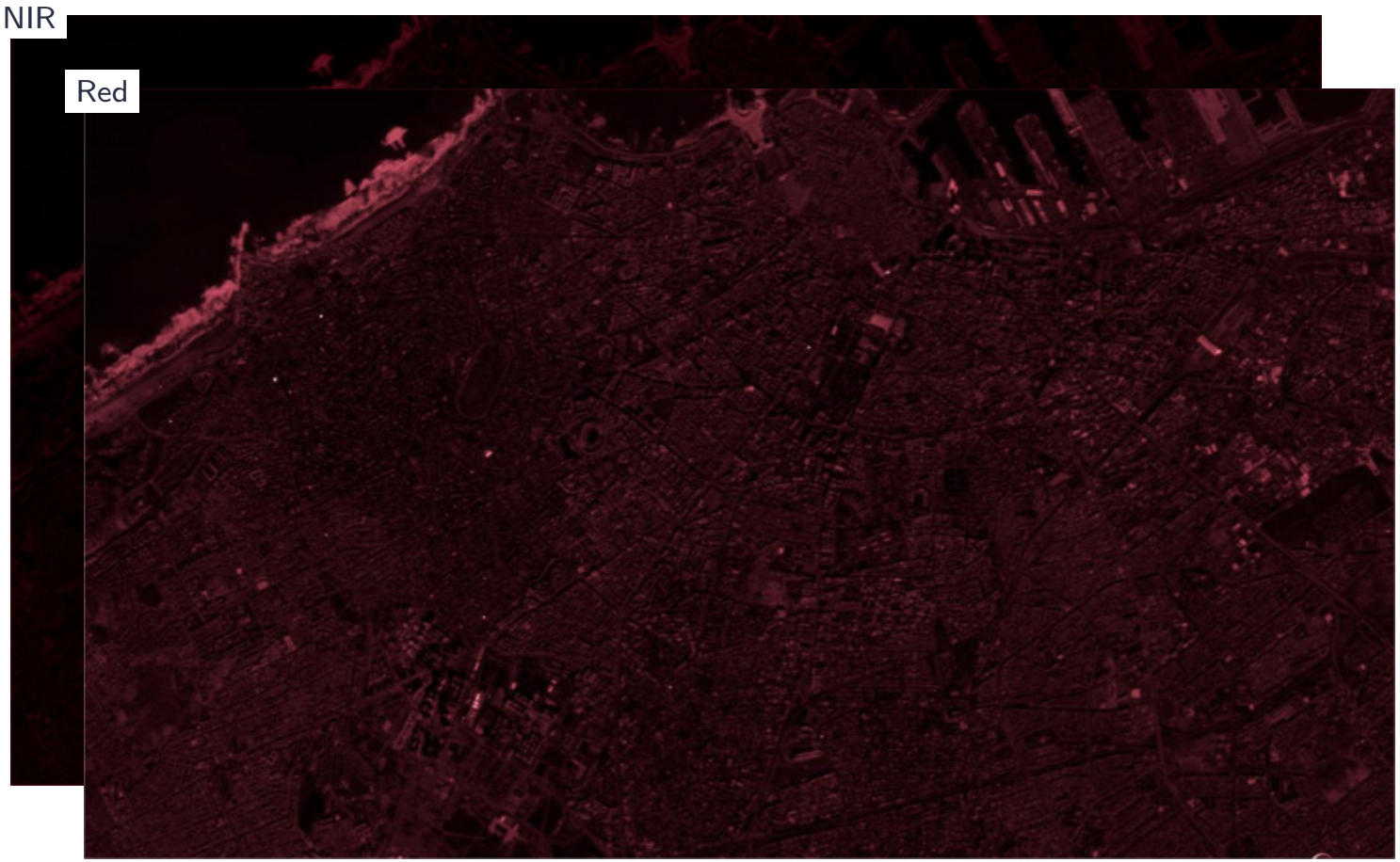
True color composite: Red–Green–Blue

How does EO work: focus on the optical domain

NIR



How does EO work: focus on the optical domain



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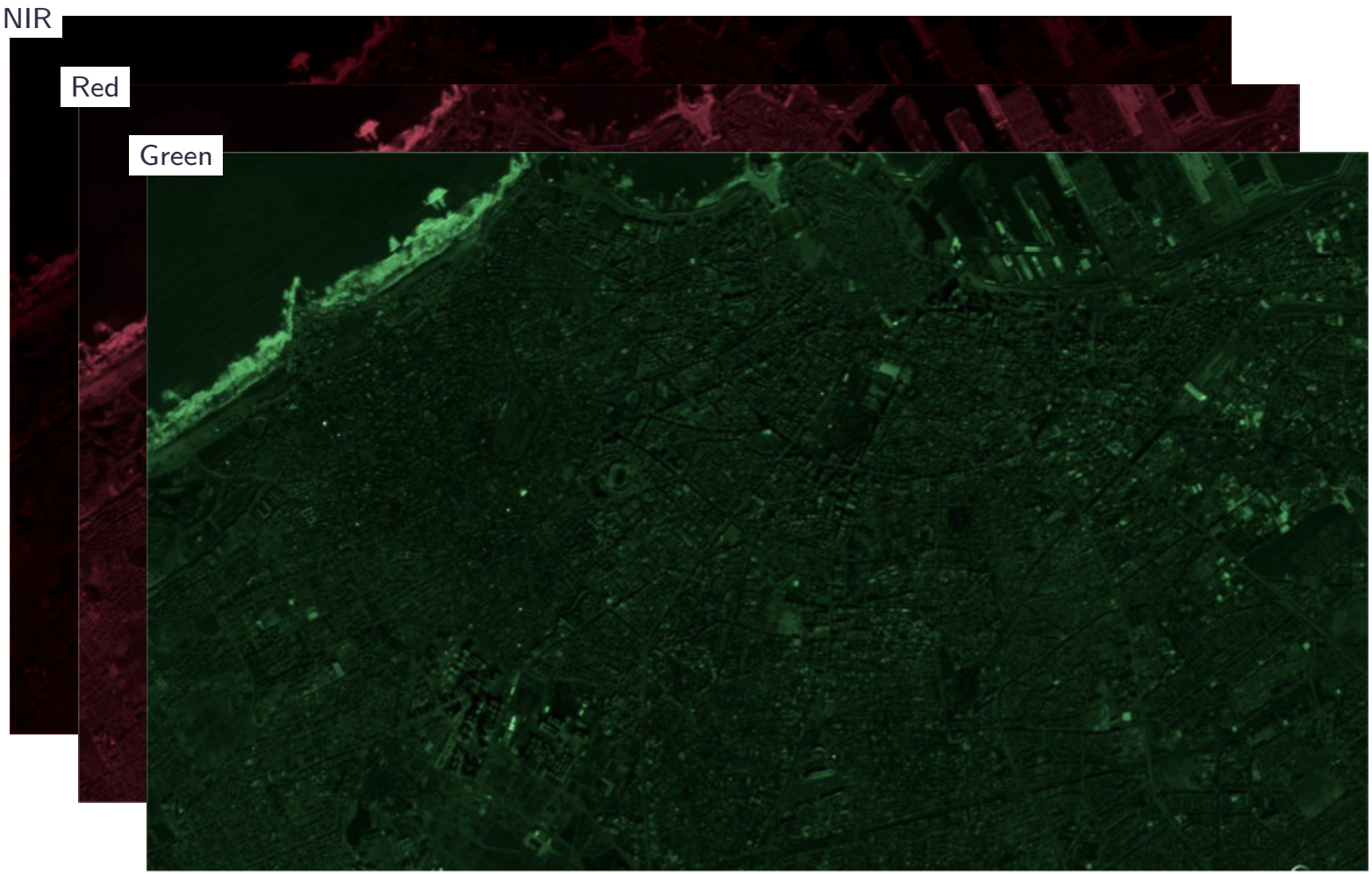
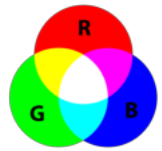


How does EO work: focus on the optical domain

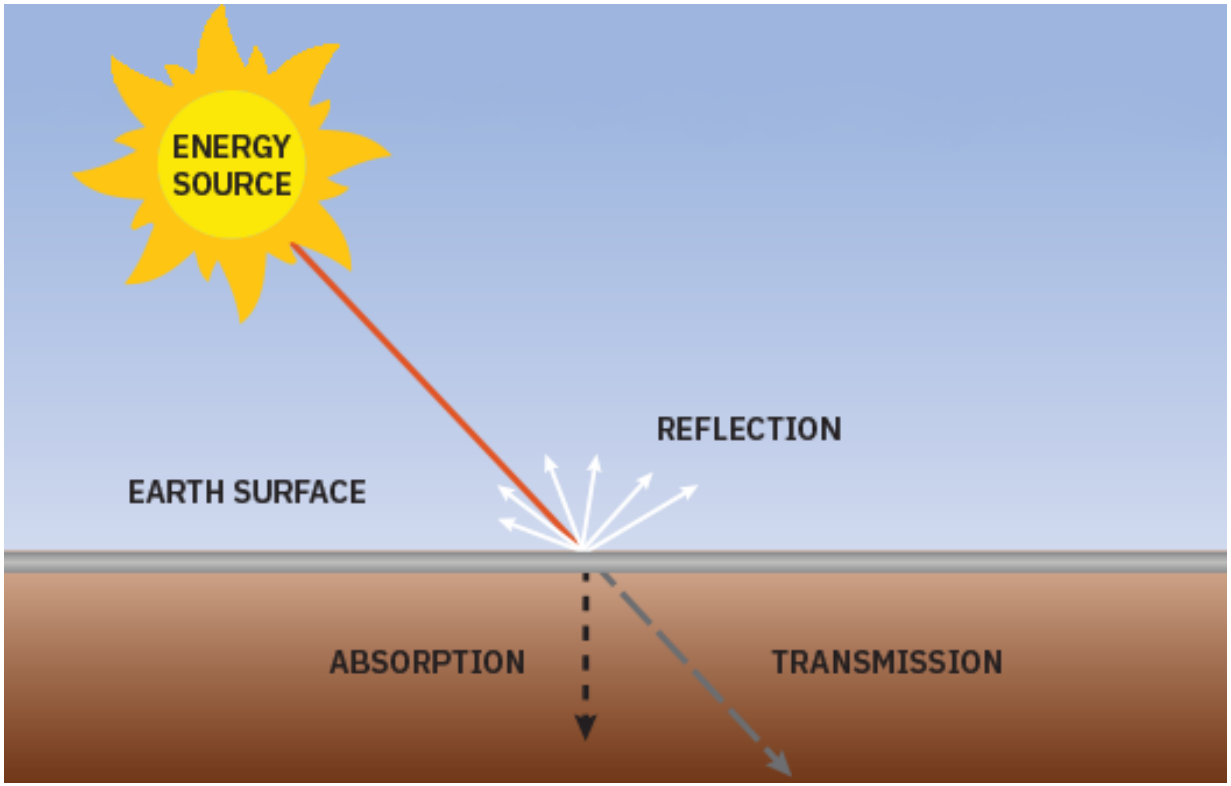


Additive color synthesis

False color composite: NIR–Red–Green

How does EO work: radiation–surface interactions

- Remote sensing measures the amount of EMR **reflected** at specific wavelengths (*bands*) to identify the characteristics of an object.



Source: NV5 Geospatial Software

Wave Propagation:

Reflectance: ρ

Absorbance: α

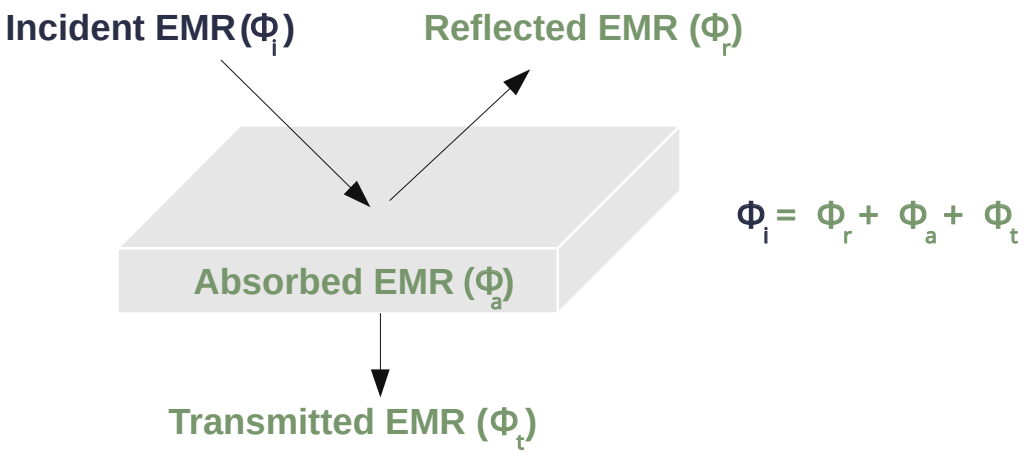
Transmittance: T

Energy Conservation:

$$\alpha + \rho + T = 1$$

How does EO work: radiation–surface interactions

- Remote sensing measures the amount of EMR **reflected** at specific wavelengths (*bands*) to identify the characteristics of an object.



- **Absorption**, **transmission**, and **reflection** depend on the surface properties, the wavelength λ, and the illumination conditions.

How does EO work: the spectral signature

🤔 Question

So why do objects appear differently?

How does EO work: the spectral signature

🤔 Question

So why do objects appear differently?

Because they absorb and reflect different wavelengths of light depending on their molecular structure, which our eyes perceive as colors.

How does EO work: the spectral signature

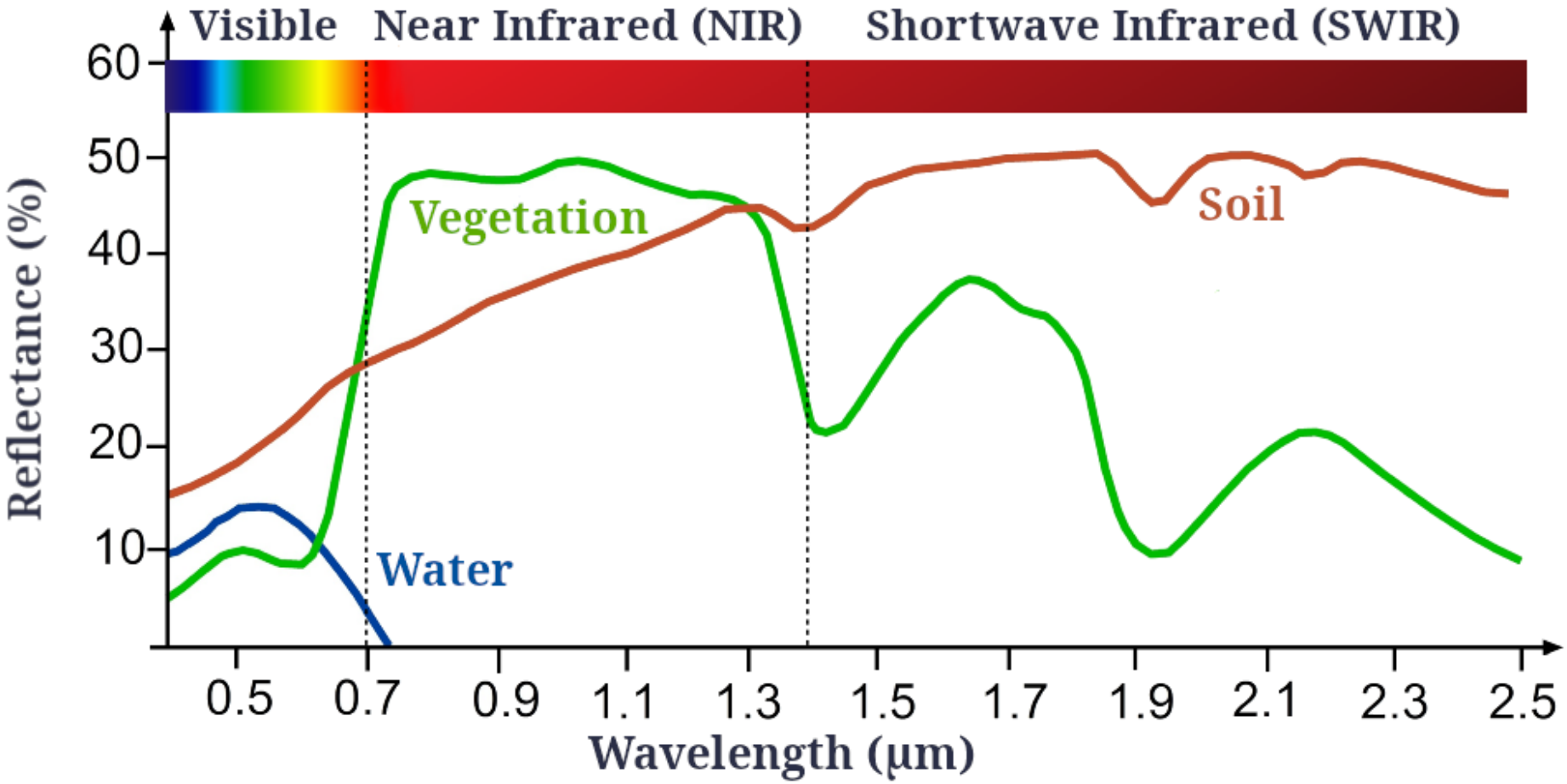
🤔 Question

So why do objects appear differently?

Because they absorb and reflect different wavelengths of light depending on their molecular structure, which our eyes perceive as colors.

In remote sensing, this wavelength-dependent response is called a **spectral signature**.

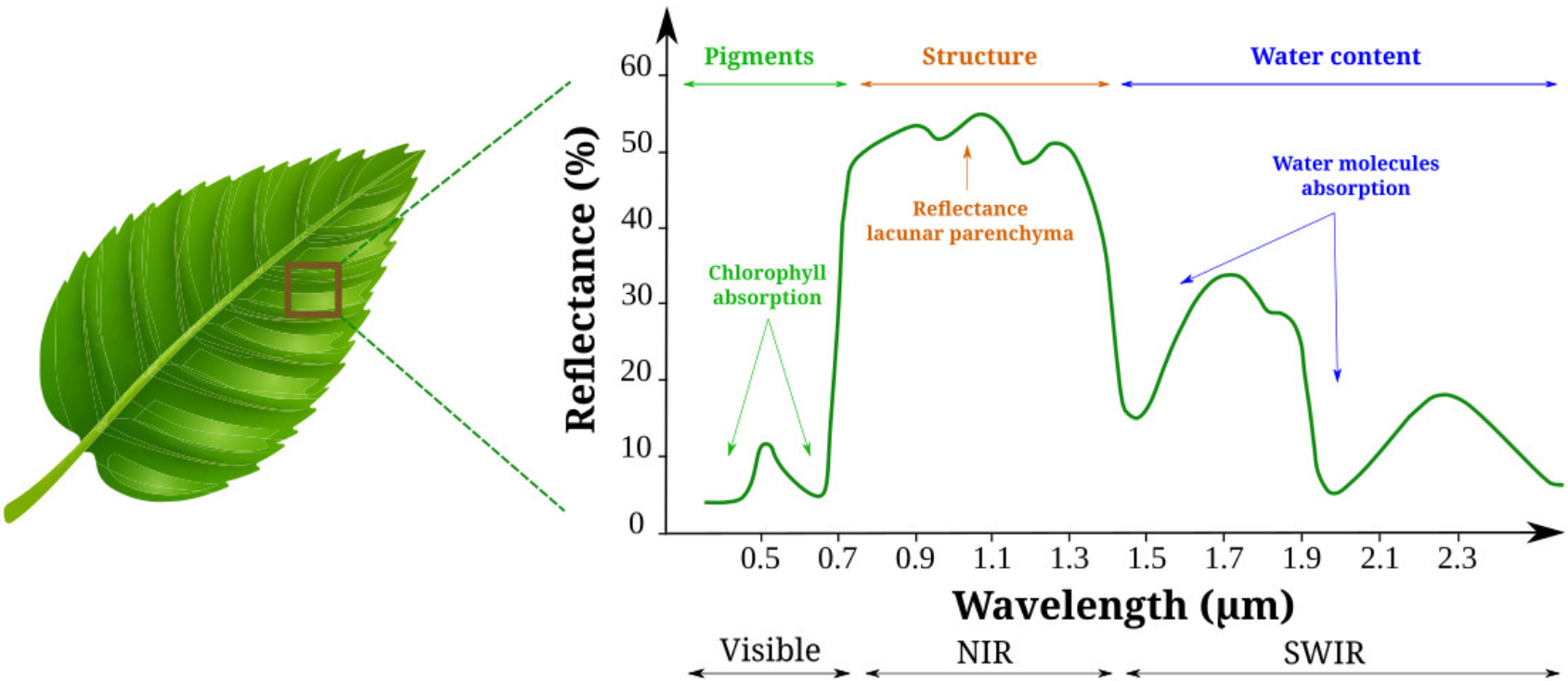
How does EO work: the spectral signature



- The spectral behavior of objects depends on their optical properties, which control how they absorb, transmit, and reflect incident EMR.

How does EO work: optical properties of vegetation

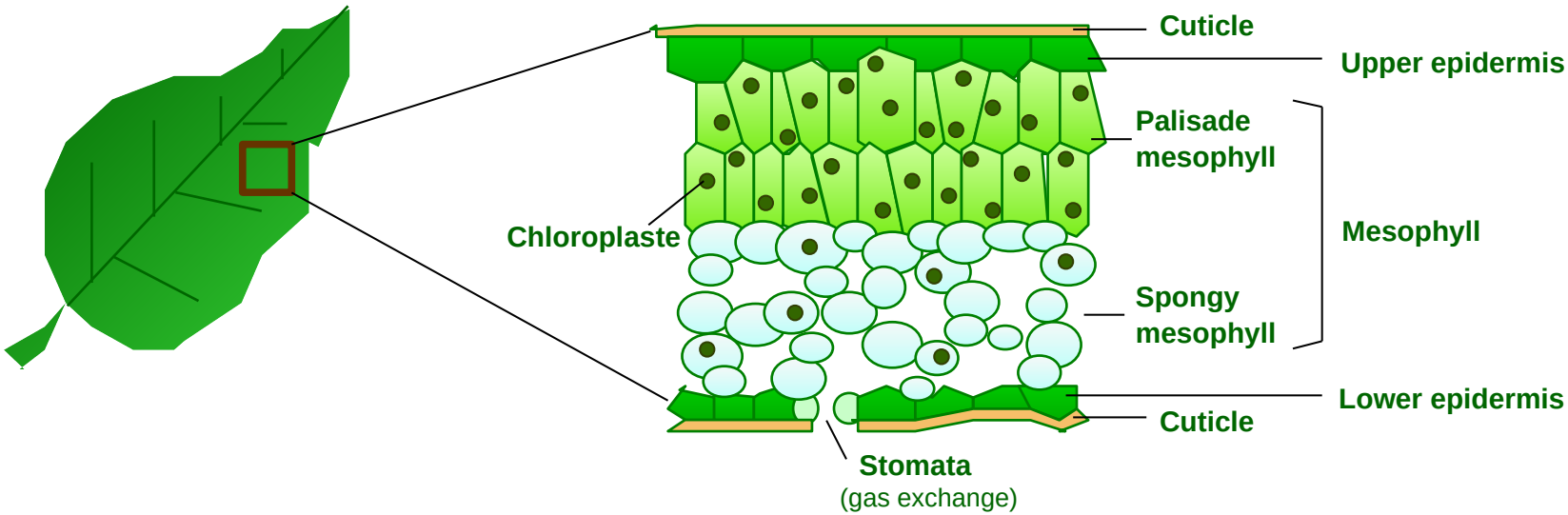
- In vegetation, leaves are the primary elements interacting with incident EMR and thus determine the spectral behavior.
- Absorption, transmission, and reflection depend on the biochemical properties of leaves and vary across the spectral regions.



