Observation de la Terre par imagerie optique : de la mesure physique à l'indicateur écologique (part I)

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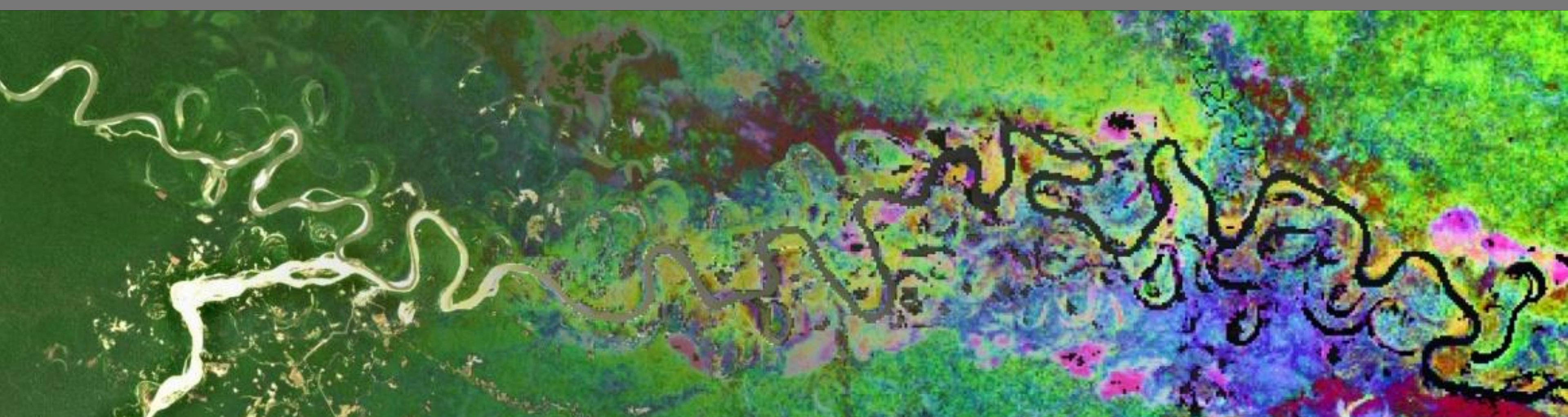


Apports, intérêts, limites de la télédétection pour mieux connaître la biodiversité

Atelier du métaprogramme BIOSEFAIR, 14 novembre 2023

- **Introduction**
- **Explore spatial, temporal and spectral dimensions from space**
- **A quick dive into the spectral space**
- **Current missions and forthcoming opportunities**
- **Earth observation and biodiversity : one approach among many**
- **Conclusions and perspectives**

Introduction & context

The erosion of biodiversity & ecological disturbances are increasing.
Need for operational methods to monitor ecosystem dynamics through time & space

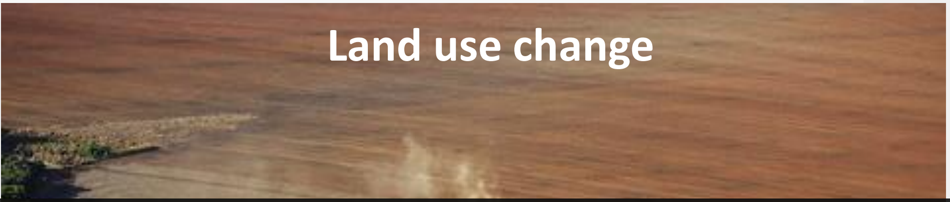
Exploitation of natural resources

Gold mining in Peruvian Amazon forest, Google Earth

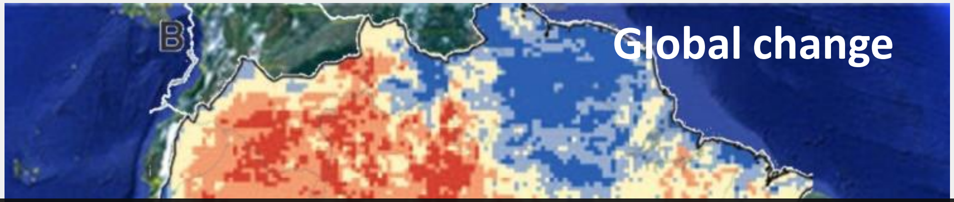
Pests & invasive species

Simon Fraser University (pine beetle)

Land use change



Global change



Remote sensing can provide information contributing to :

- Monitor complex systems a various spatial scales (local to regional & global)
- Link Earth observation with ecological knowledge & climate data
- Feed regional / national / international statistics on biodiversity & ecosystem degradation
- Fuel higher level models and analyses integrating ecology & socio-economical perspectives

What information do we need to monitor biodiversity with EBVs ?

What does 'biodiversity' encompass?