Source: adapted from Girard et al. (1999)

How does EO work: optical properties of vegetation

- Internal leaf structure

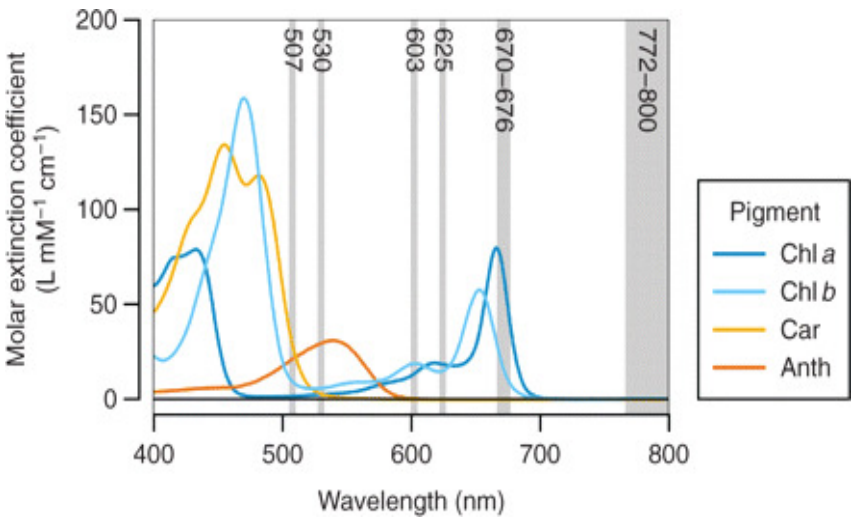


Source: adapted from Girard et al. (1999)

How does EO work: optical properties of vegetation

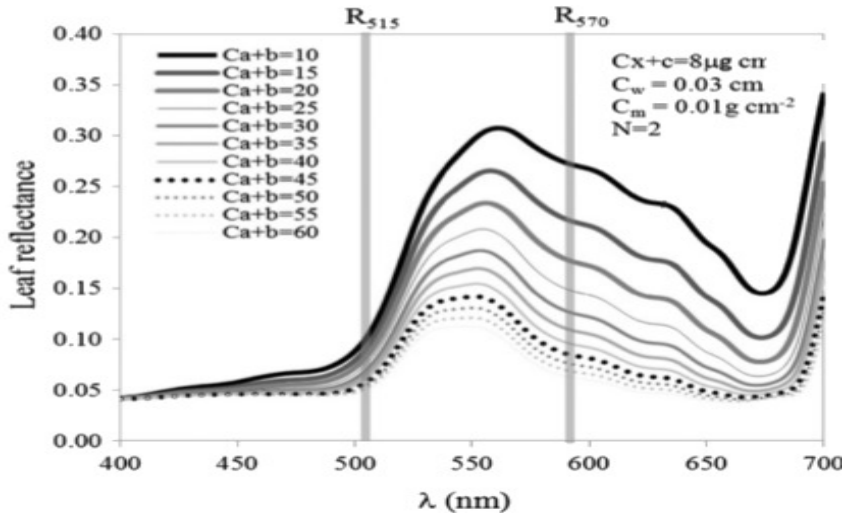
- **Visible (0.4–0.7 μm):** spectral behavior mainly driven by leaf pigments (chlorophyll, carotenoids, anthocyanins).
  - **Strong absorption** in blue and red, low reflectance with a **higher value** in green (10 to 15%).
  - The higher the chlorophyll content, the lower the reflectance in the visible domain.

Absorption spectra of the major leaf pigments



Source: Matsuda et al. (2012)

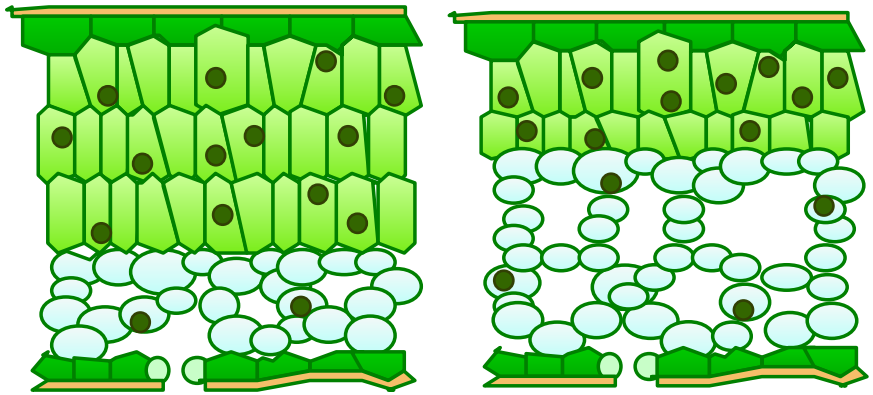
Reflectance variation with chlorophyll content



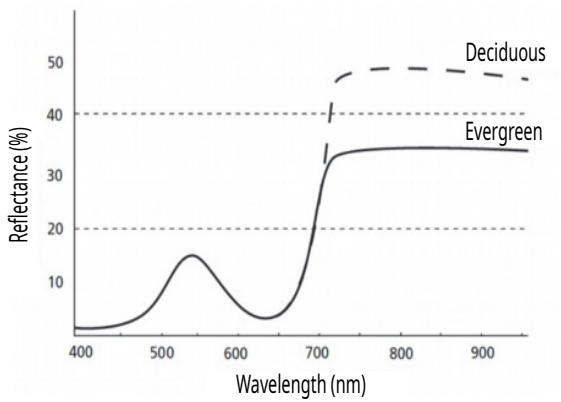
Source: Hernández-Clemente et al. (2012)

How does EO work: optical properties of vegetation

- **NIR (0.8–1.1 μm):** reflectance is mainly controlled by the internal structure of the leaf, particularly the **spongy mesophyll**.
  - Leaf pigments are transparent → low absorption (<10%) and high reflectance and transmittance (>50%).
  - Reflectance increases when the spongy mesophyll is well developed and the palisade mesophyll is thin (typical of deciduous species).



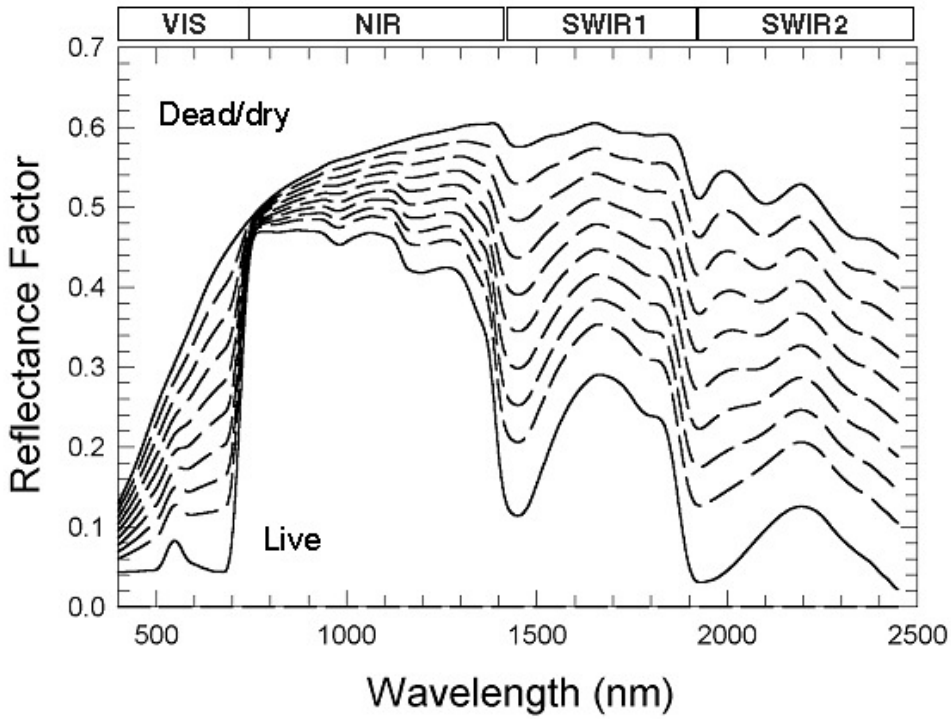
Evergreen species Deciduous species



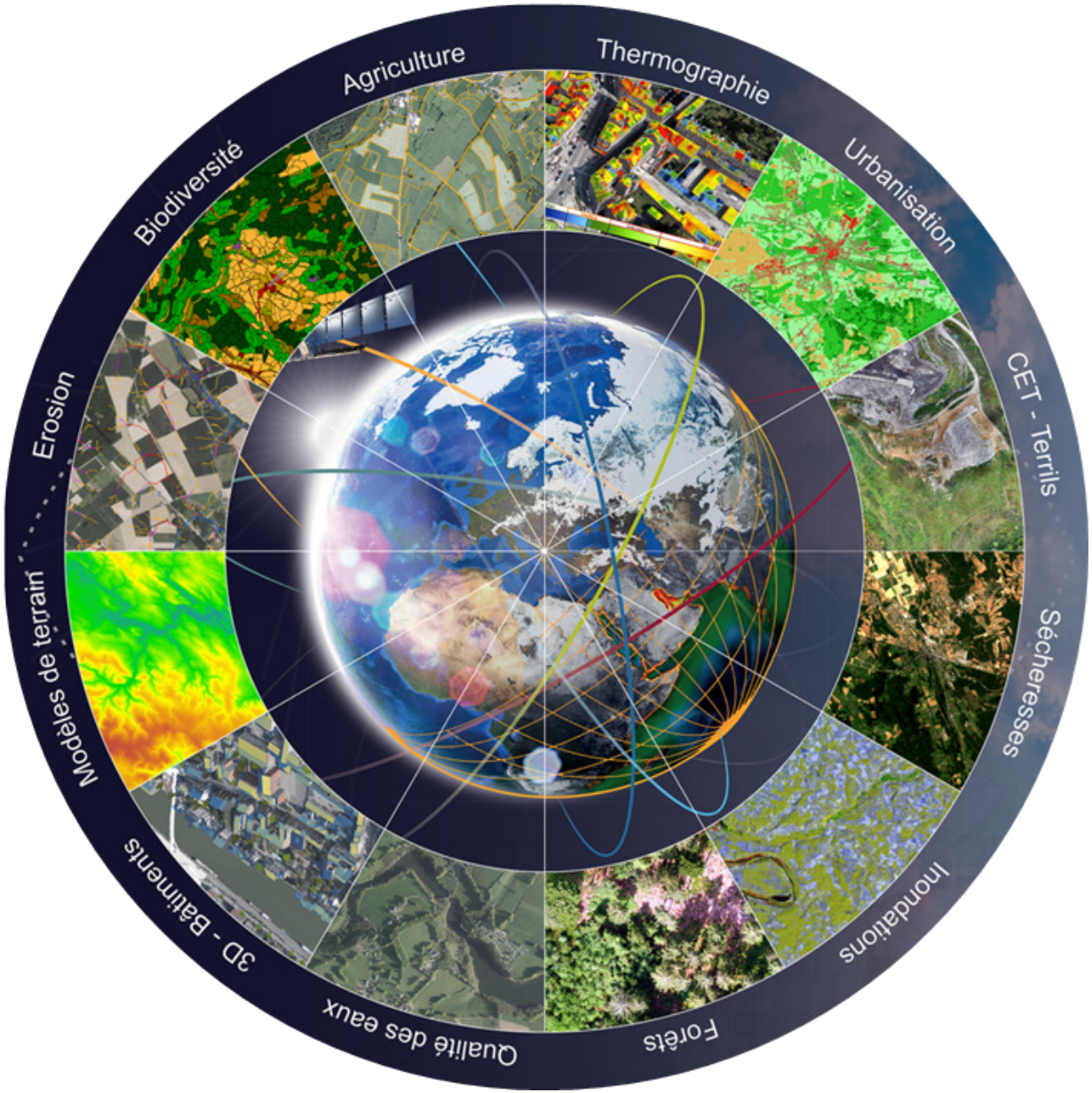
Source: adapted from Girard et al. (1989)

How does EO work: optical properties of vegetation

- **SWIR (1.1–2.5 μm):** spectral response mainly governed by leaf water content.
  - Strong absorption at 1450 and 1900 nm due to water molecules, and to a lesser extent due to dry matter (cellulose, lignin) as the leaf dries
  - Higher water content leads to a **lower reflectance**.

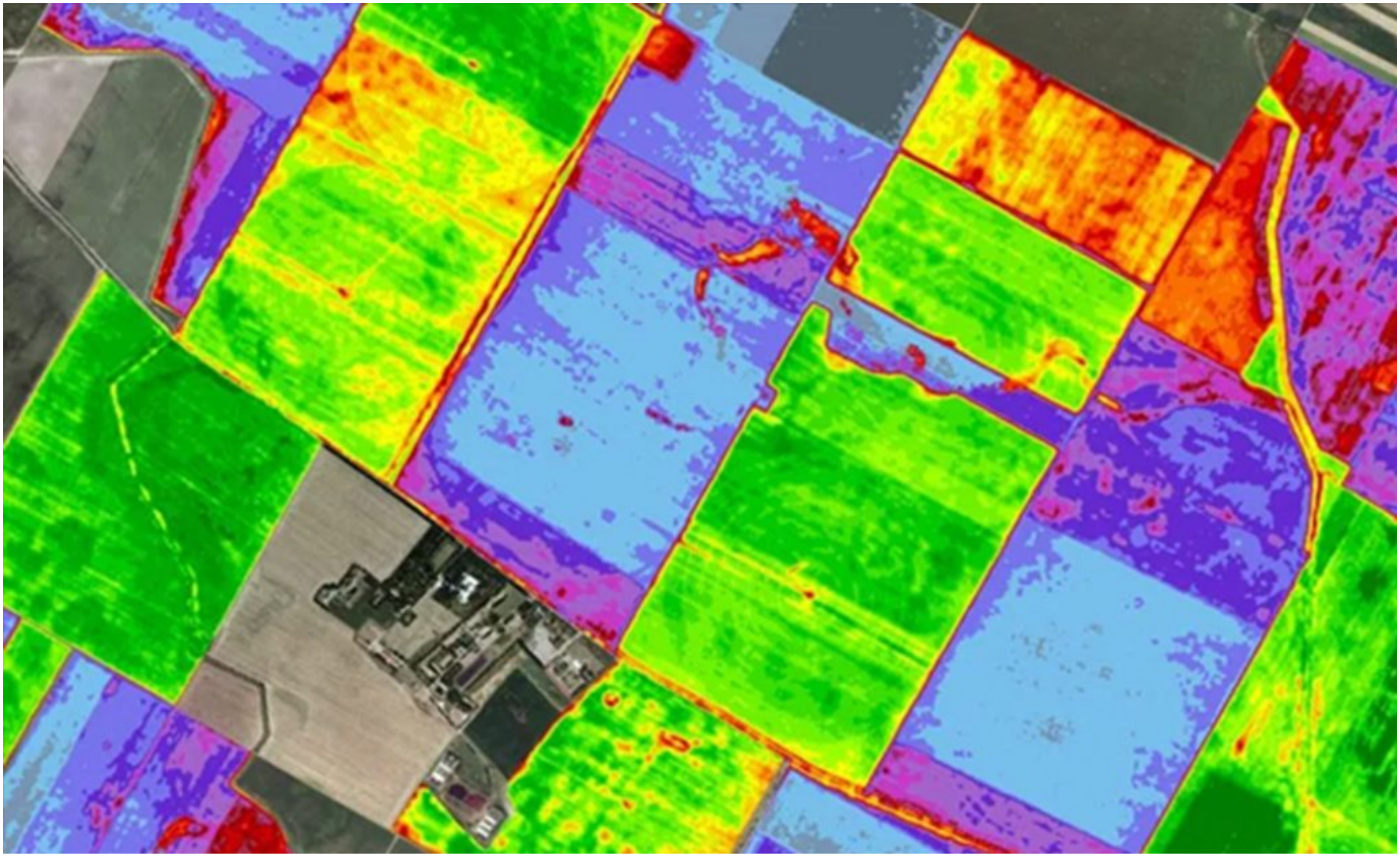


Source: Asner (1998)



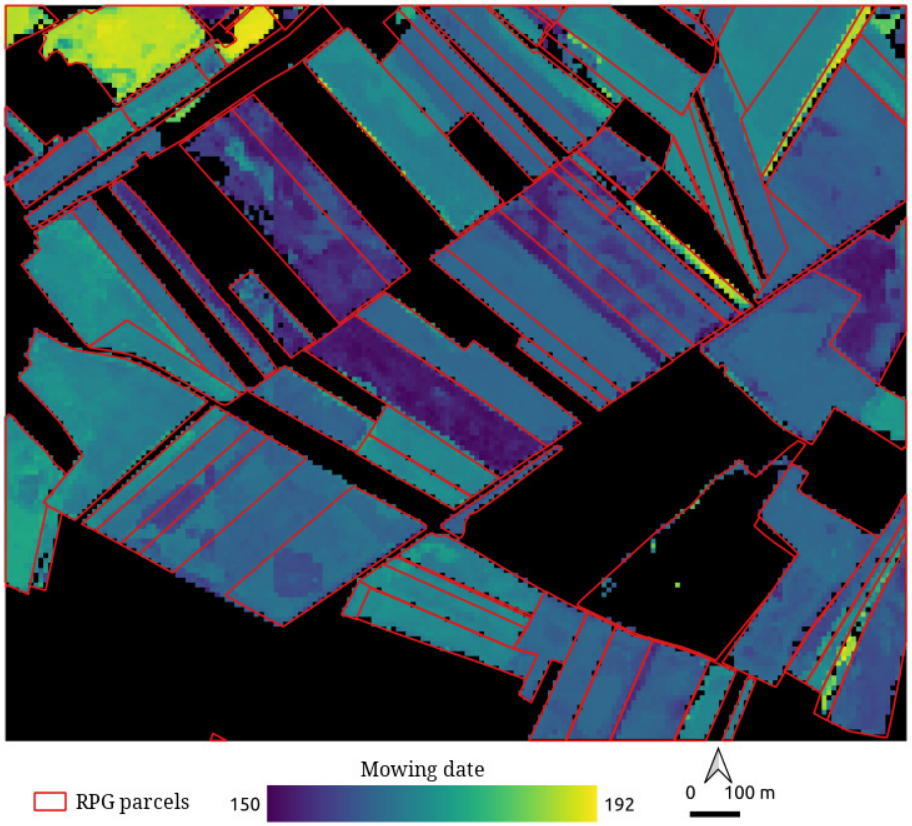
Source: adapted from ISSeP (2026)

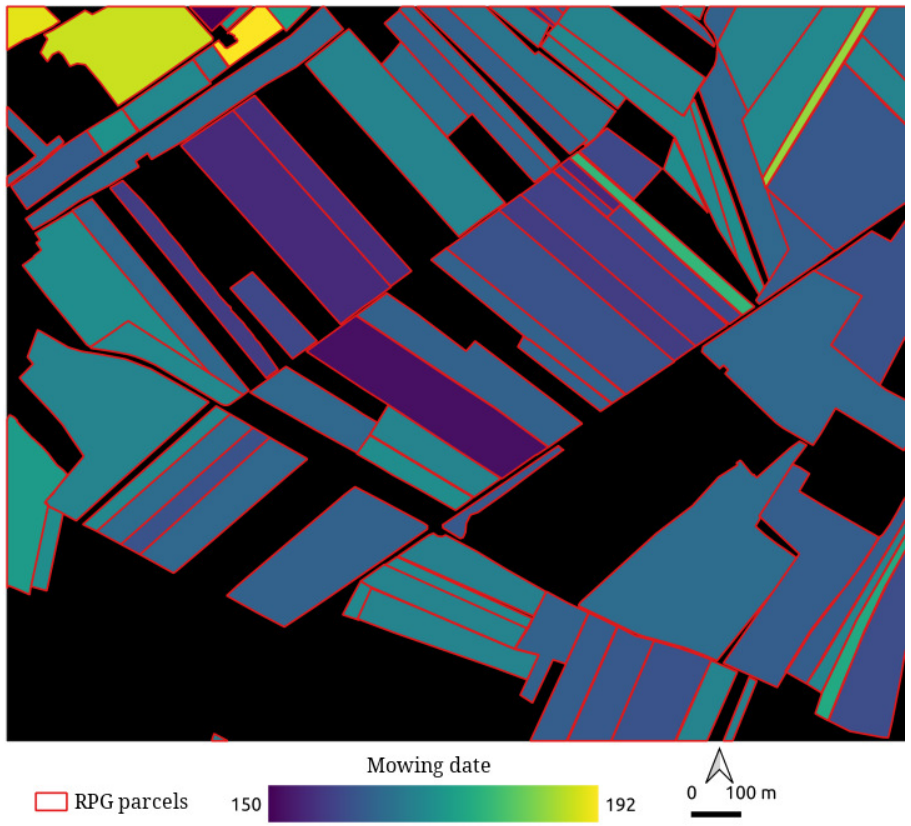
Agriculture: crop monitoring and yield prediction



Source: Sentinel-hub

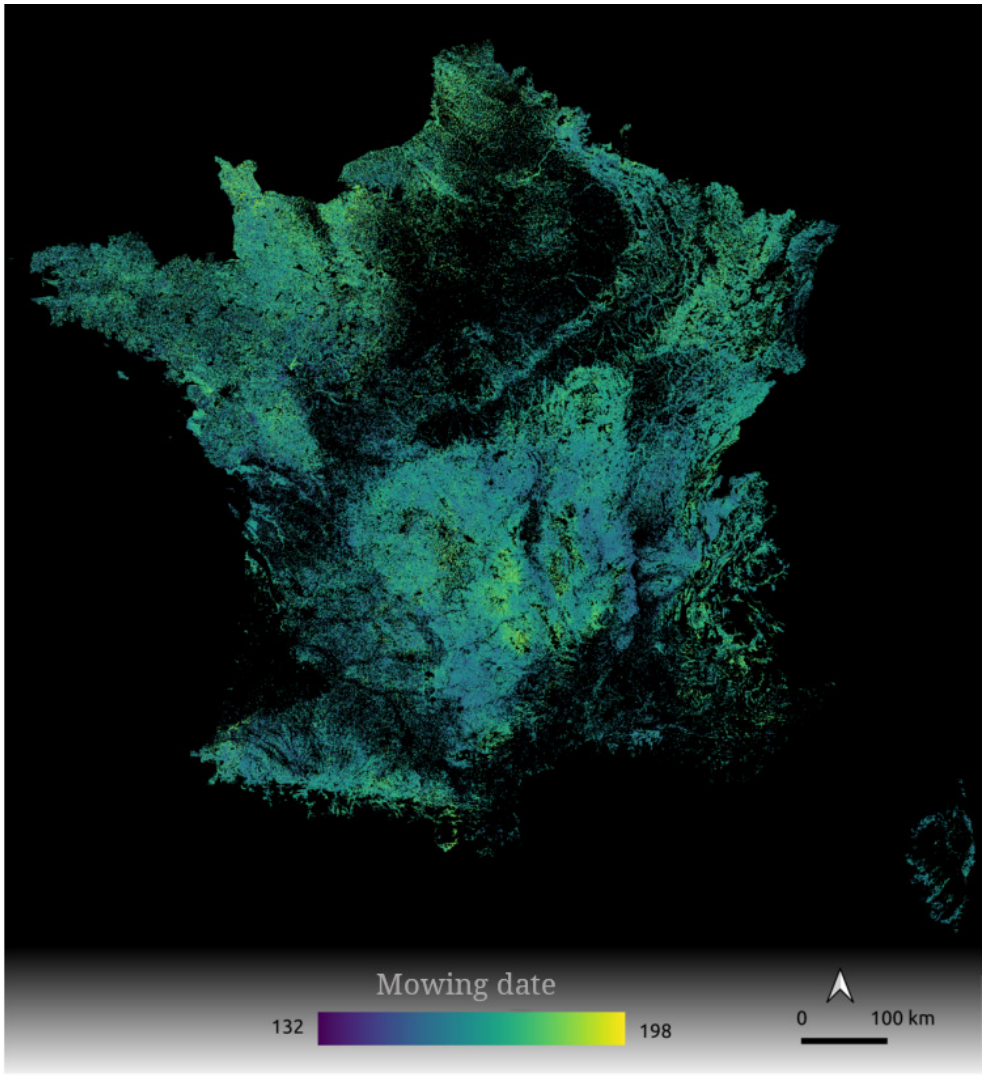
Agriculture: mowing date detection





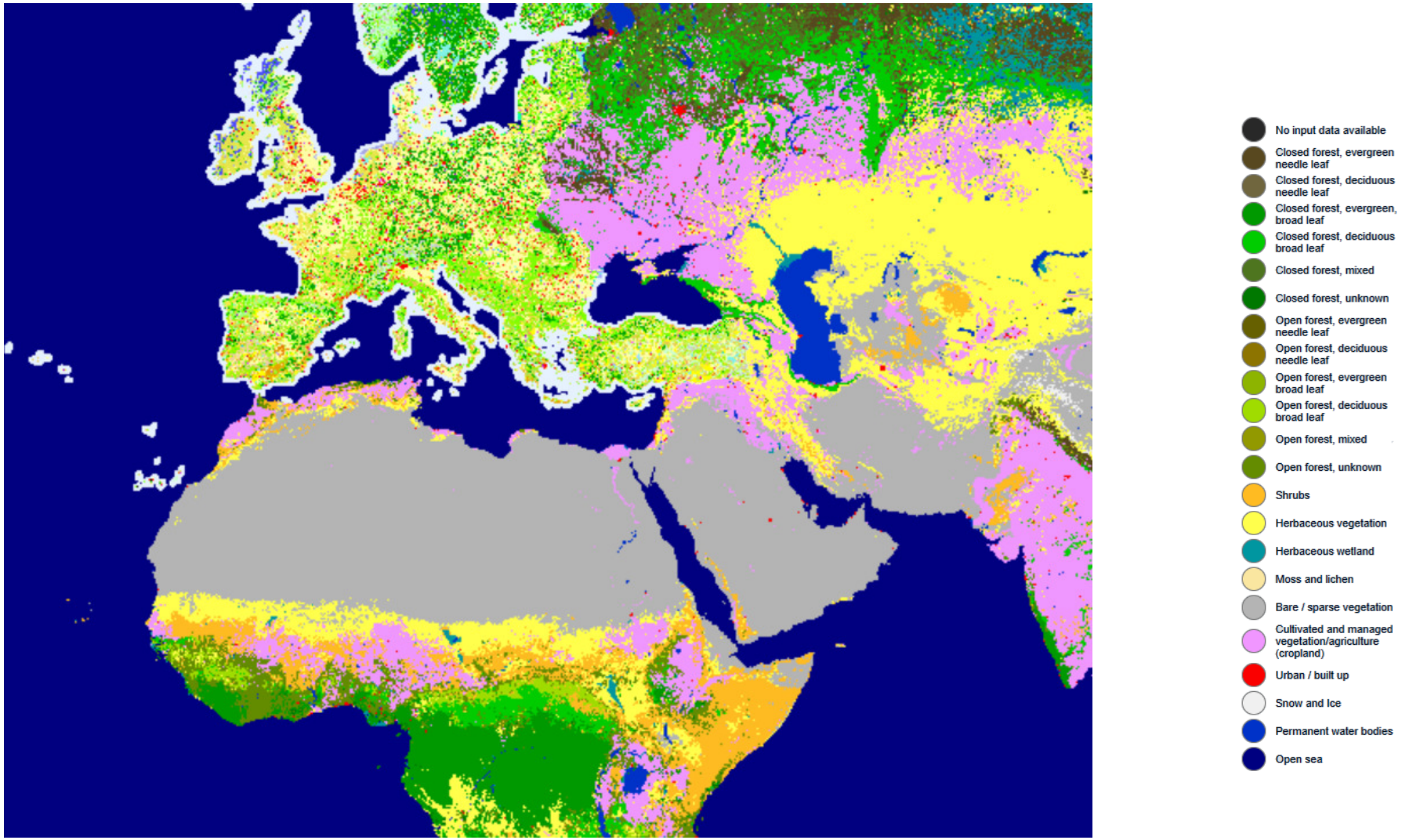
Source: Fauvel et al. (2023)

Agriculture: mowing date detection



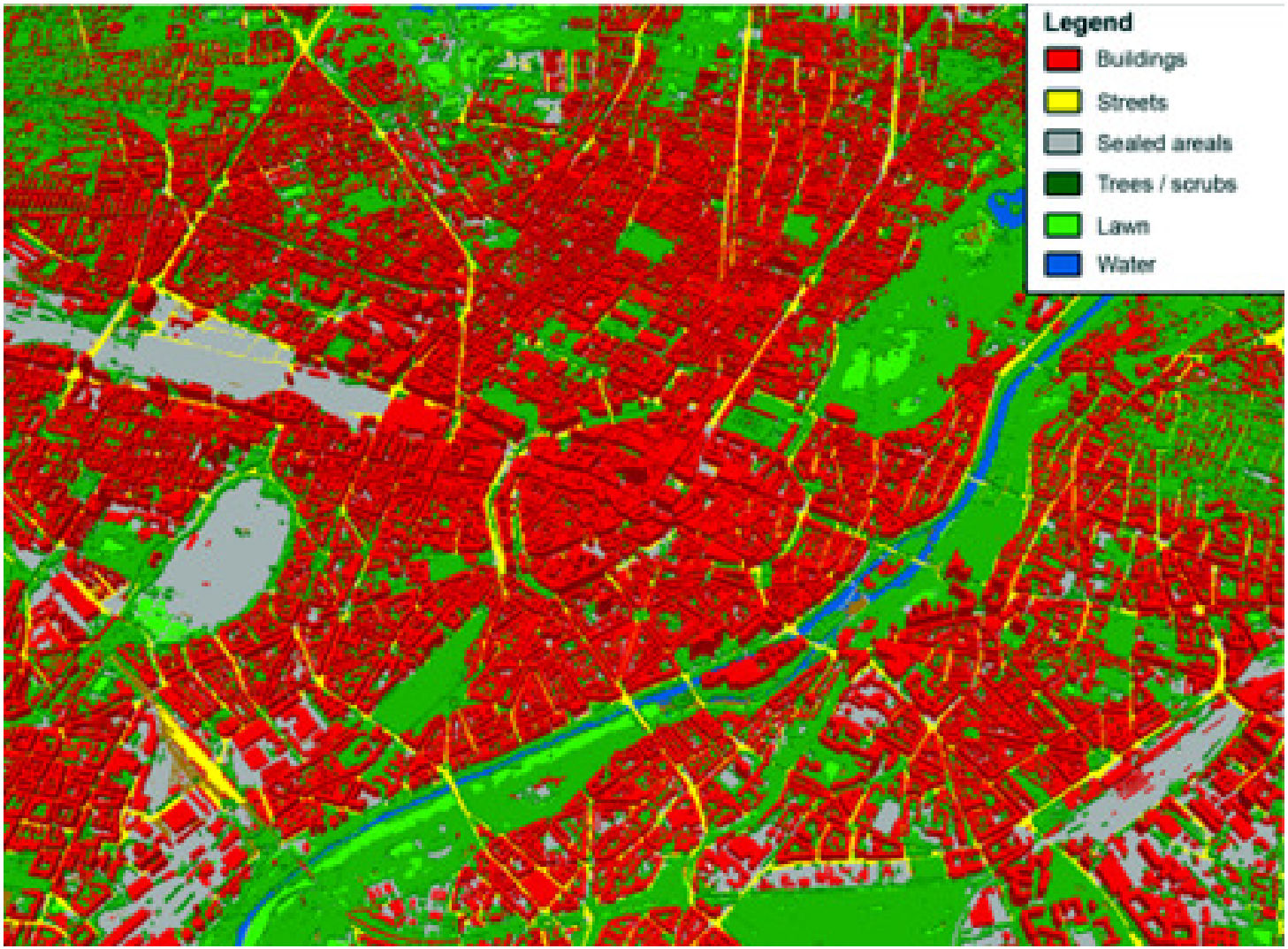
Source: Fauvel et al. (2023)

Agriculture: land cover classification



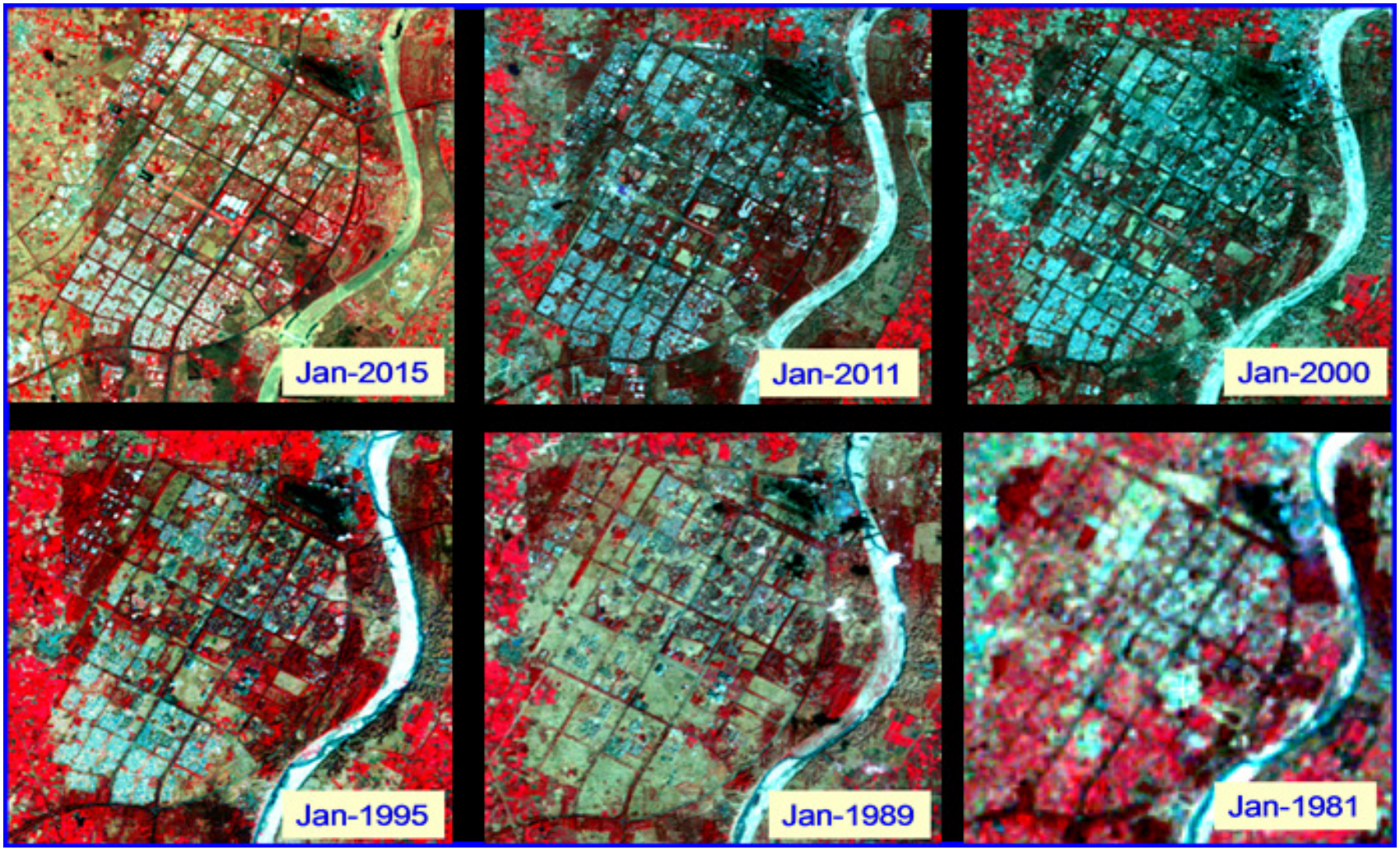
Corine Land Cover 2023

Urban planning: building and streets detection



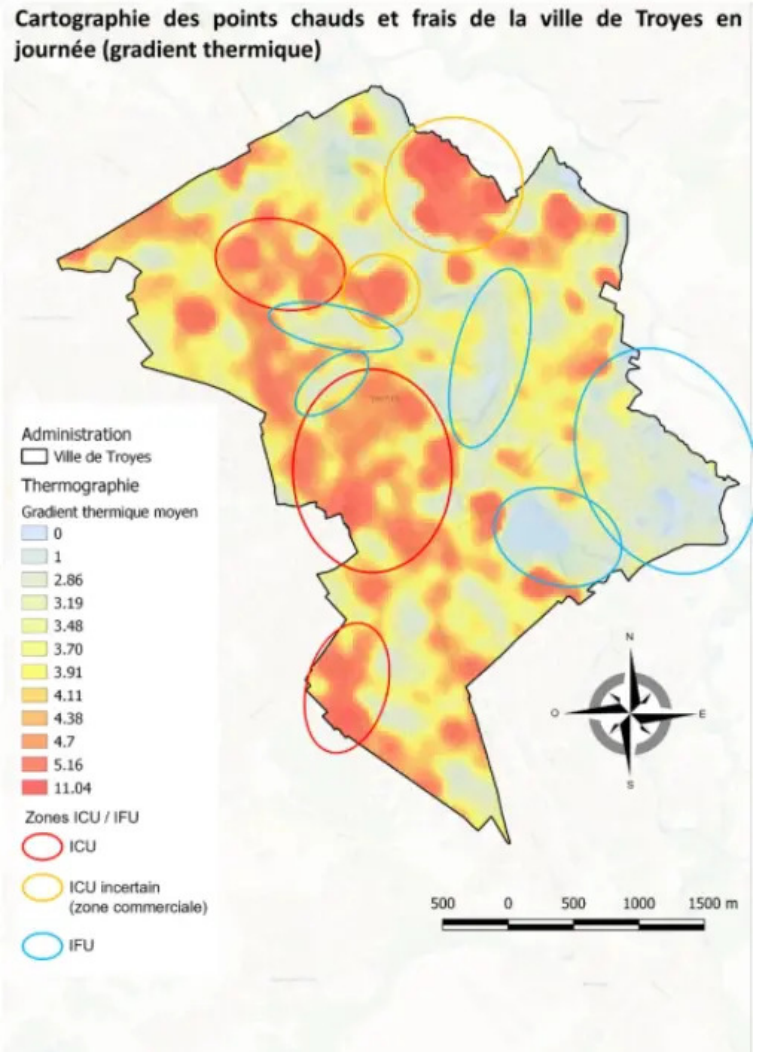
3D City Model of central Munich, source: Taubenböck, H. & Dech S. (2010)

Urban planning: urban sprawling



Urban growth in Gandhinagar (India), source: Badlani et al. (2017)

Urban planning: heat islands analysis

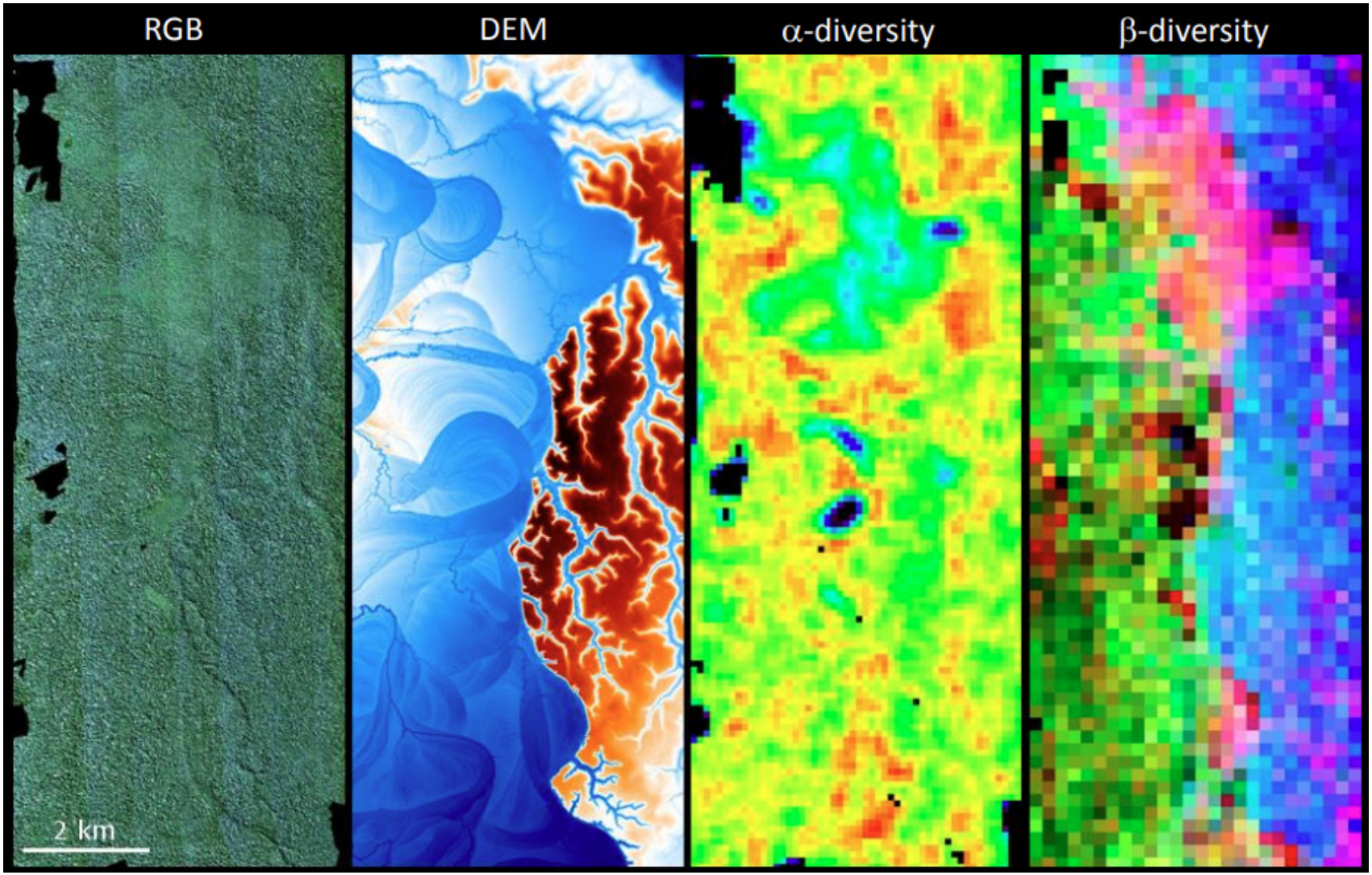


Source: Kermap

Urban planning: heat islands analysis

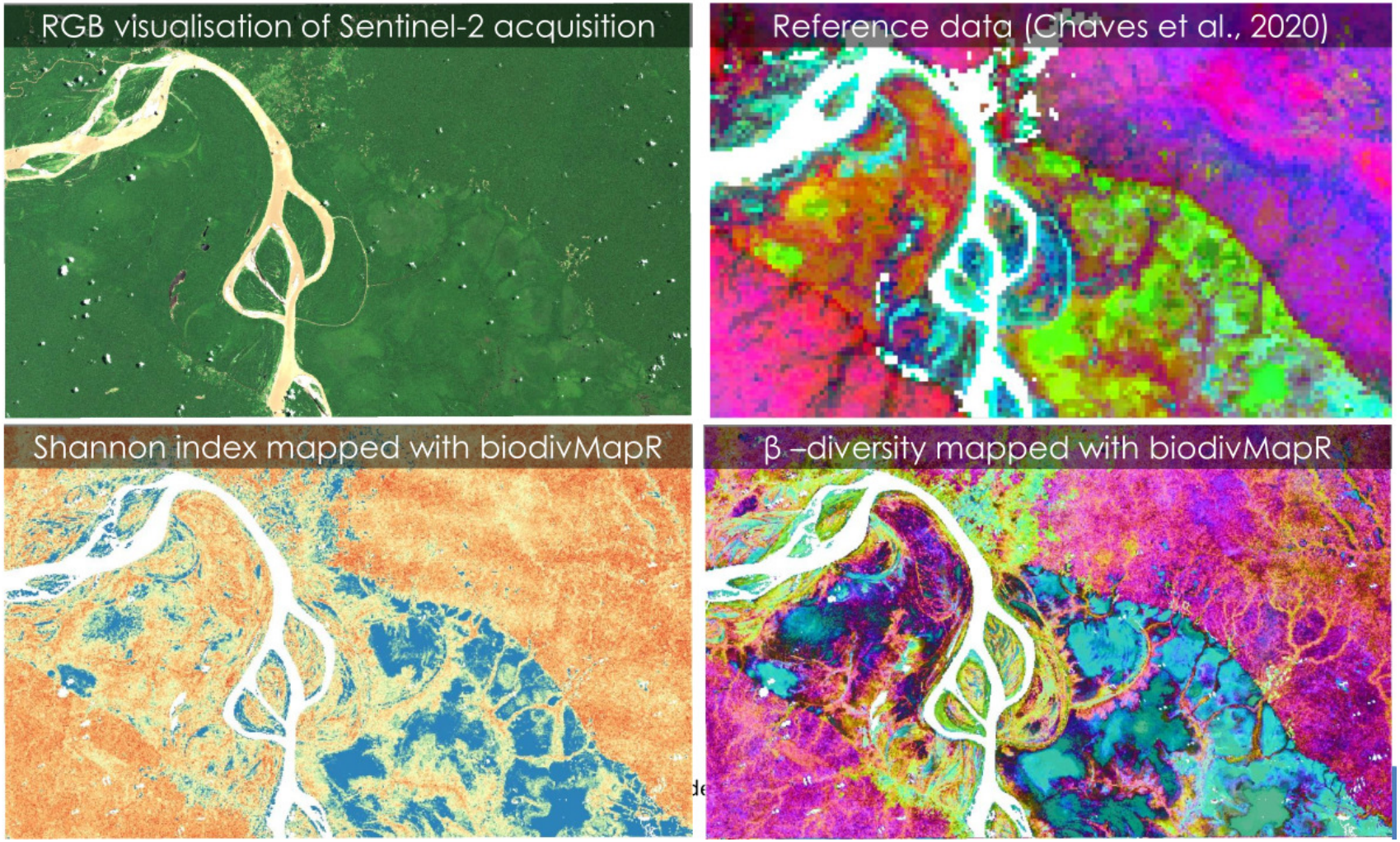
Aerial views of Sacramento, source: NASA-Marshall Space Flight Center