- Multidimensional concept linked to species, ecosystem functions & processes
- Spatial organization & appropriate scale of analysis change with ecosystem types

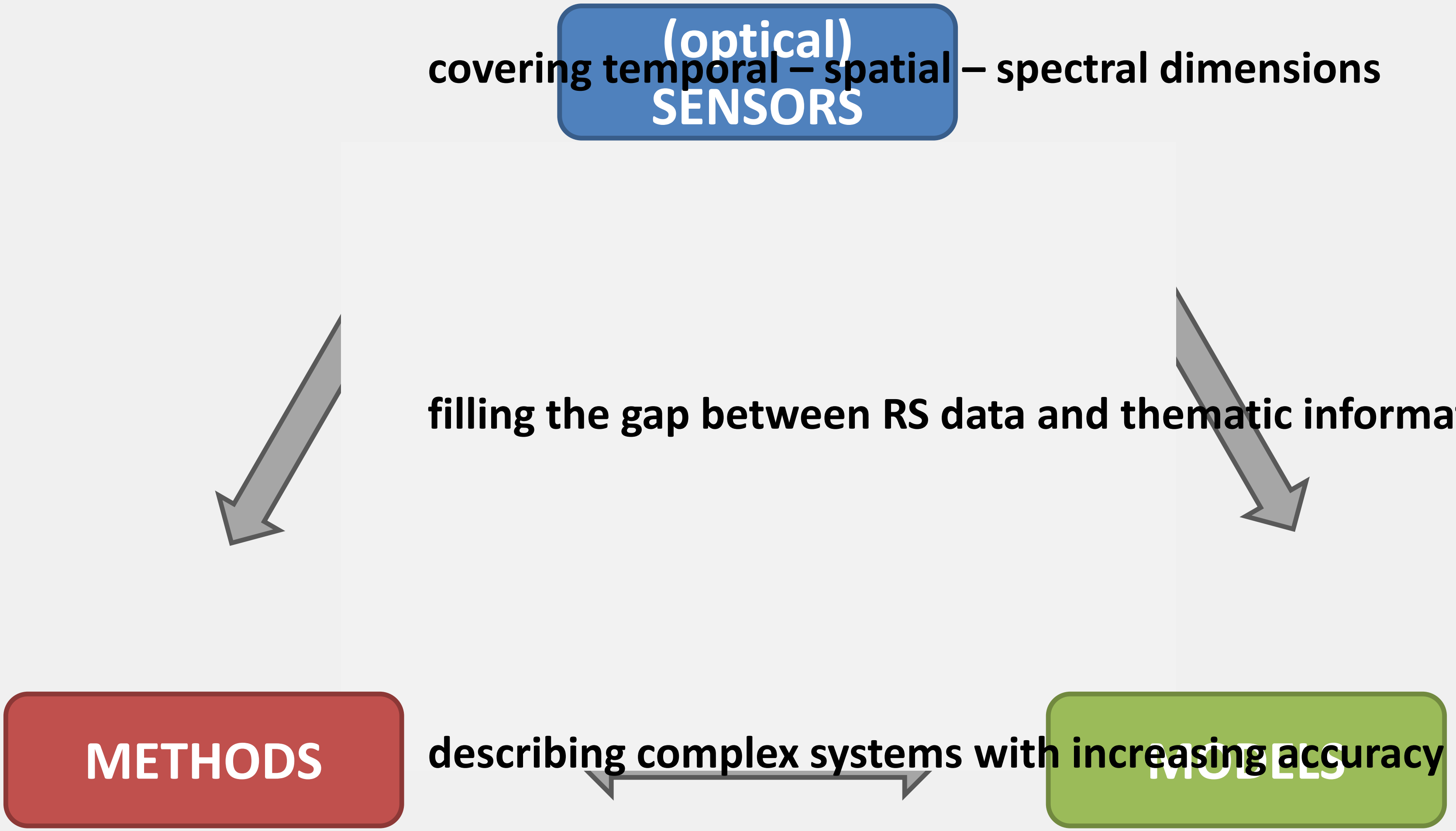
→ **No such 'One method / sensor / indicator fits all'**

→ **Measuring and monitoring biodiversity requires a diversity of indicators to cover all ecosystems and multiple dimensions of biodiversity**

http://www.doc.govt.nz/nature/habitats/wetlands/ https://defenders.org/grasslands/basic-facts

How can remote sensing meet current environmental challenges ?

Increasing accessibility and maturity of methods and sensing technologies
→ Original inputs for applications in ecology



covering temporal – spatial – spectral dimensions

filling the gap between RS data and thematic information

describing complex systems with increasing accuracy

How can remote sensing meet current environmental challenges ?