Ecology: natural habitat mapping



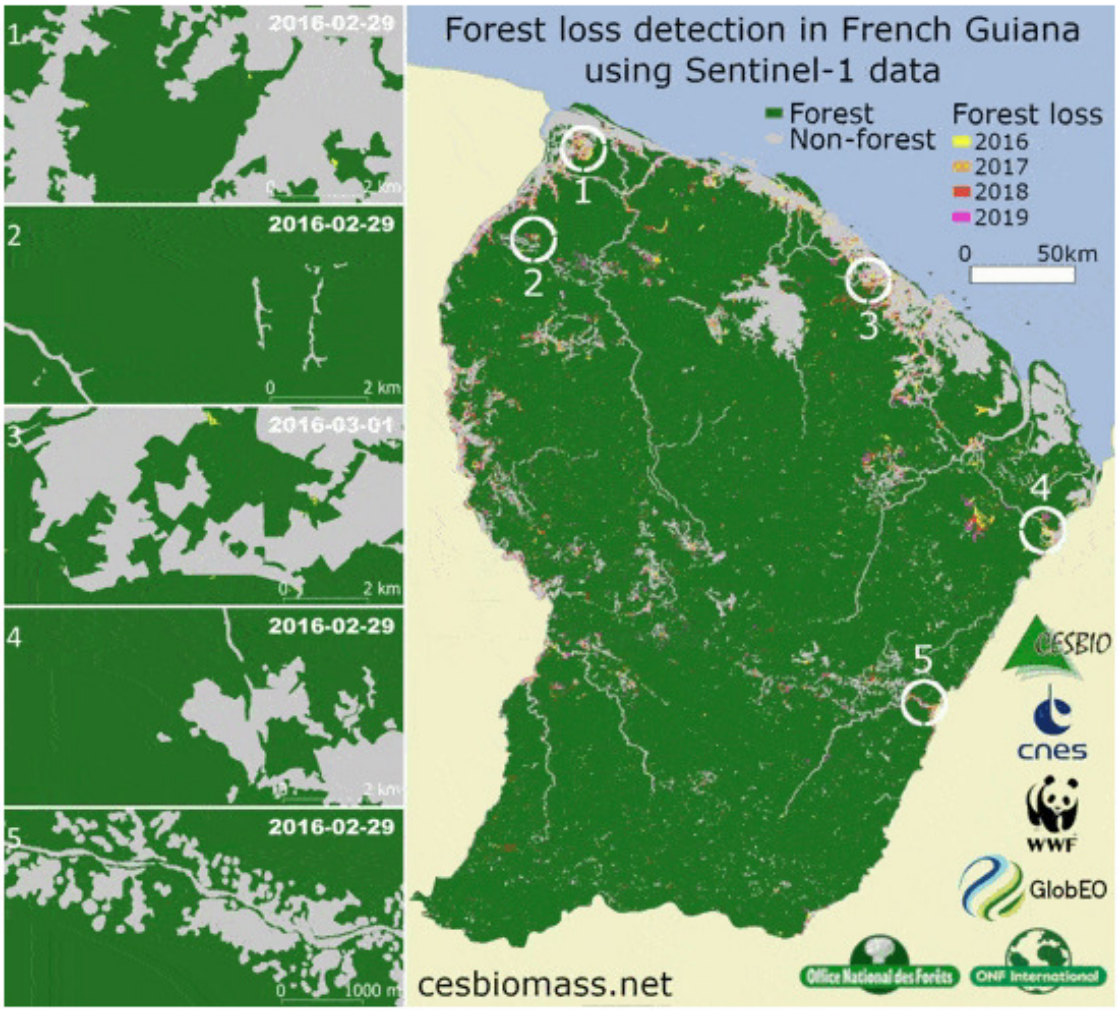
Source: Féret et al. (2024)

Ecology: biodiversity mapping



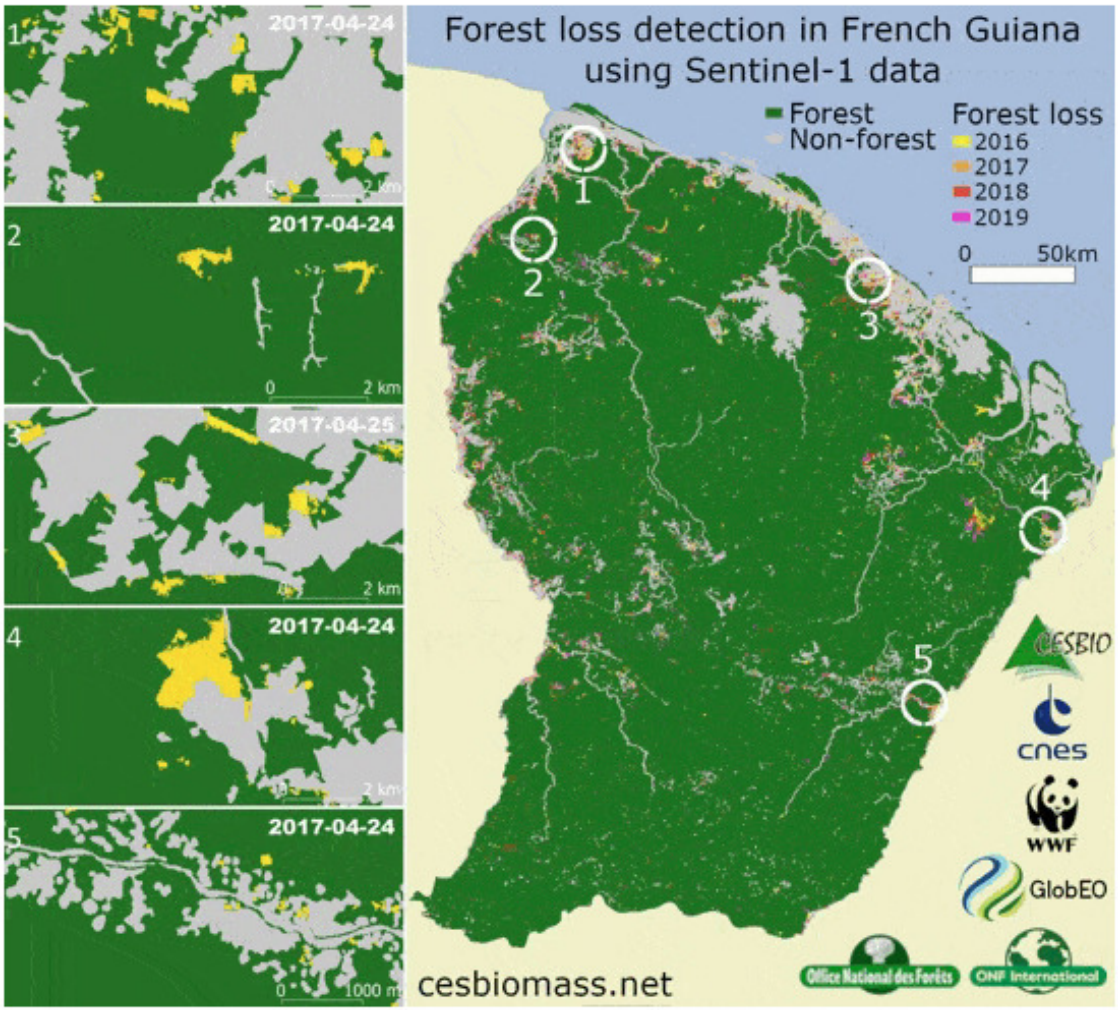
Source: Lang et al. (2025)

Forest monitoring: deforestation



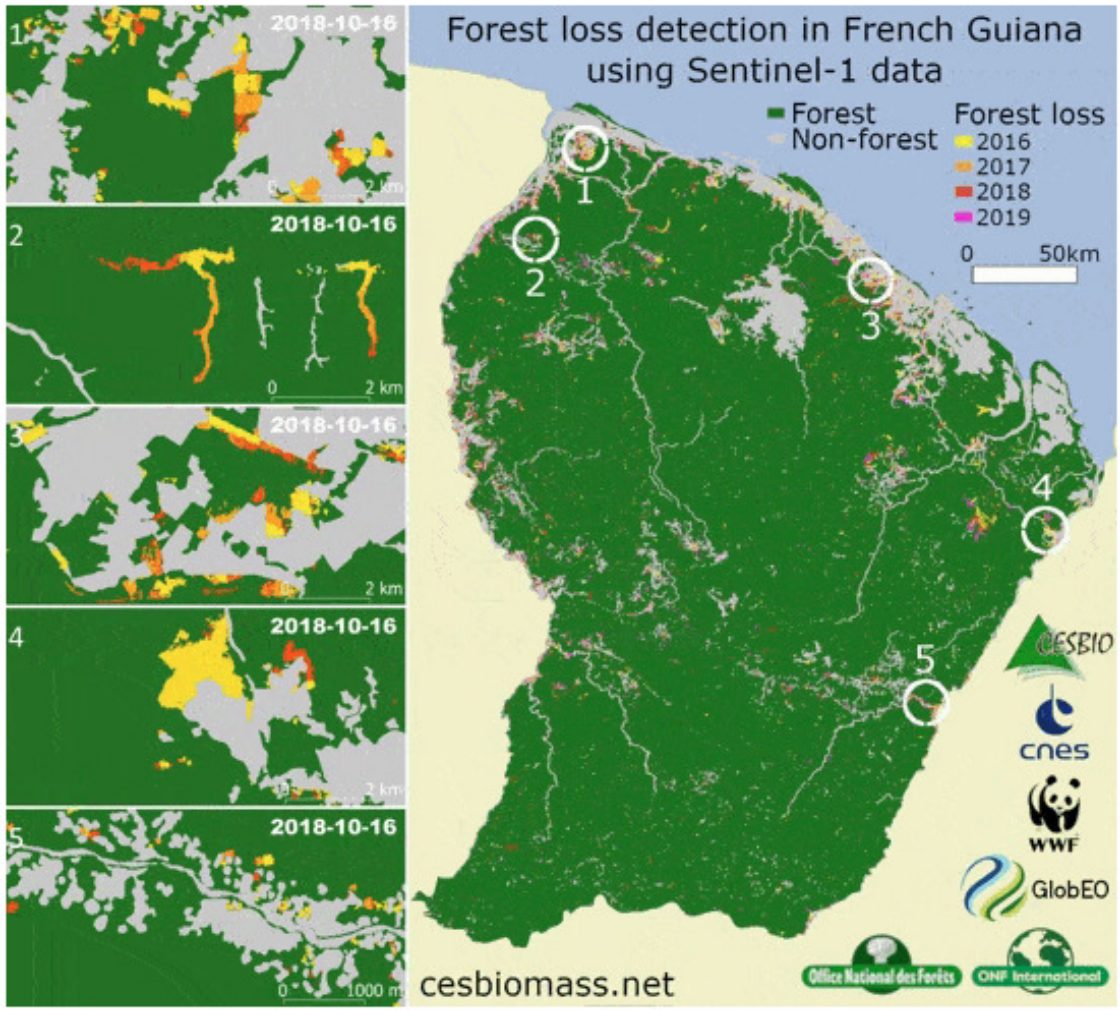
Deforestation in French Guiana over time between 2016 and 2019, source: Space for Climate Observatory

Forest monitoring: deforestation



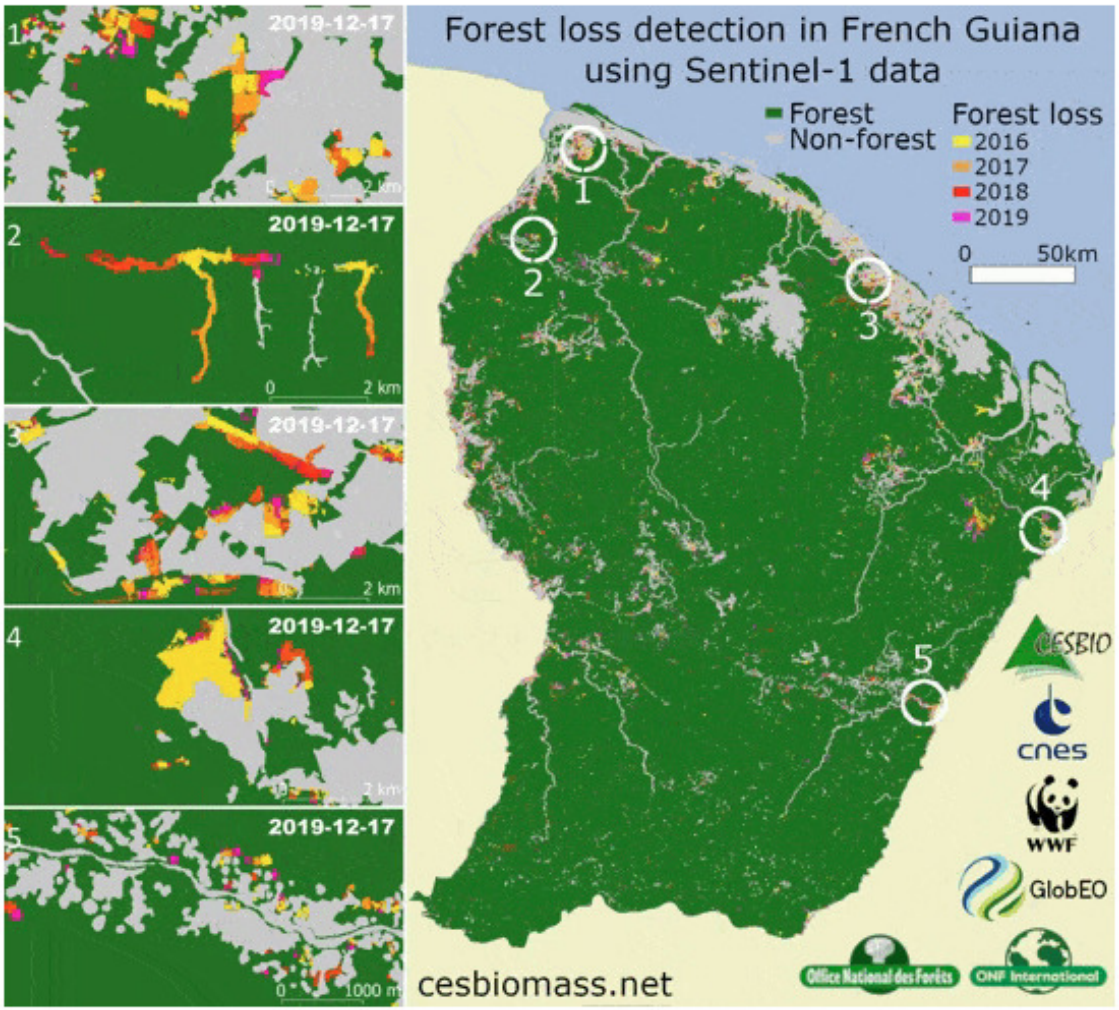
Deforestation in French Guiana over time between 2016 and 2019, source: Space for Climate Observatory

Forest monitoring: deforestation



Deforestation in French Guiana over time between 2016 and 2019, source: Space for Climate Observatory

Forest monitoring: deforestation

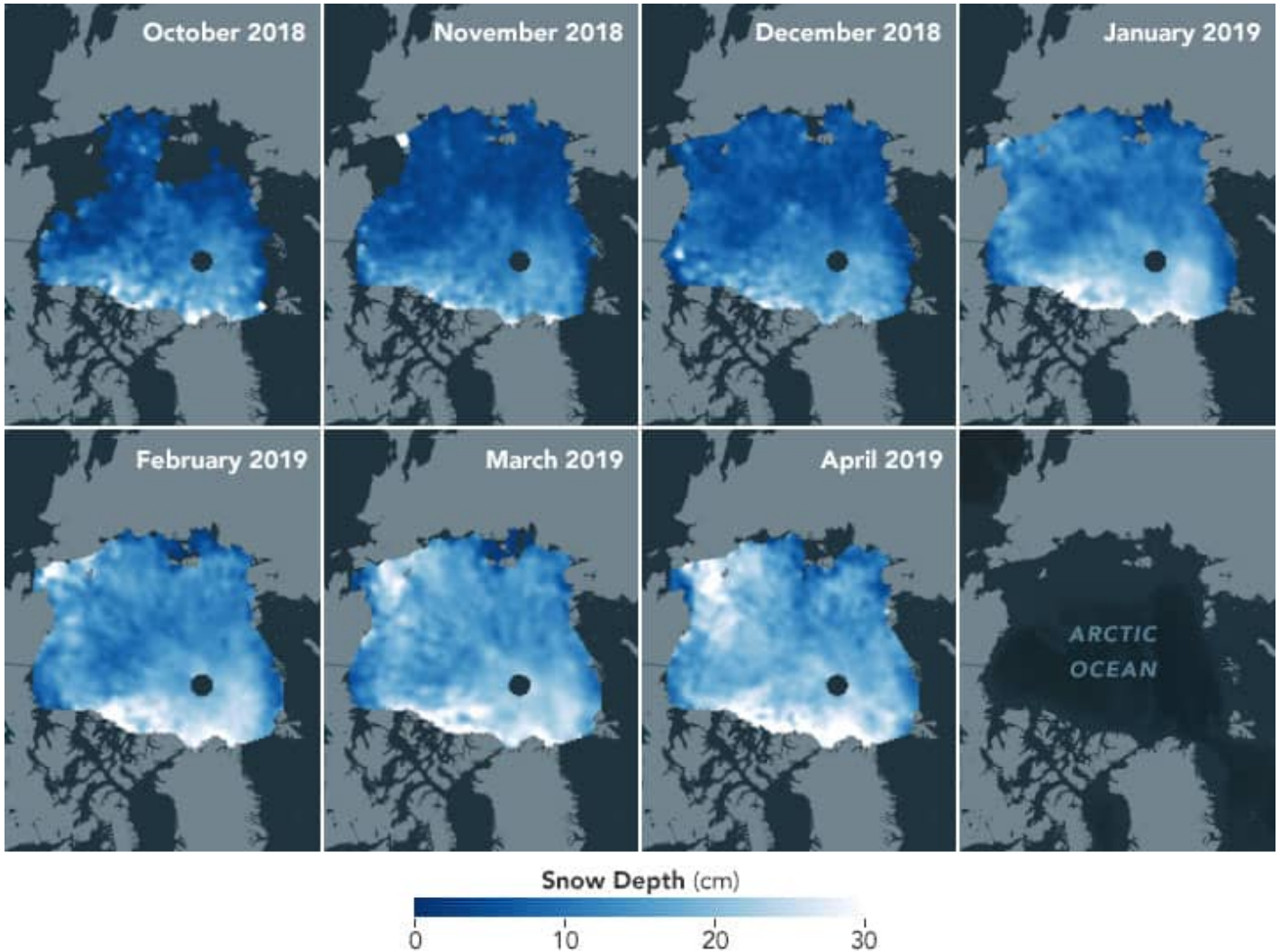


Deforestation in French Guiana over time between 2016 and 2019, source: Space for Climate Observatory

Forest monitoring: forest clear-cuts detection

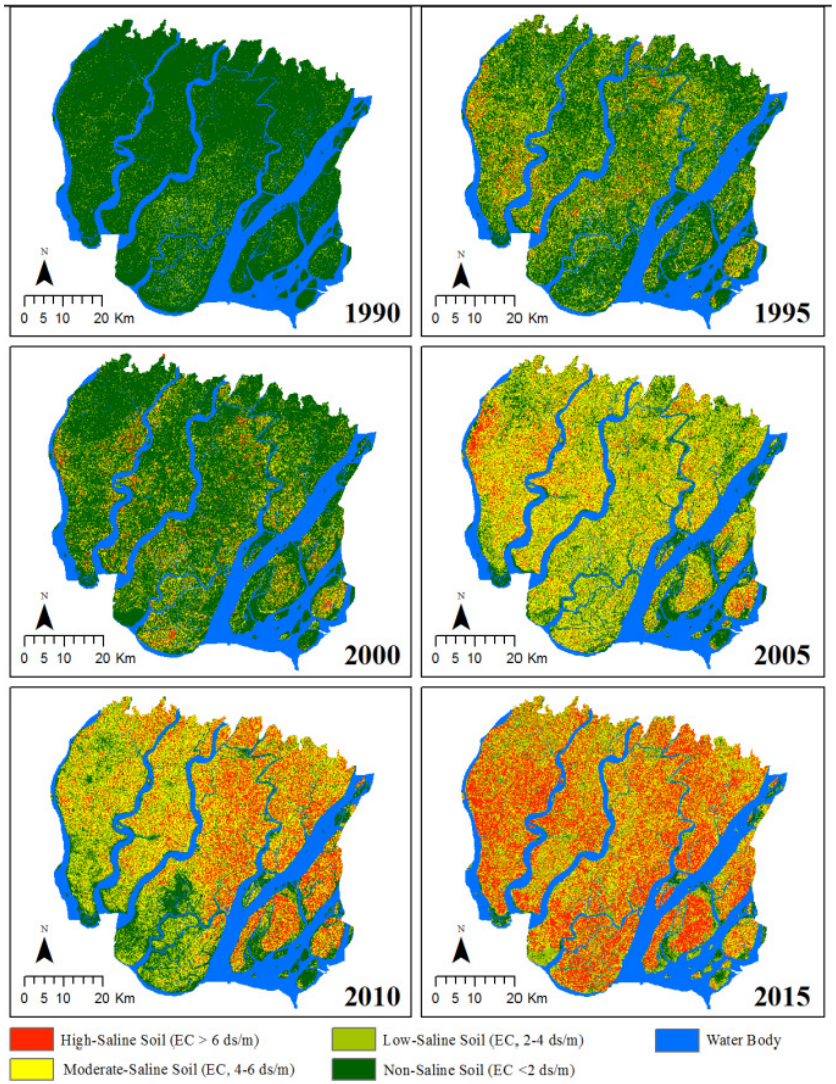
Forest clear-cuts in mainland France, source: Mermoz et al. (2025)

Climate change: ice melt monitoring



Snow depths across Arctic sea ice, source: NASA

Climate change: soil salinity mapping

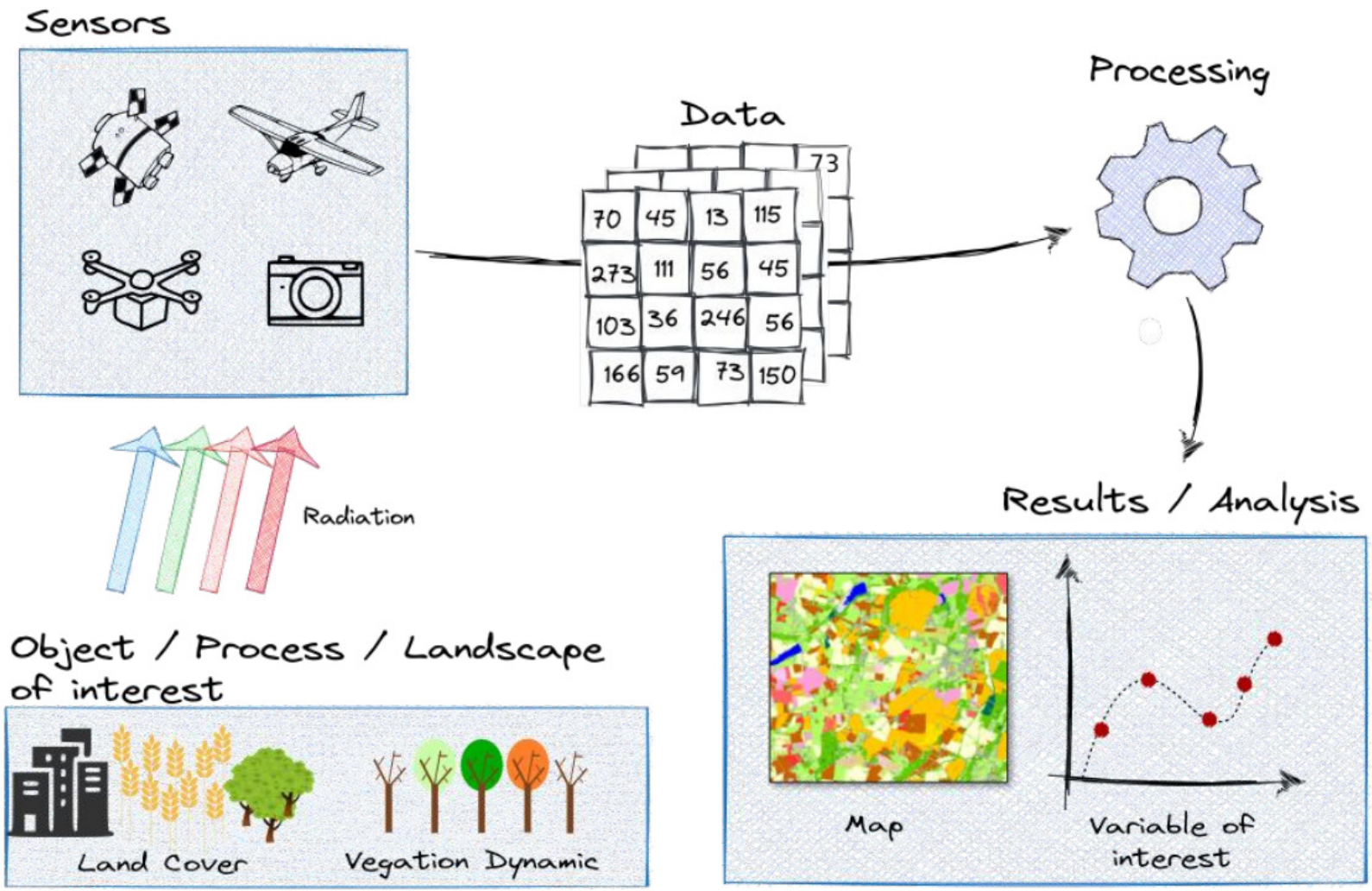


Soil salinity map in coastal Bangladesh, source: Rahman et al. (2018)

Historical mapping: change detection

Historical mapping: change detection

General remote sensing workflow



Source: M. Lang

What is a digital image?

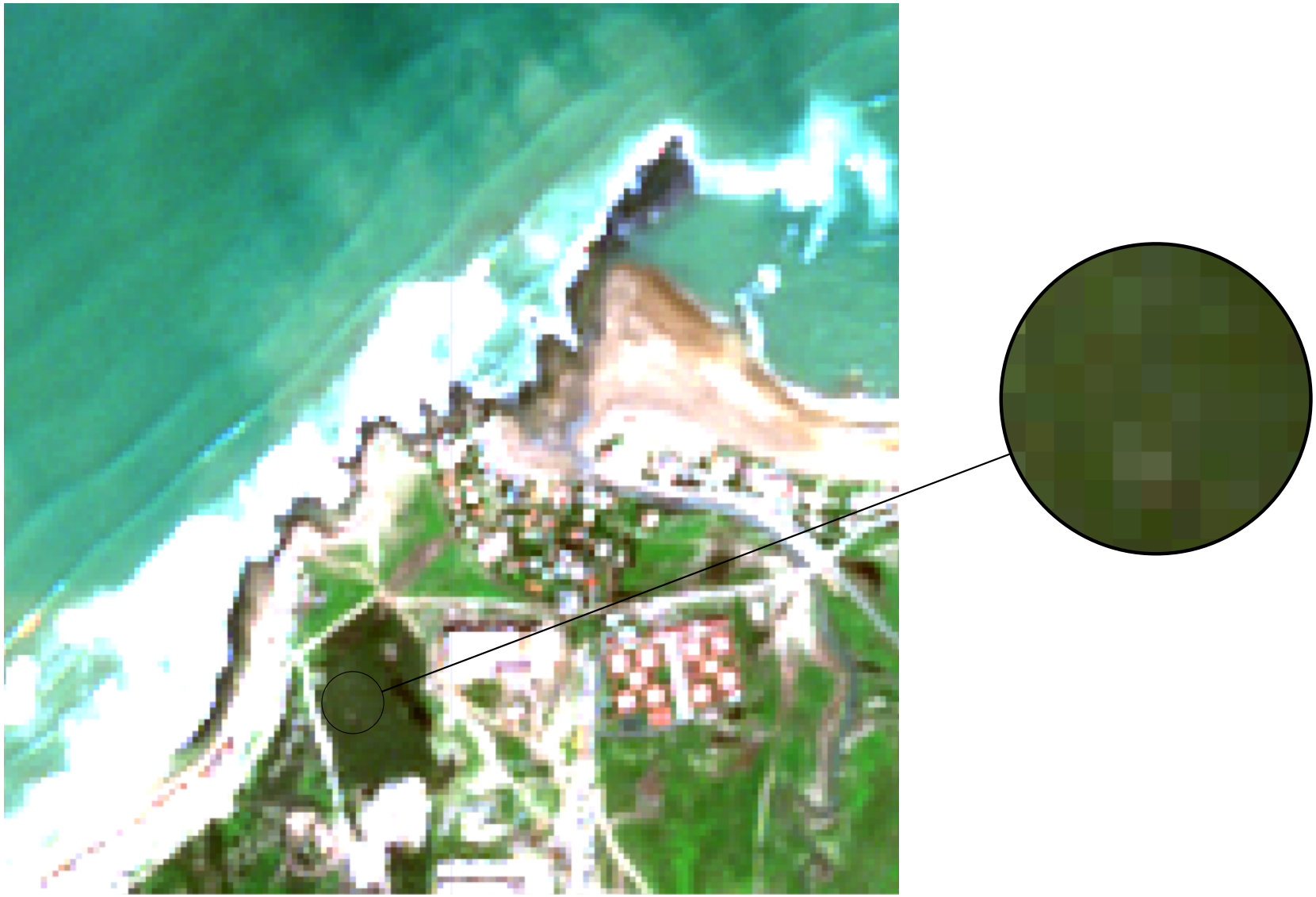
- A digital remote sensing image is a **numerical** representation of the Earth's surface.
- It is obtained by measuring the electromagnetic signal reflected or emitted by the surface using a sensor.
- Each image is composed of pixels, and each pixel contains a numerical value representing the measured signal.

Key idea

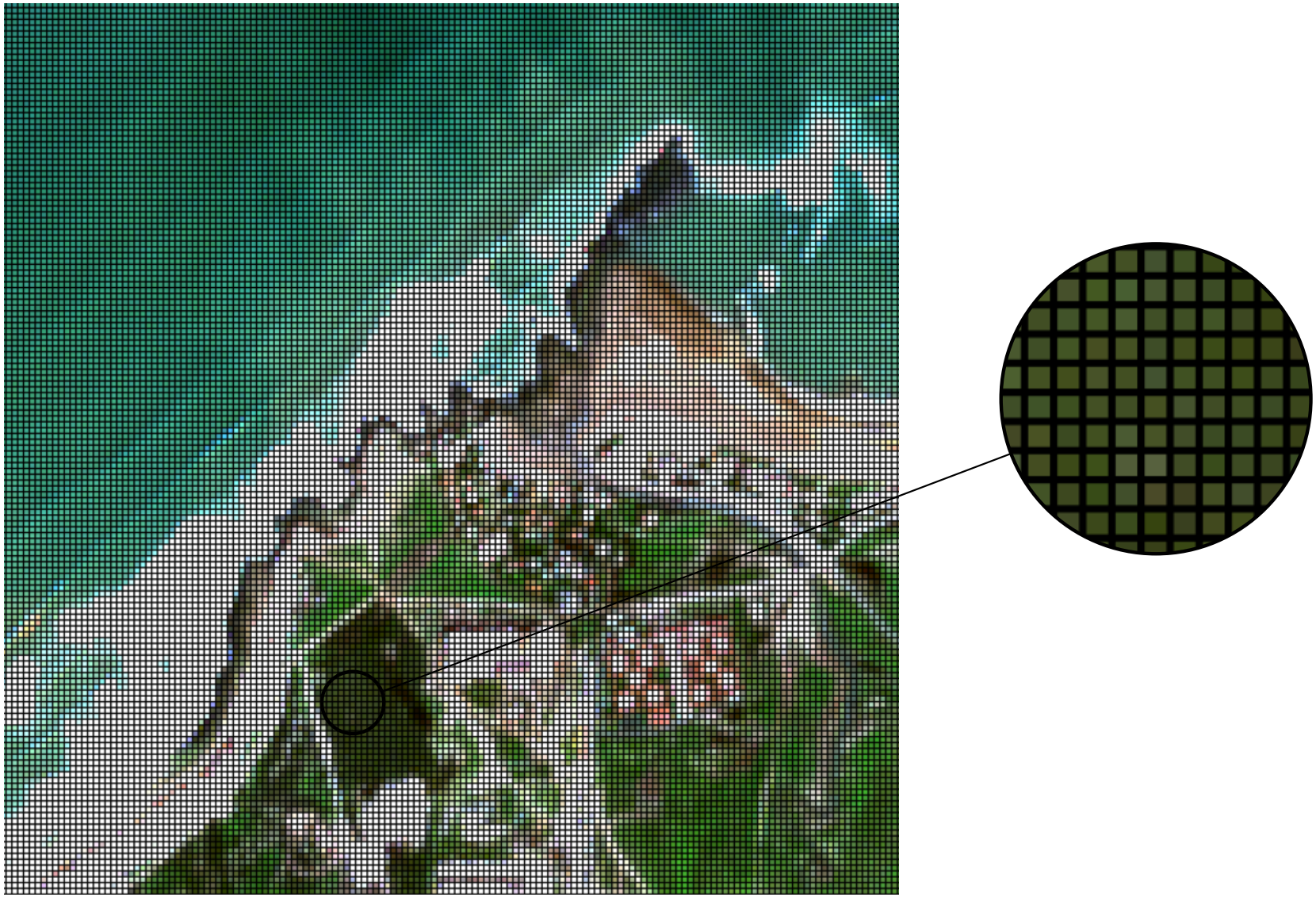
A remote sensing image is a **spatial**, **spectral** and **temporal** sampling of the Earth's surface.

What is a digital image?

What is a digital image?

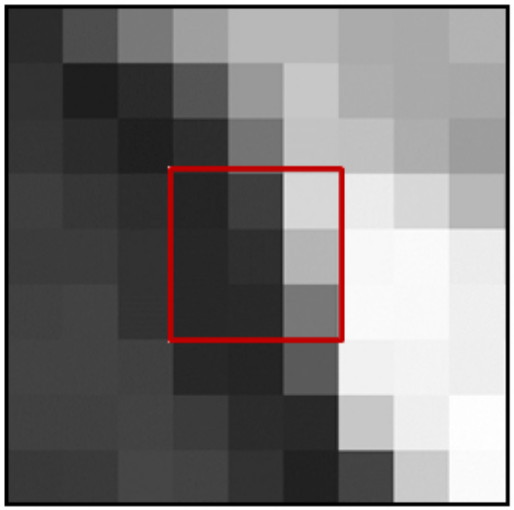


What is a digital image?



What is a digital image?

- A digital image can be represented as a matrix whose elements are pixels (picture elements).
- The individual pixel value is known as a digital number (DN).
- This type of data structure is called a **raster**.
- Raster data are commonly used to represent continuous phenomena (e.g., elevation, temperature) or categorical data (e.g., land cover)

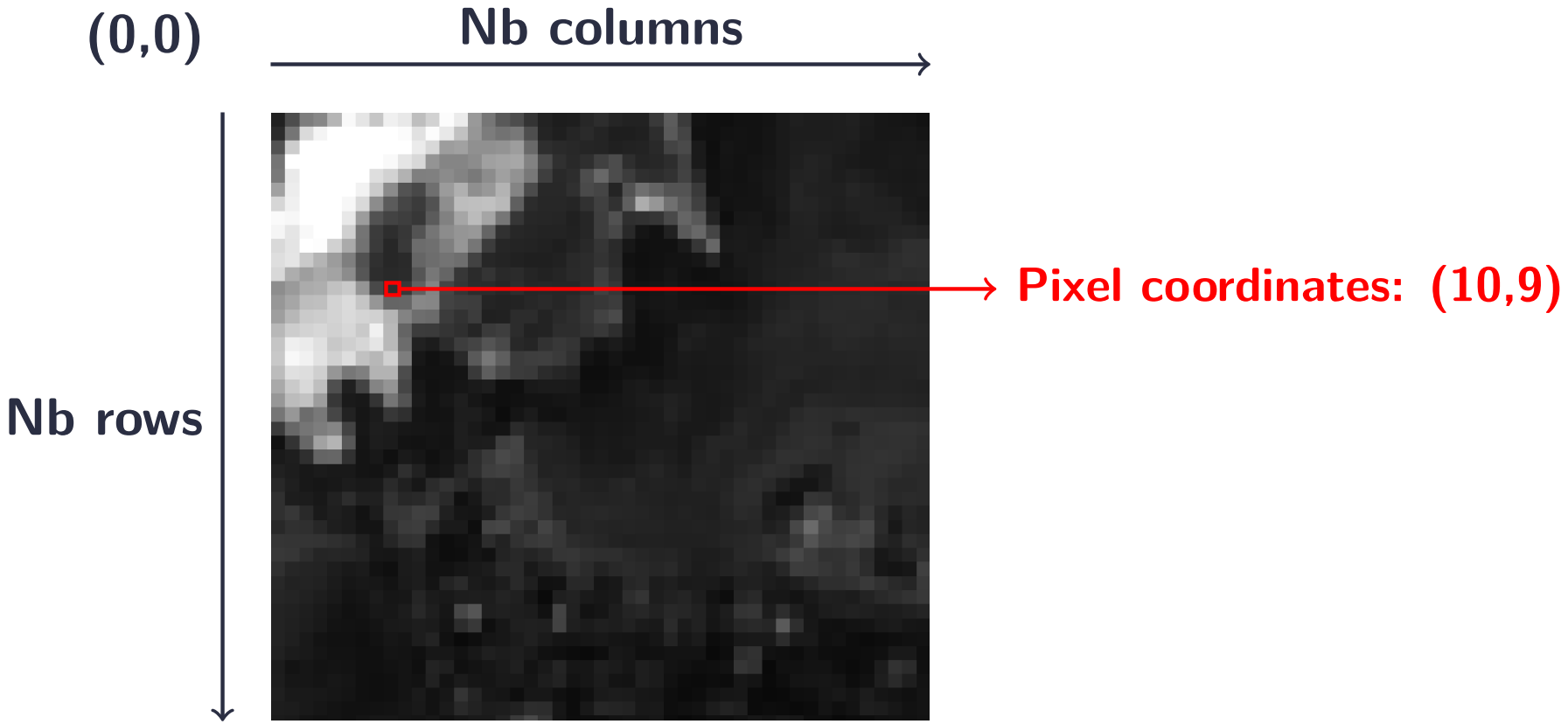


43	102	169
35	58	191
38	44	155

Source: https://gsp.humboldt.edu/

What is a digital image?

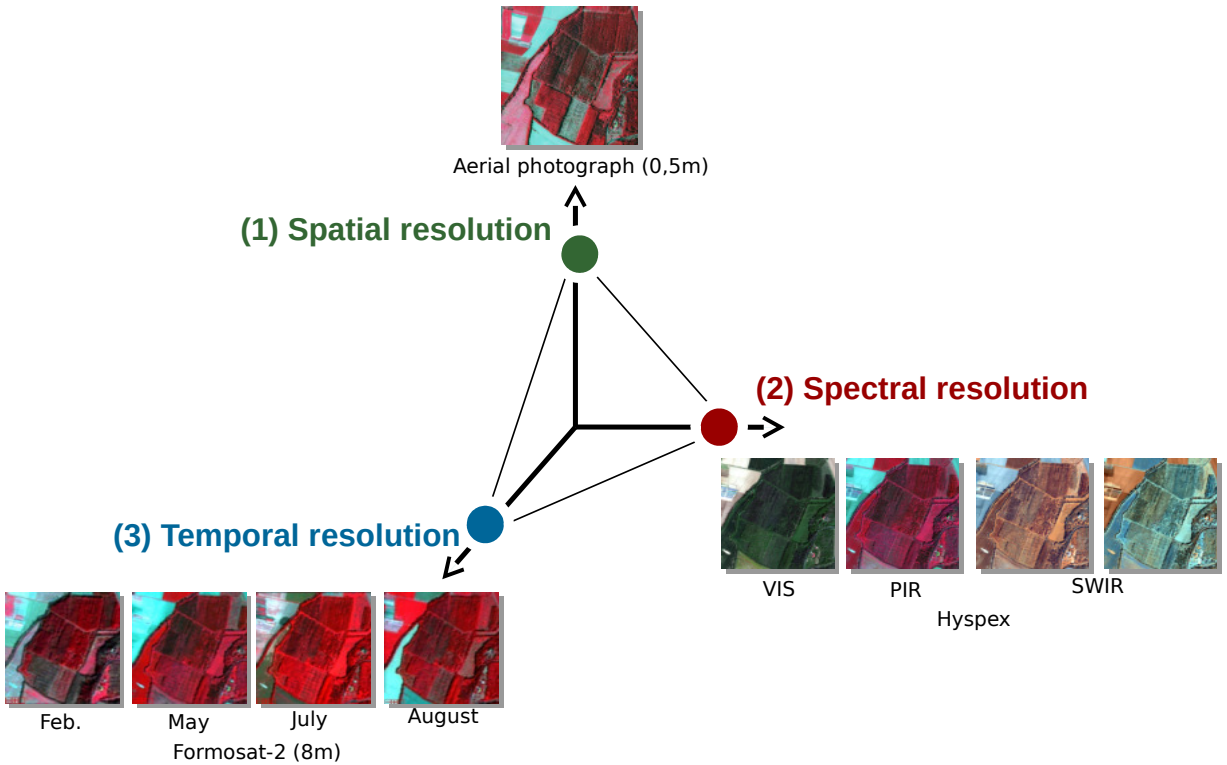
- Remote sensing images are raster datasets composed of a grid of pixels arranged in rows and columns.
- The origin of the image is the **upper-left pixel**, with coordinates (row 0, column 0).



Key characteristics of remote sensing images

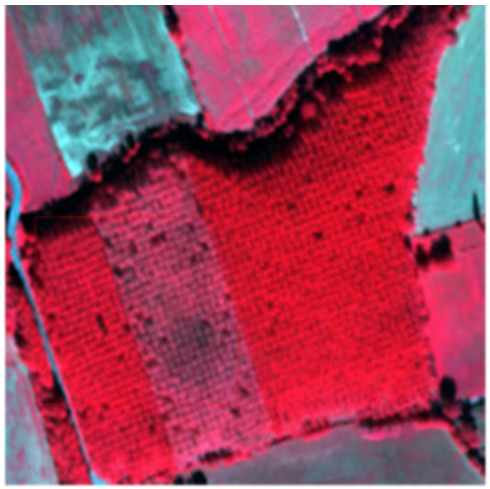
- Remote sensing images are characterized by different resolutions:
  - Spatial resolution
  - Spectral resolution
  - Temporal resolution

⚖ **You just can't have it all!**

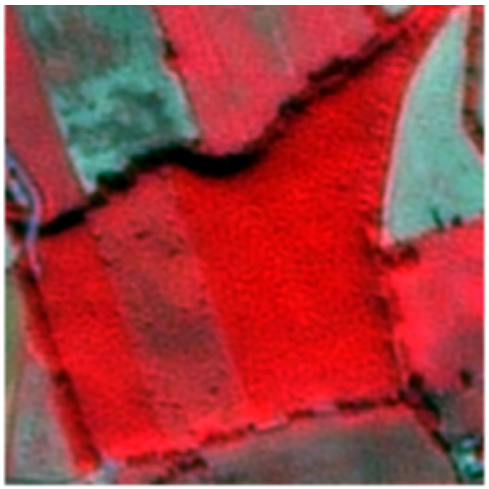


Key characteristics of remote sensing images

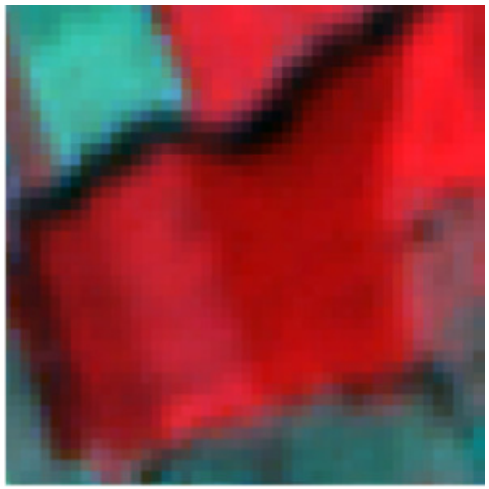
- **Spatial** resolution refers to the size of the ground area represented by one pixel in an image
- It determines the level of spatial detail that can be observed
- It is usually defined as the length of one side of a pixel on the ground
- A spatial resolution of 20 m: one pixel represents an area of 20 m x 20 m on the ground



WorldView-2 MS (1.8 m)



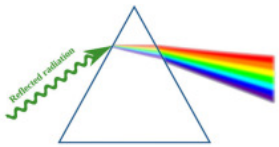
Spot-5 (2.5 m)



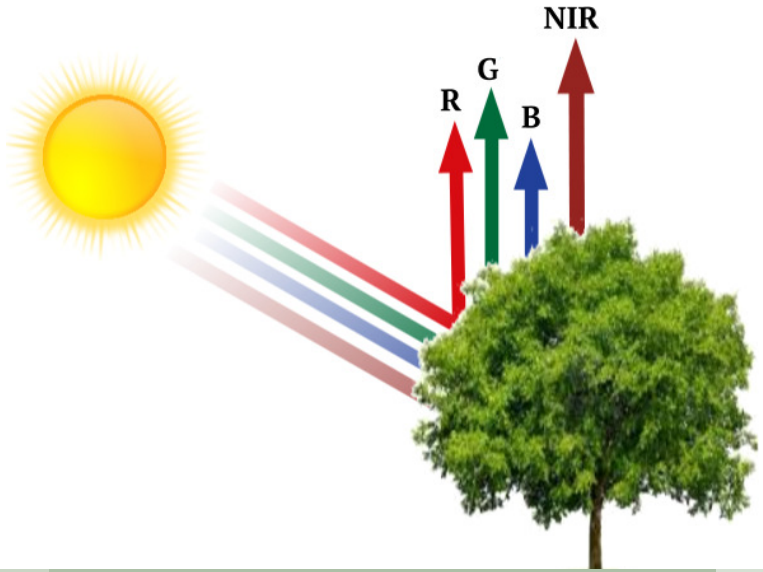
Spot-4 MS (20 m)

Key characteristics of remote sensing images

- **Spectral** resolution reflects the ability of a sensor to distinguish between electromagnetic radiations of different wavelengths



- The sensor acts as a prism: it separates the reflected radiation into different **spectral bands**, so sensors can be classified as:
  - **Panchromatic**: a single broad spectral band (grayscale image)
  - **Multispectral**: a limited number of discrete spectral bands
  - **Hyperspectral**: hundreds of narrow and contiguous spectral bands



Key characteristics of remote sensing images

- **Temporal** resolution refers to the time interval between two observations of the same location by a sensor. It is important for:
  - change detection
  - near real-time monotoring
- Poplar plantations observed with Sentinel-2 in 2019:

24/08/2019

13/09/2019

08/10/2019

Key characteristics of remote sensing images

🤔 Question

What differences do you observe between these two images?

Image 1

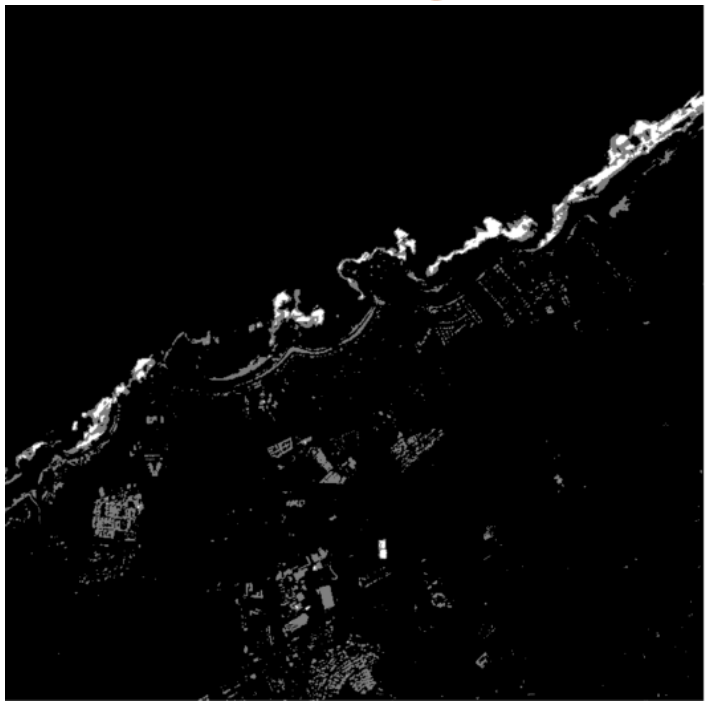
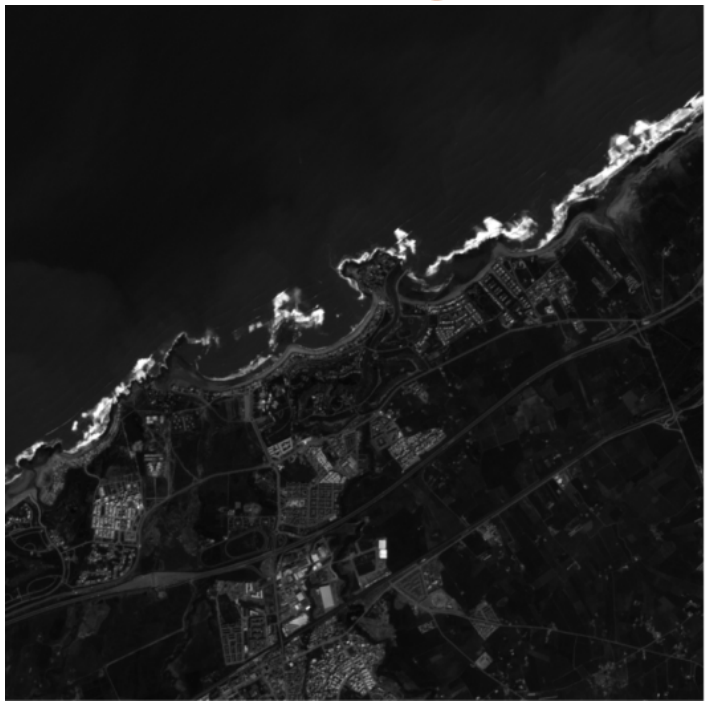


Image 2



Key characteristics of remote sensing images

🤔 Question

What differences do you observe between these two images?

Image 1

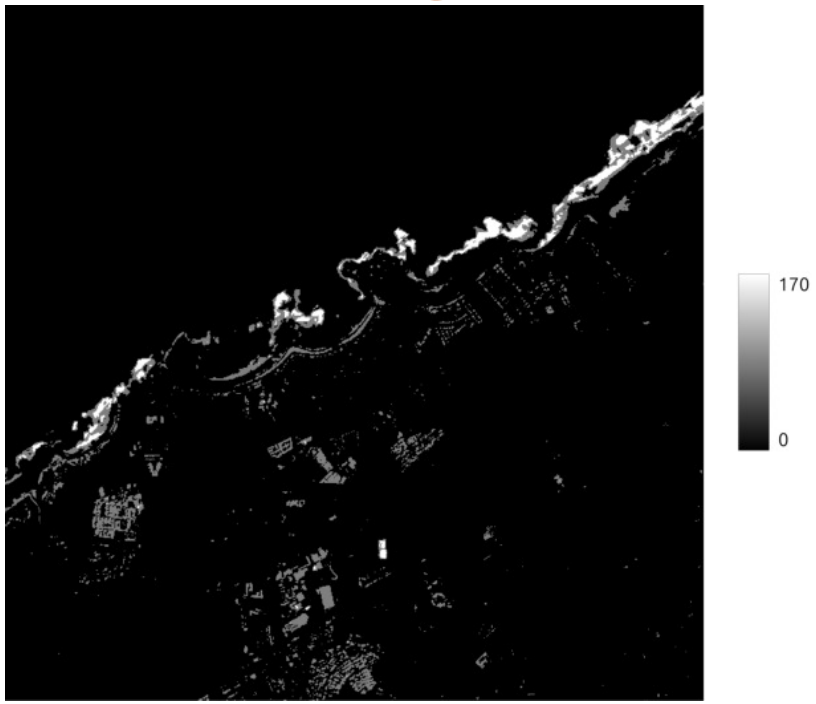
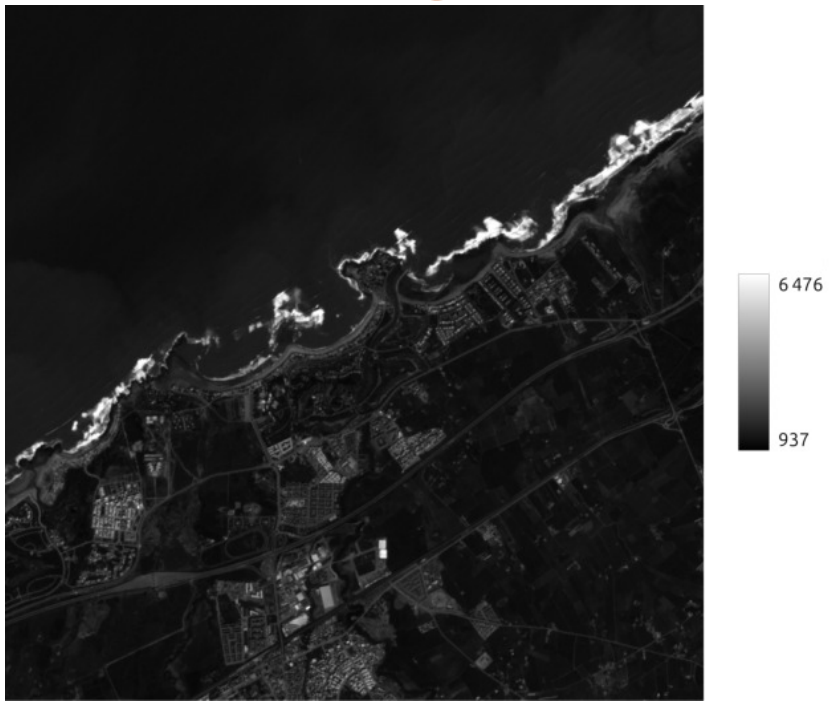


Image 2



Key characteristics of remote sensing images

🤔 Question

What differences do you observe between these two images?

Image 1: 4 gray levels

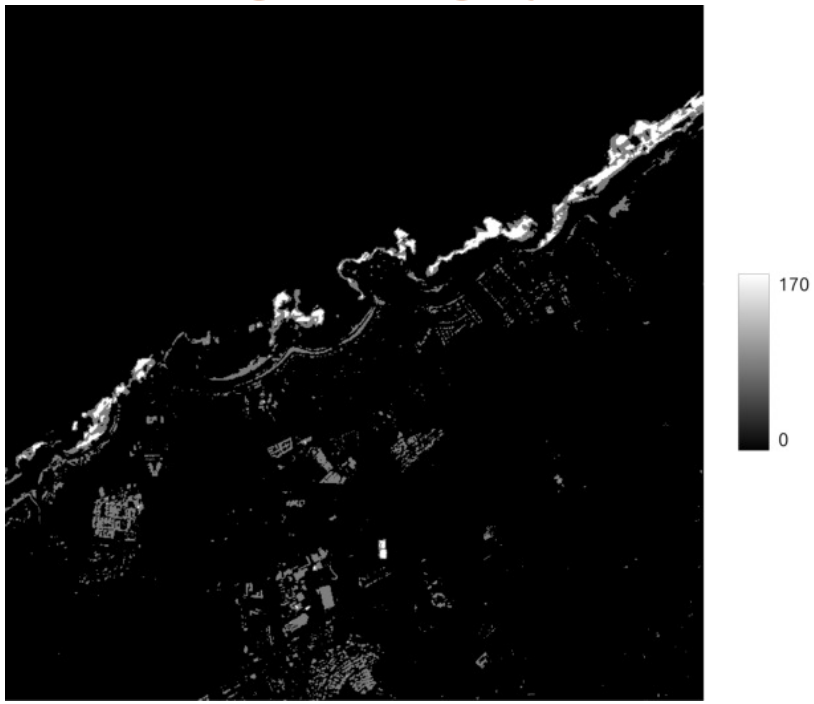
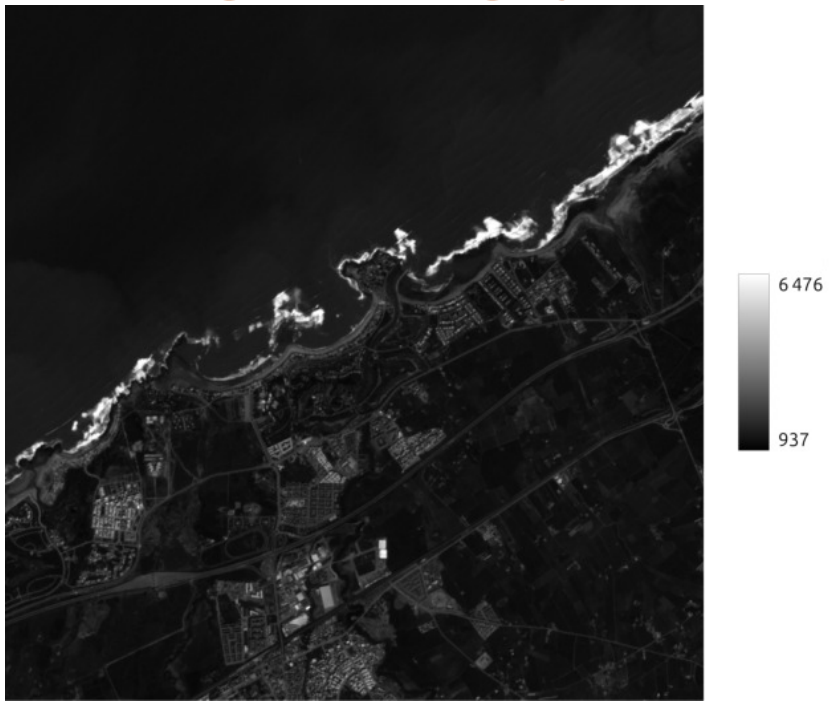


Image 2: 256 gray levels



Key characteristics of remote sensing images

- **Radiometric** resolution defines the number of gray levels used to represent the brightness of each pixel.
- The maximum number of brightness levels depends on the **number of bits** used to encode pixel values.
- The number of possible digital values is given by:

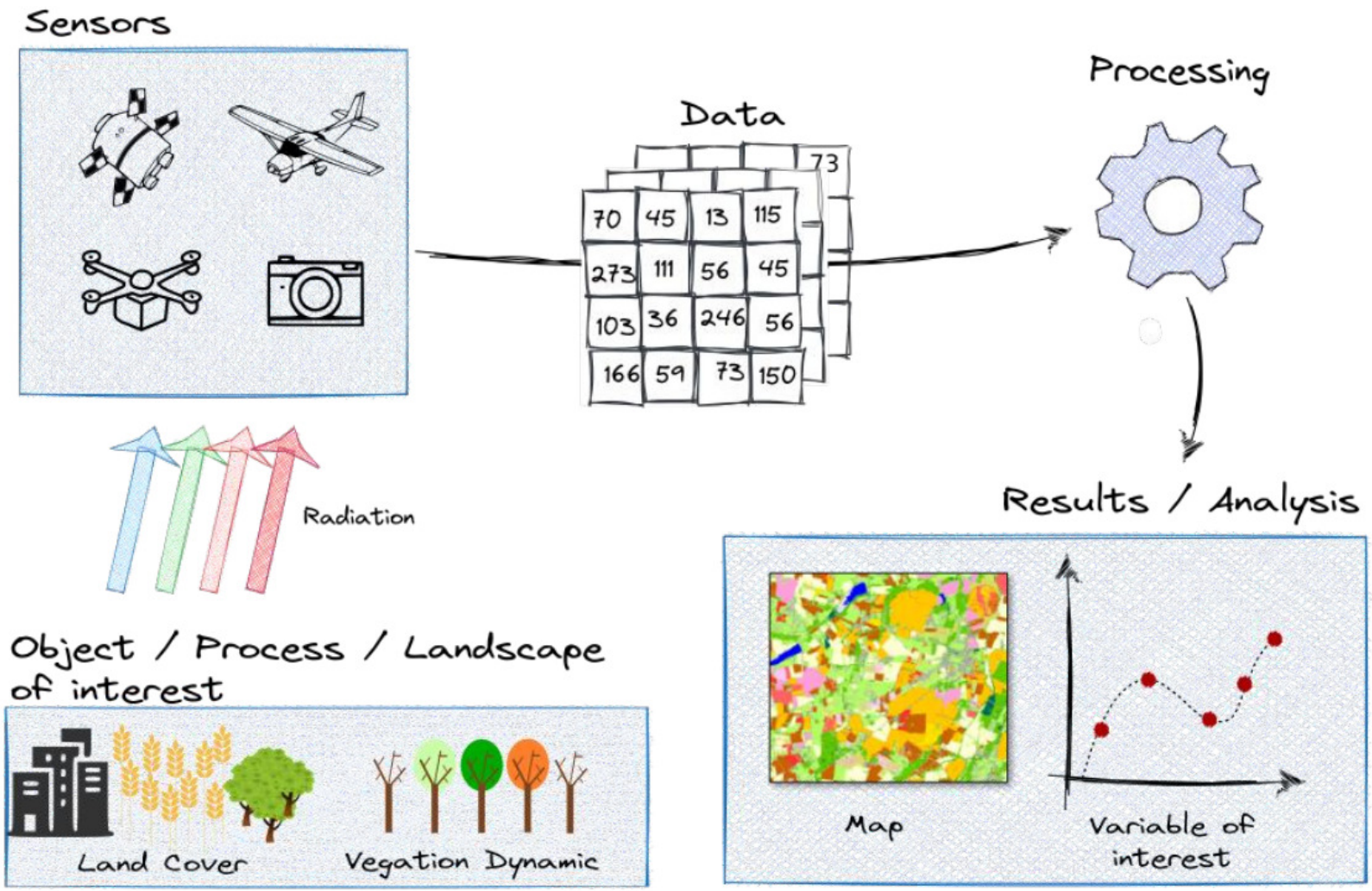
$$\text{Number of gray levels} = 2^{\text{number of bits}}$$

- Examples:
  - 2 bits $\rightarrow 2^2 = 4$ gray levels
  - 8 bits $\rightarrow 2^8 = 256$ gray levels
  - 16 bits $\rightarrow 2^{16} = 65\,536$

Key idea

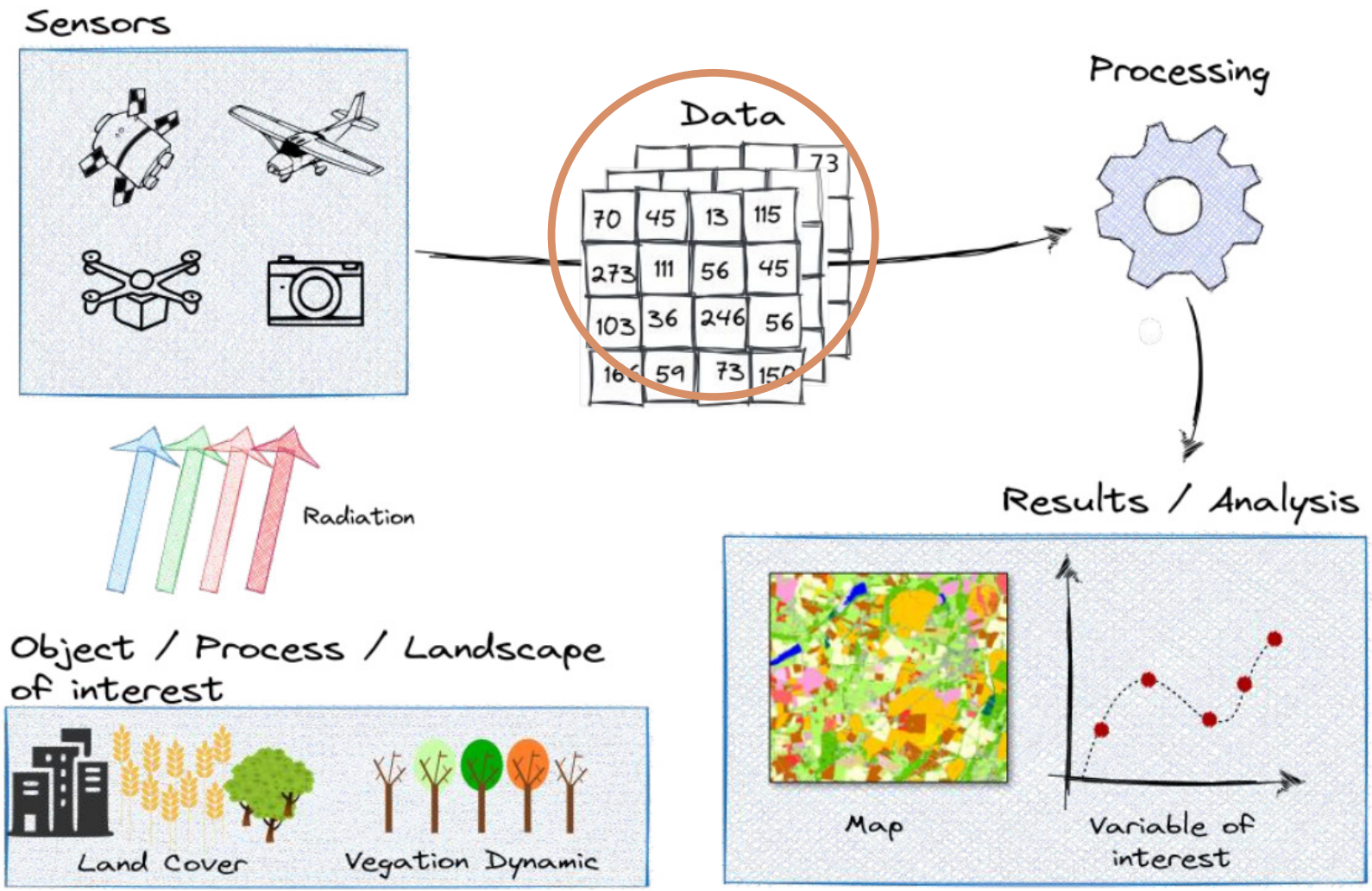
Higher radiometric resolution allows finer discrimination of brightness variations in an image, but also larger data volume and higher sensitivity to noise!

From satellite images to useful information



Source: M. Lang

From satellite images to useful information



Source: M. Lang

From satellite images to useful information

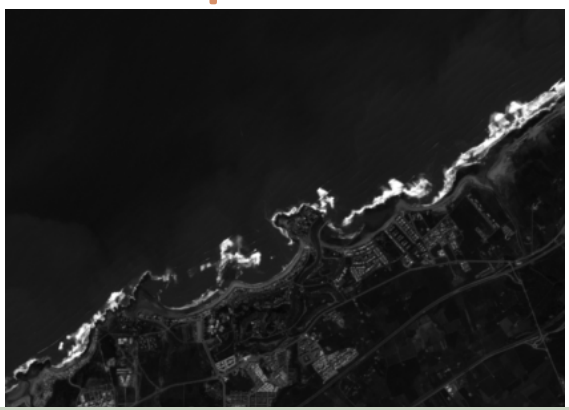
What lies behind the data used for analysis?

From satellite images to useful information

What lies behind the data used for analysis?

- **Spectral information**: spectral bands and spectral indices (e.g. NDVI, reflectance in different bands)
- **Spatial information**: texture or spatial patterns describing pixel arrangement (e.g. urban structures, forest canopy patterns)
- **Temporal information**: spectral changes observed at different dates (e.g. crop phenology, seasonal dynamics)
- These variables are used as **inputs** for image analysis and machine learning models.

Blue spectral band



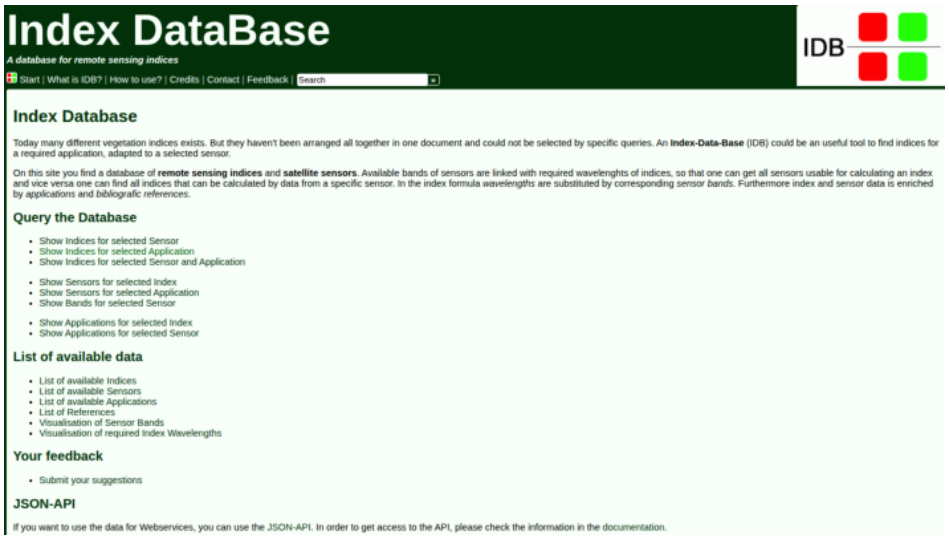
RGB composite

NDVI spectral index

From satellite images to useful information

Focus on spectral indices

- **Main objective:** Highlight specific surface properties (e.g., vegetation, water, soil) or phenomema by enhancing differences in spectral reflectance.
- **Principle:** Combine two or more spectral bands using mathematical operations (e.g., ratios or normalized differences) to emphasize particular features.



Spectral Index Database: https://www.indexdatabase.de

From satellite images to useful information

Focus on spectral indices: NDVI

- Normalized Difference Vegetation Index (NDVI):
  - estimate vegetation presence and vigor
  - healthy vegetation reflects strongly in the **near-infrared (NIR)** and absorbs strongly in the **red** wavelengths.

$$\mathbf{NDVI} = \frac{\mathbf{NIR} - \mathbf{Red}}{\mathbf{NIR} + \mathbf{Red}}$$

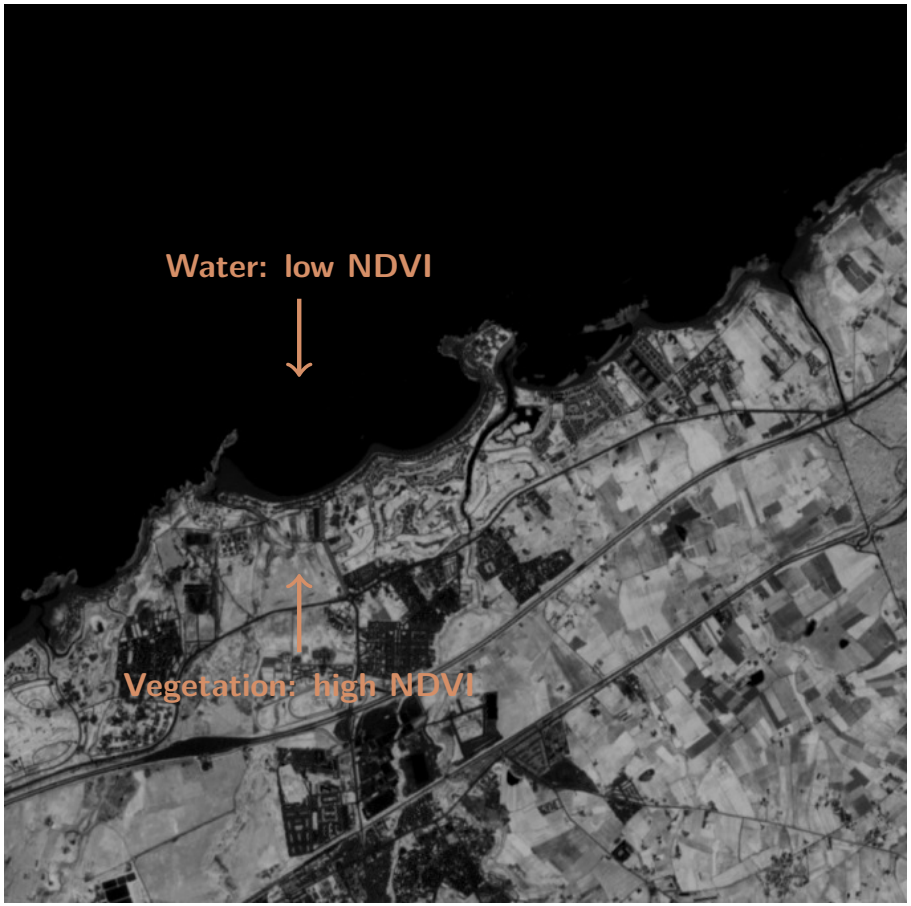
- NDVI values typically range from **-1 to 1**
- Higher values generally indicate **denser and healthier vegetation**
  - healthy vegetation: NIR ↑, Red ↓ → large difference → **high NDVI**
  - sparse/stressed vegetation: NIR ↓, Red ↑ → small difference → **low NDVI**

From satellite images to useful information

Focus on spectral indices: NDVI

RGB

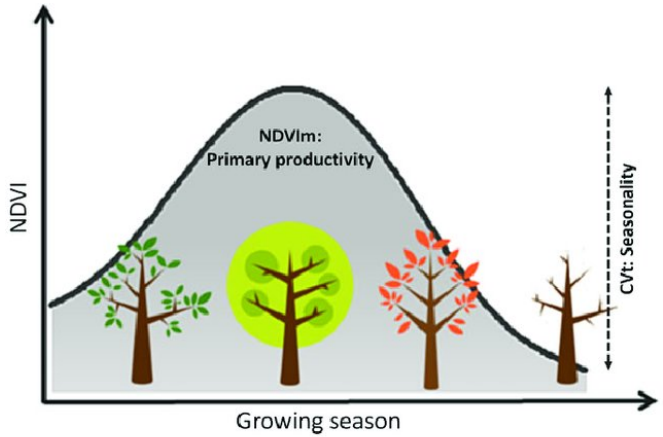
NDVI



From satellite images to useful information

Focus on spectral indices: NDVI

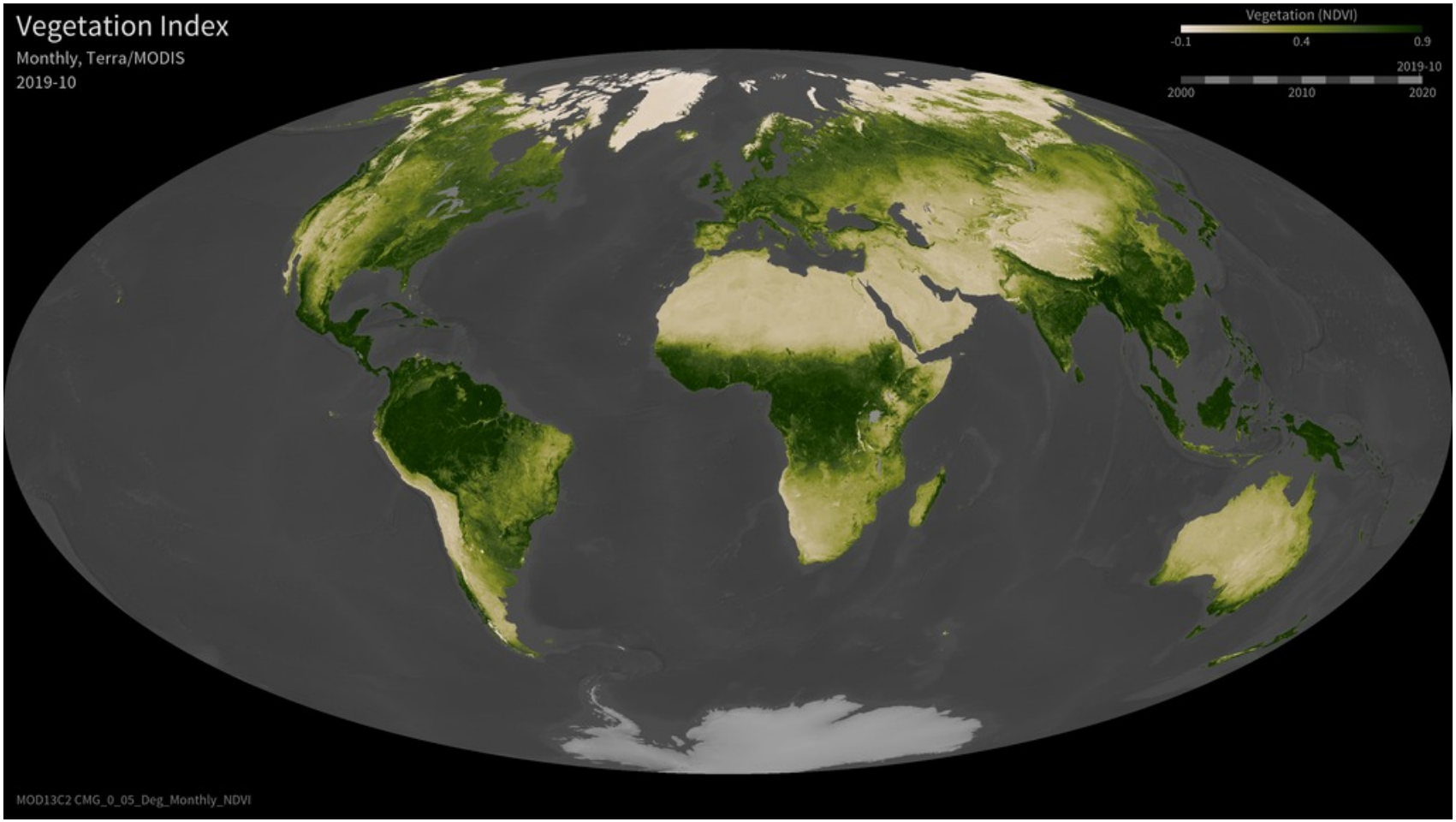
- NDVI can also provide information about **vegetation seasonality**
- By analysing a **time series of NDVI**, we can observe changes in vegetation activity throughout the year
- This allows to identify:
  - crop growth cycles
  - phenological stages
  - seasonal vegetation dynamics



Source: Dieguez and Paruelo (2017)

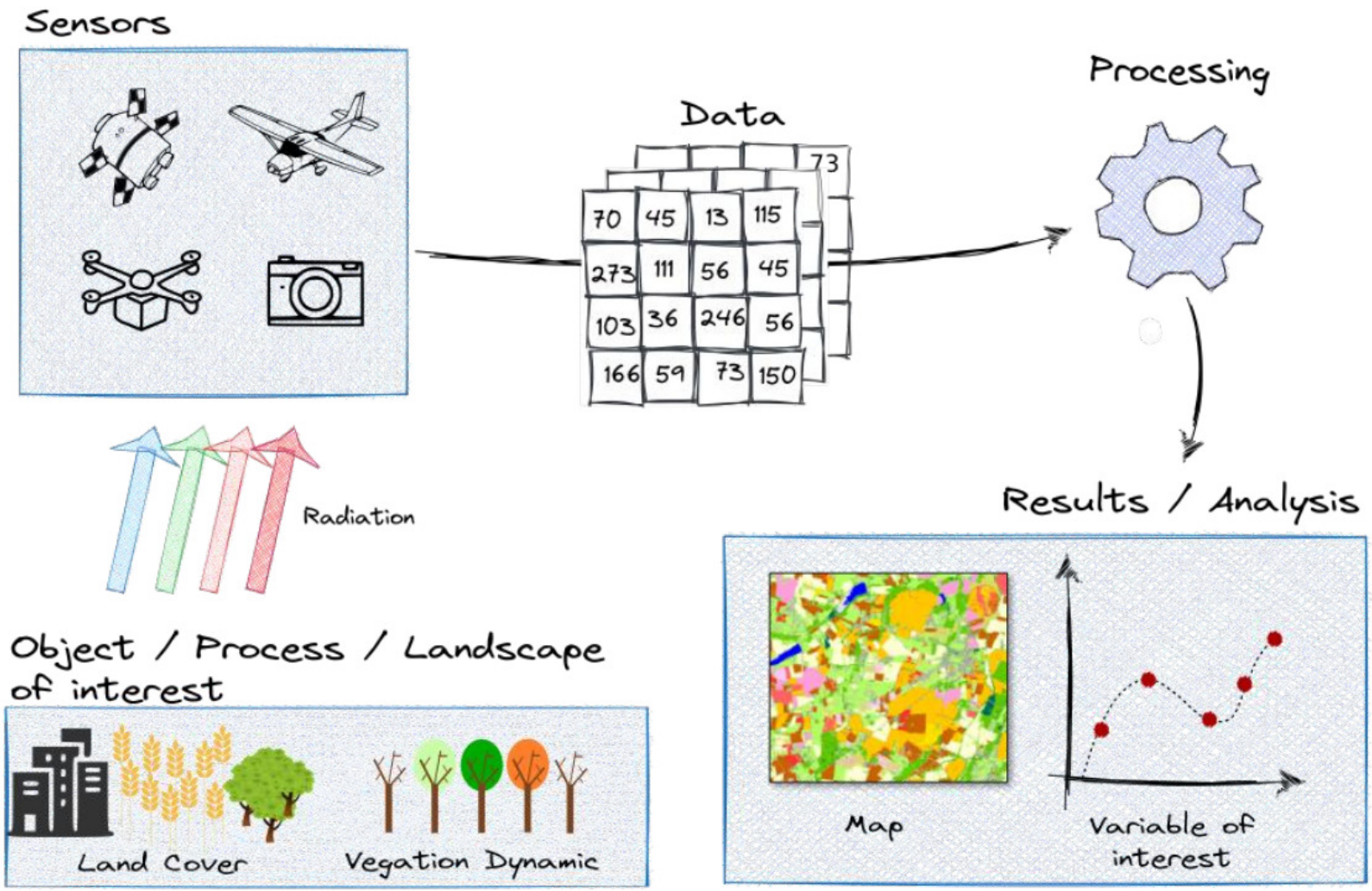
From satellite images to useful information

Focus on spectral indices: NDVI



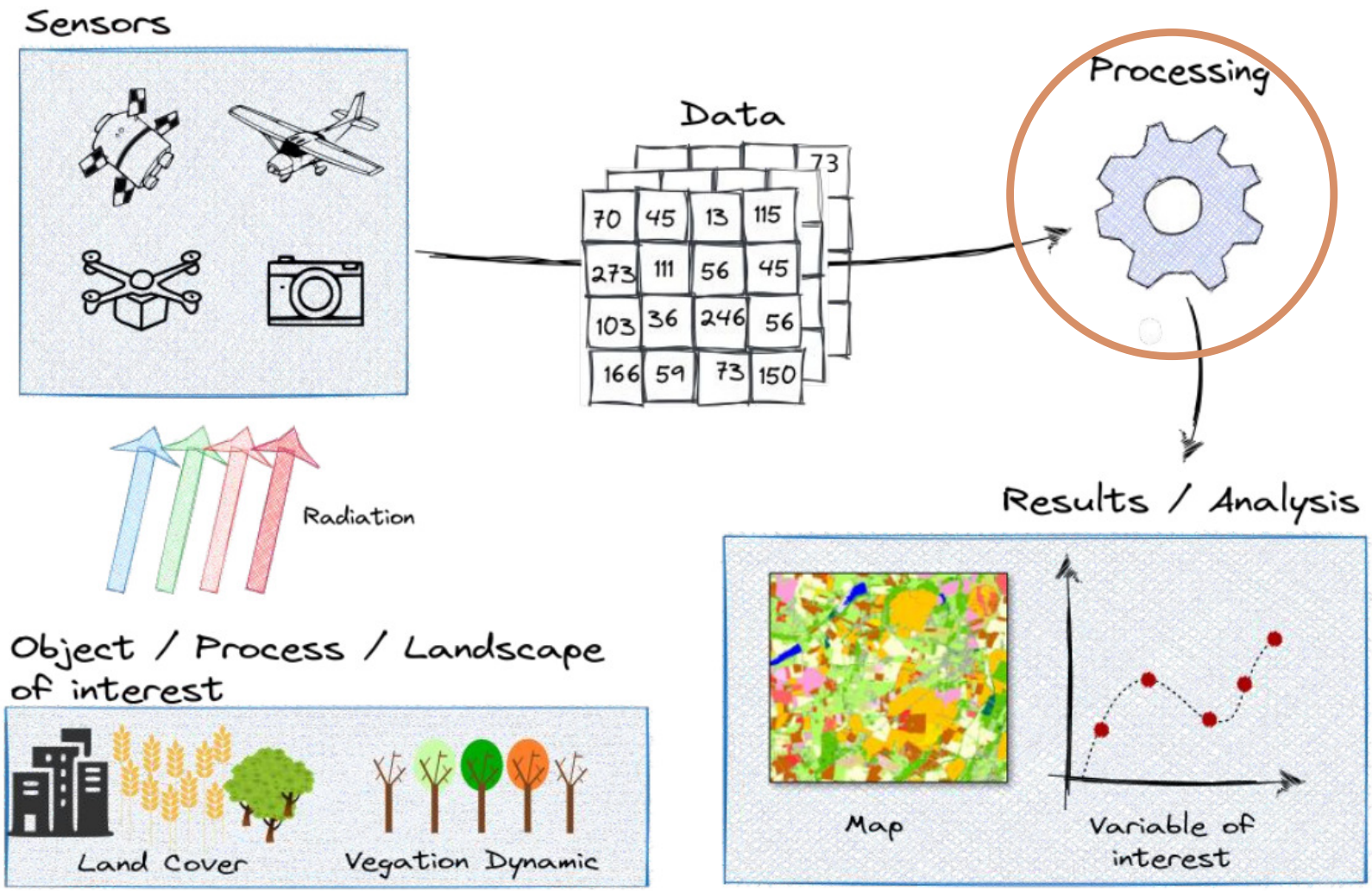
NDVI collected by MODIS on NASA's Terra satellite (16-day composites, monthly)

From satellite images to useful information



Source: M. Lang

From satellite images to useful information



Source: M. Lang

From satellite images to useful information

How can spectral, spatial and temporal information be transformed into thematic maps or decision-support information?

From satellite images to useful information

How can spectral, spatial and temporal information be transformed into thematic maps or decision-support information?

- One common approach is to use **machine learning algorithms**
- These algorithms learn relationships between:
  - **input variables** (bands, indices, texture, time series)
  - **target variables** (e.g. land cover classes, biomass, yield)

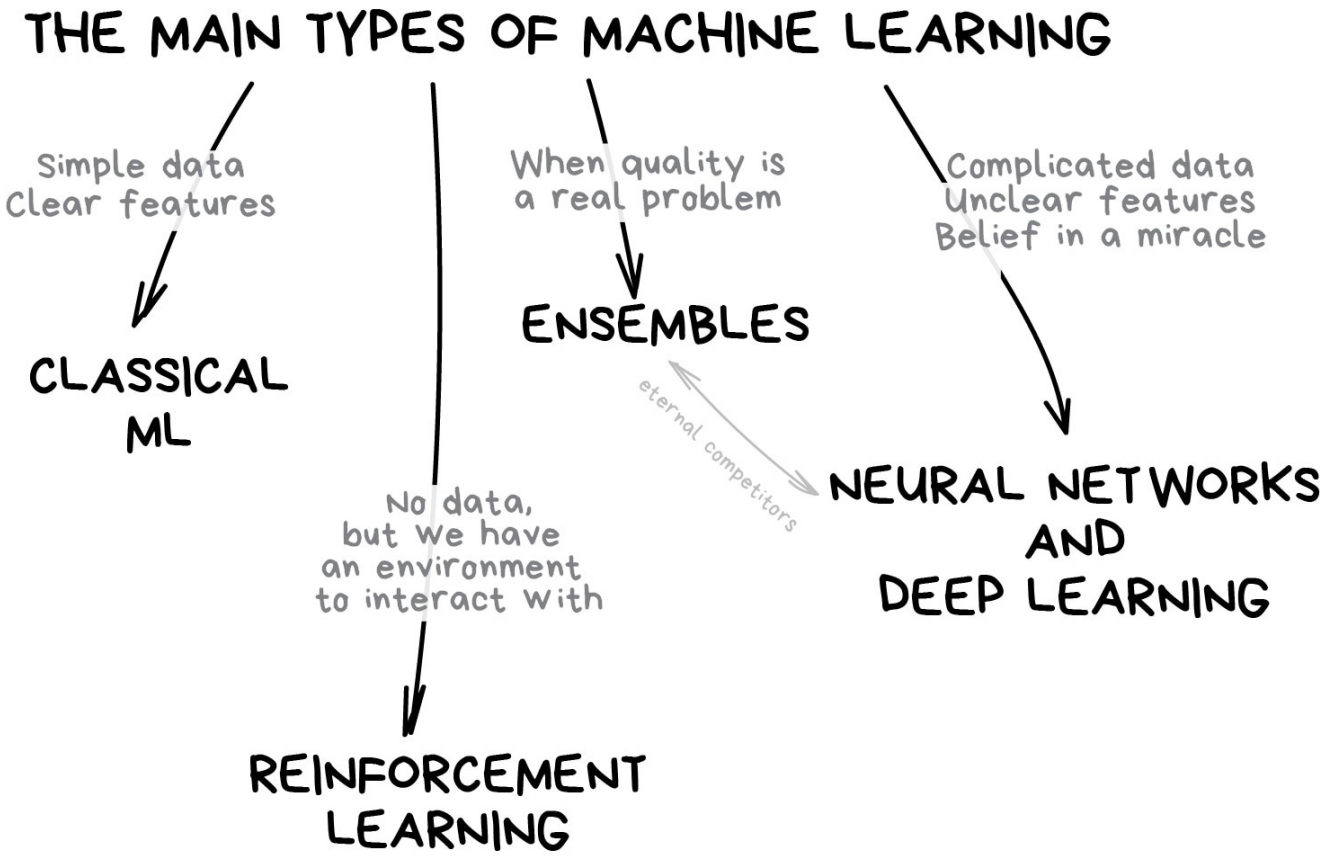
Key idea

Machine learning models learn relationships between input variables and a target variable.

- If the **target variable is discrete** → **classification problem**: crop type mapping, land cover classification
- If the **target variable is continuous** → **regression problem**: biomass estimation, yield prediction

From satellite images to useful information

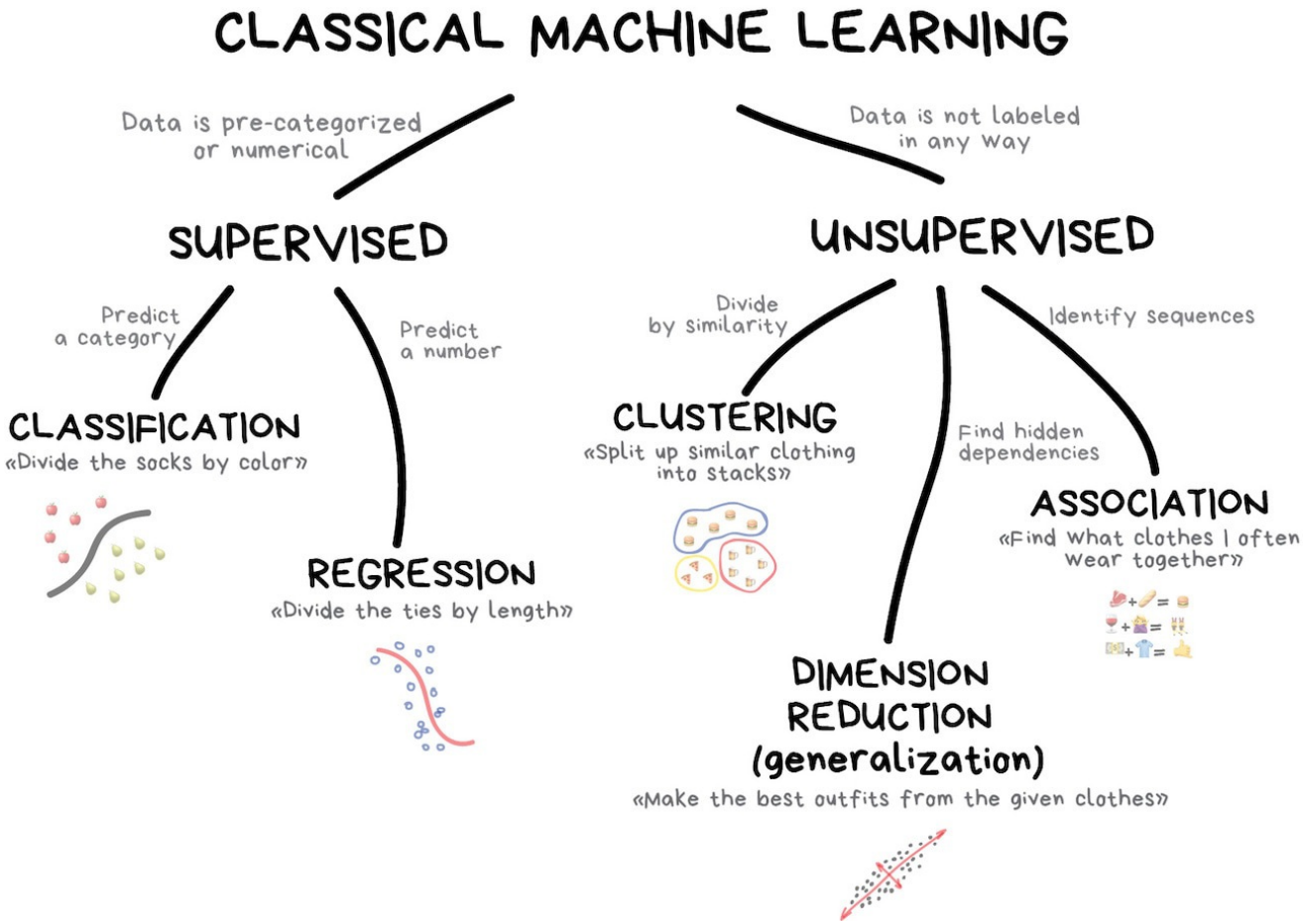
Machine learning algorithms



Source: noeliagorod

From satellite images to useful information

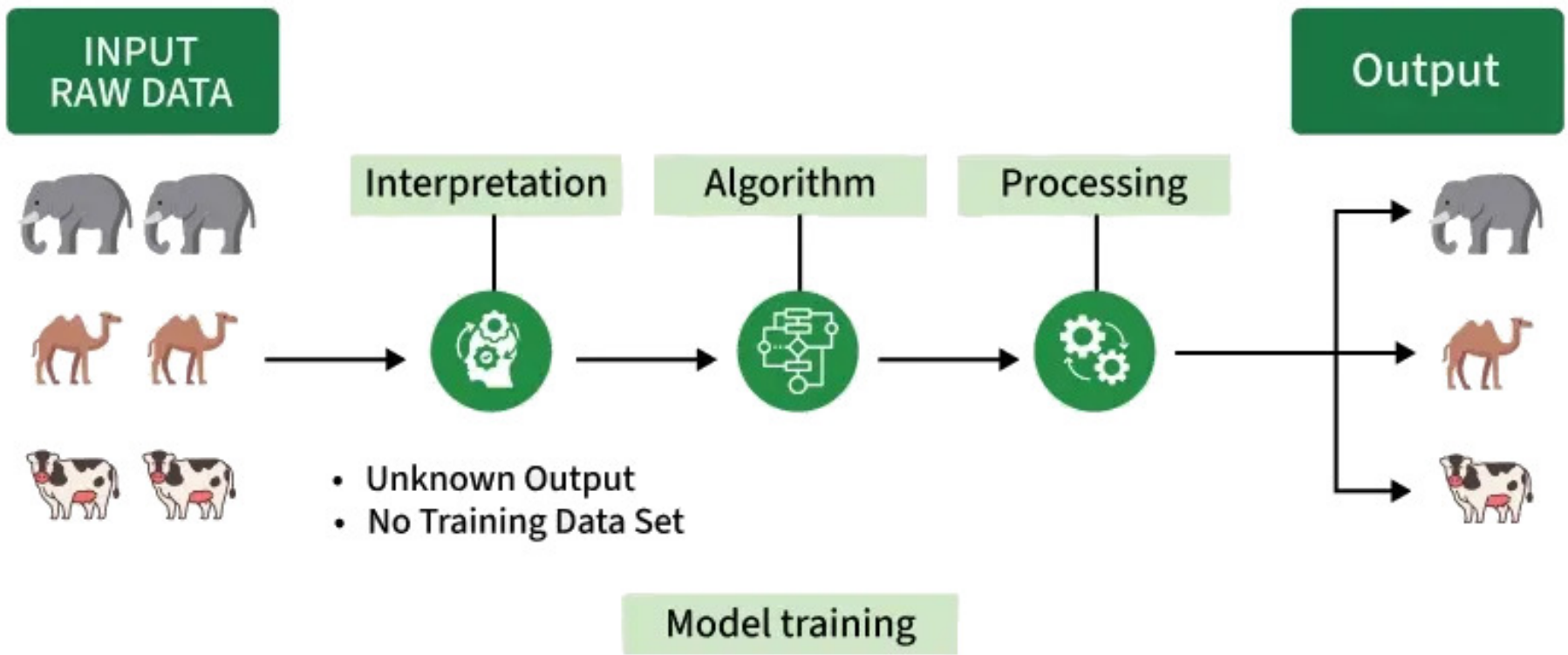
Machine learning algorithms



Source: noeliagorod

From satellite images to useful information

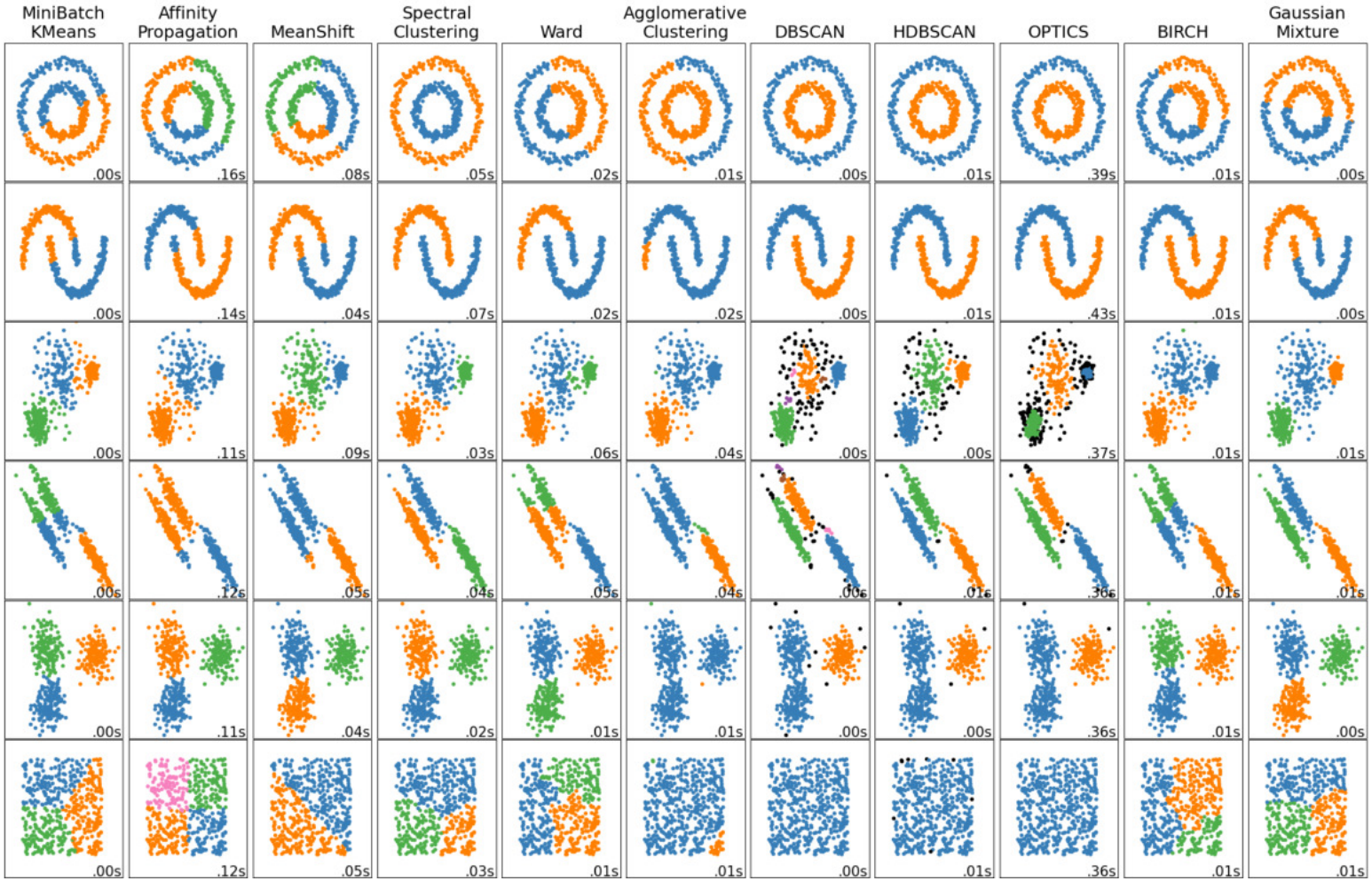
Unsupervised machine learning



Source: Geeks for geeks

From satellite images to useful information

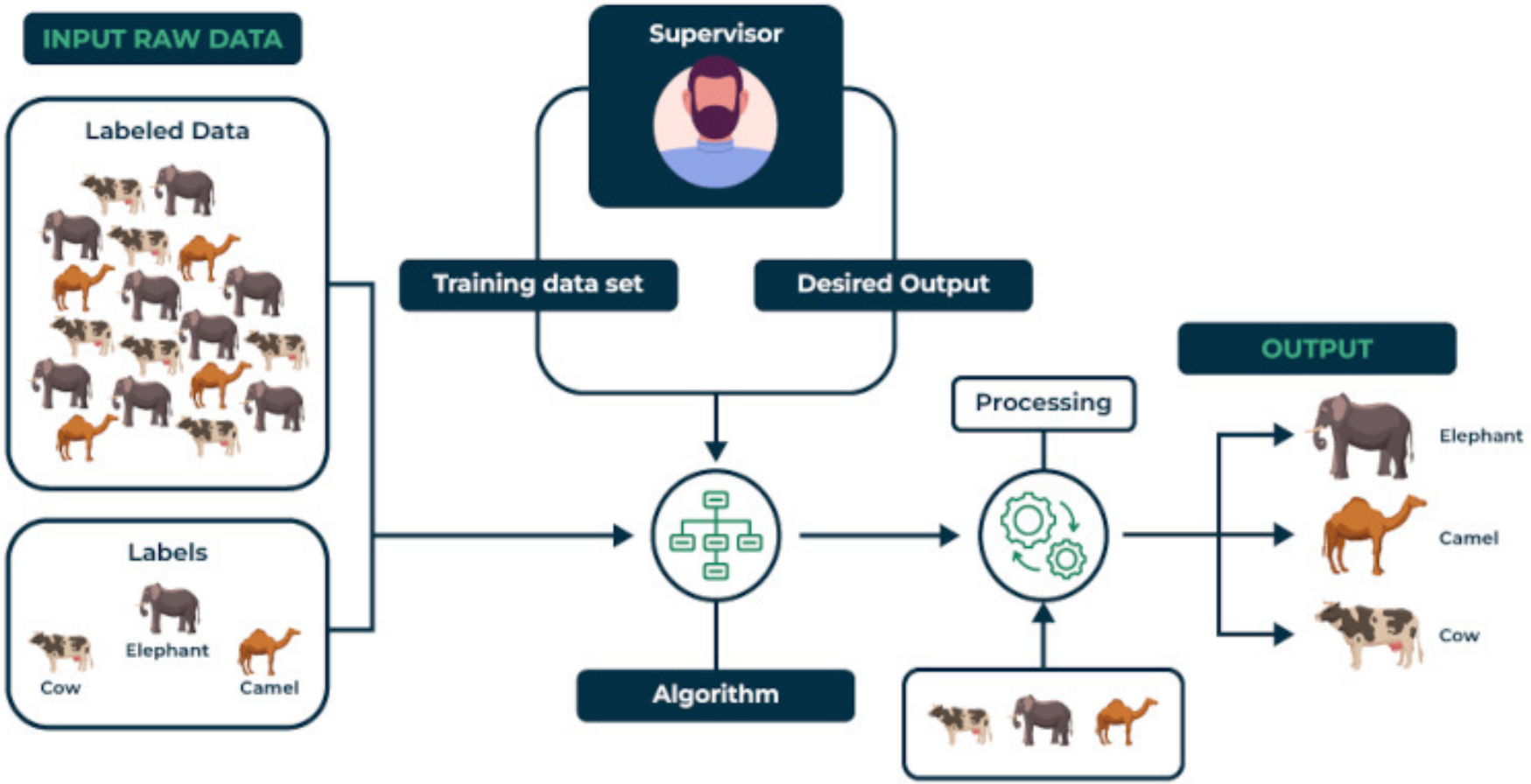
Unsupervised machine learning: wide variety of algorithms



Source: Scikit-learn

From satellite images to useful information

Supervised machine learning



Source: Geeks for geeks

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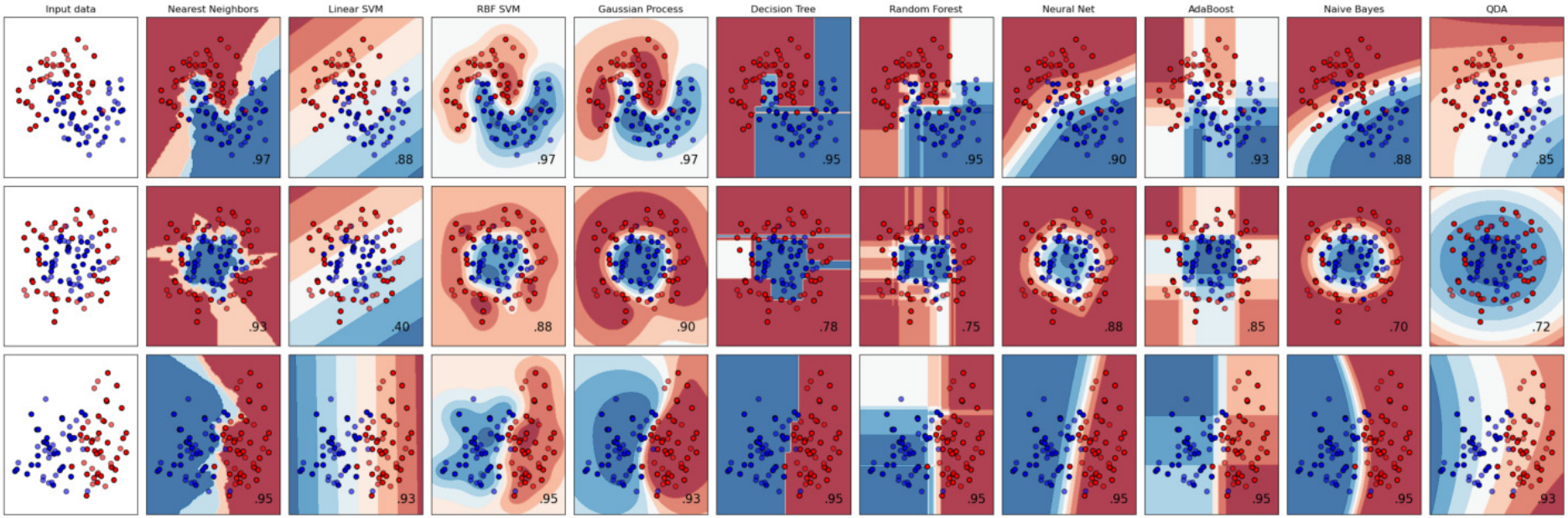
Supervised machine learning: wide variety of algorithms



Source: Scikit-learn

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Supervised machine learning algorithms: focus on regression

- Goal: predict a **continuous variable** (e.g. biomass, yield, vegetation parameters)
- Model performance is evaluated by measuring the **difference between observed and predicted values** using:
  - Root Mean Square Error (**RMSE**)
  - Mean Absolute Error (**MAE**)
  - Coefficient of determination (R^2)

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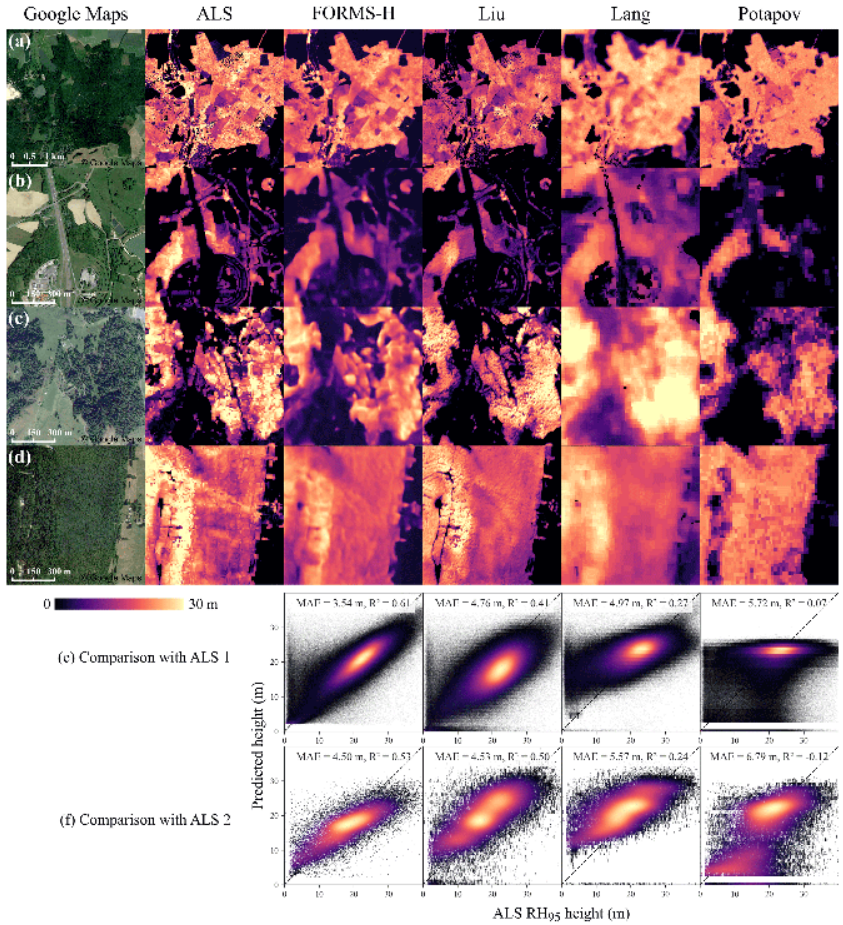
Supervised machine learning algorithms: focus on regression



MAE between observed and predicted tree height values derived from remote sensing. Source: Schwartz et al. (2023)

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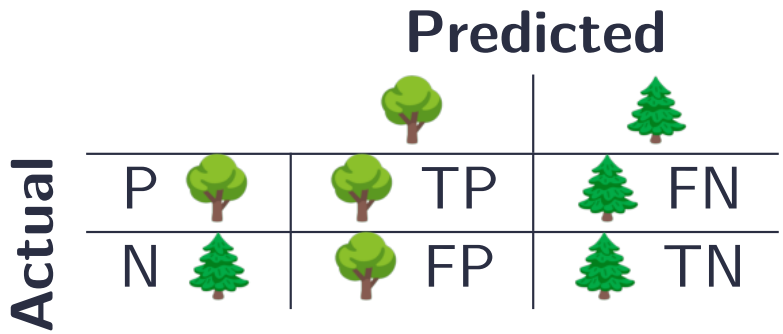
Supervised machine learning algorithms: focus on classification

- Goal: predict **categorical classes** (e.g. crop types, land cover classes)
- Model performance is evaluated using a **confusion matrix and** its derived metrics:
  - Overall accuracy
  - Precision
  - Recall
  - F1-score
- The confusion matrix compares the **predicted classes** with the **reference (true) classes**



- **Positive (P)**: deciduous and **Negative (N)**: evergreen
- **True Positive (TP)**: correctly predicted deciduous
- **True Negative (TN)**: correctly predicted evergreen
- **False Positive (FP)**: evergreen misclassified as deciduous
- **False Negative (FN)**: deciduous misclassified as evergreen

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Why a confusion matrix?

- Confusion matrix shows both **correct classifications** and **errors** for each class
- A single accuracy value is often **not sufficient**, especially when classes are imbalanced
- Suppose we classify trees in an image.
- Example dataset:
  - 95 pixels = evergreen trees
  - 5 pixels = deciduous trees
- A model predicting only **evergreen trees** would reach:

$$Accuracy = 95\%$$

- But the model would **never detect deciduous trees** $\Rightarrow$ importance of using a **confusion matrix and additional evaluation metrics**

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Why a confusion matrix?

		Predicted 🌳	Predicted 🌲	Total	Recall	Omission
Actual	🌳	0	5	5	0	1
	🌲	0	95	95	1	0
	Total	0	100	100		
	Precision	–	0.95			
	Commission	–	0.05			

- **Overall Accuracy (OA)** $= \frac{(TP+TN)}{(P+N)} = \frac{95+0}{5+95} = 0.95$
- **Recall** $= 1-$ Omission
- **Precision** $= 1-$ Commision

From images to decisions: not so simple

- Satellite images are **indirect measurements of the Earth's surface**
- The recorded signal depends on several factors:
  - illumination conditions
  - atmospheric effects
  - sensor characteristics
- The same land cover may appear **very different depending on the date or the sensor**

Key implication

Machine learning models may learn **sensor or seasonal artifacts** instead of the real phenomenon!

Key pitfalls

- **Clouds and shadows** introduce noise and missing data
- **Seasonality and phenology** change vegetation appearance
- **Domain shift:** models trained in one region or season may fail elsewhere
- **Label uncertainty:** ground truth data are often sparse or imperfect
- **Spatial autocorrelation:** random train/test splits can overestimate model performance

⚠ Important

A high accuracy does not necessarily mean that a model **generalizes well**.

Key pitfalls

Why EO expertise matters for computer vision models?

- Object detectability strongly depends on **spatial resolution**
- Vegetation indices rely on **spectral information** (e.g. NIR and red bands)
- Change detection requires **consistent temporal observations**
- Robust ML models require **stable radiometry across time and sensors**

Key message

In Earth Observation, **understanding the data is as important as choosing the model**.

A modern perspective on EO and Machine Learning

- **Strong classical ML baselines** (e.g., Random Forest) remain very competitive in Earth Observation
- **Deep learning is powerful**, but it often requires:
  - large labelled datasets
  - significant computational resources
  - careful model design and tuning
- Operational EO systems often combine:
  - **domain knowledge** (spectral indices such as NDVI)
  - **machine learning models**
  - sometimes **multi-source data** (e.g. optical + radar)

Key idea

In Earth Observation, improving **data quality and feature design** often matters more than increasing model complexity.