Increasing accessibility and maturity of methods and sensing technologies
→ Original inputs for applications in ecology

S2 : RGB color composition

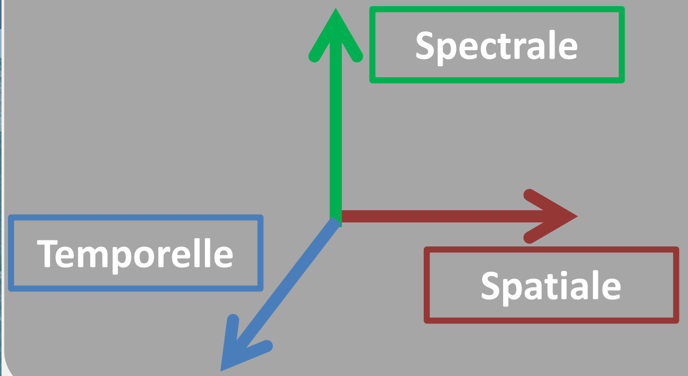
Time series analysis

Near real time monitoring

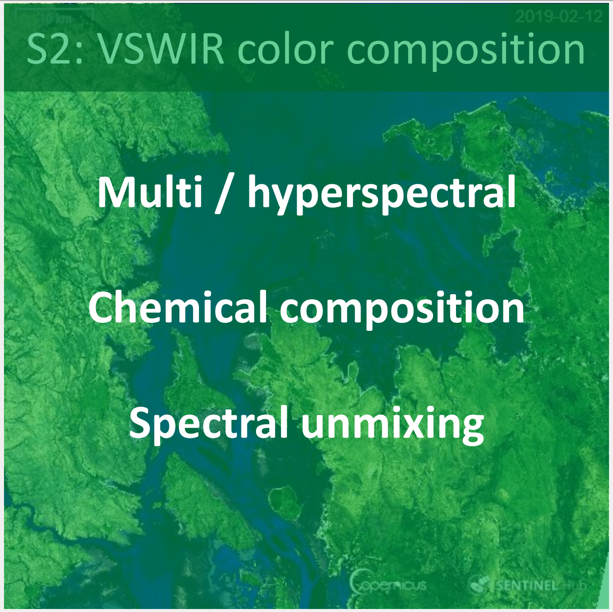
Phenology

Cloud free acquisitions

Dimensions explorables en télédétection



S2: VSWIR color composition



Multi / hyperspectral

Chemical composition

Spectral unmixing

Very High Spatial Resolution (UAV, airborne, satellite)

Medium spatial resolution (Sentinel-2, Landsat)

Moderate spatial resolution (MODIS, Sentinel-3)

Aqua (MODIS)
250m Resolution

https://radiant.earth/

Explore spatial, temporal and spectral dimensions from space

Need to identify a trade-off satisfying application-specific requirements

- **Spatial resolution**
    - Very high spatial resolution
        - Tree species identification
        - Habitat openness
        - Local analysis
    - Medium / high spatial resolution
        - Ecosystem extent
        - Regional mapping
    - Moderate resolution
        - Regional / Global mapping

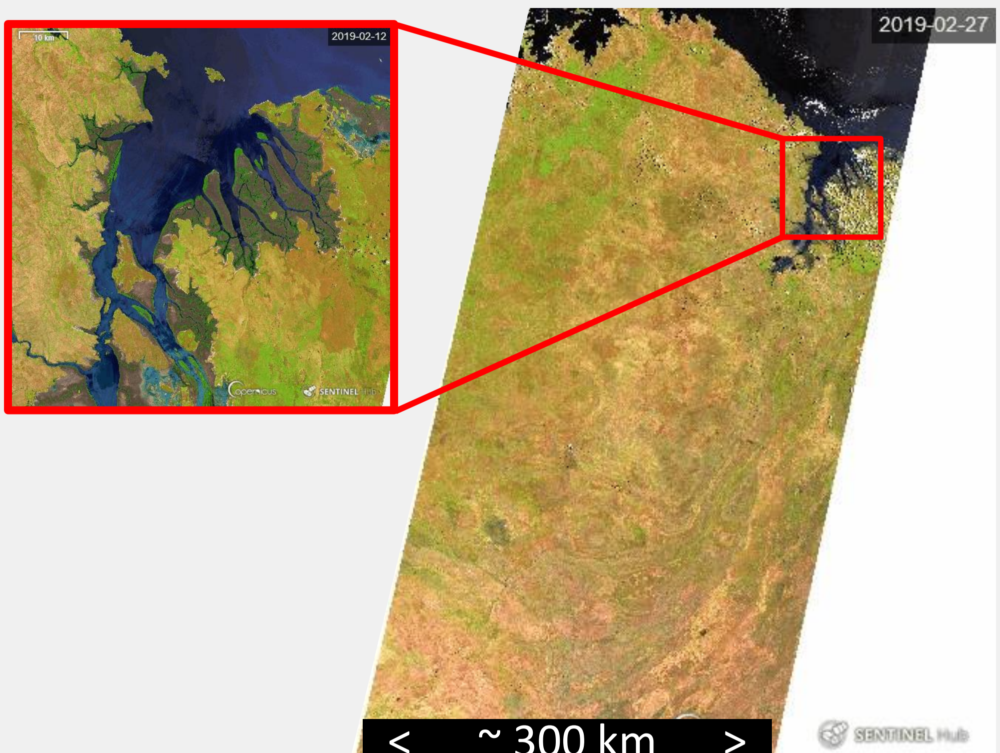
→ Requirements in terms of spatial extent and spatial grain (resolution) ?

→ See next presentation from Marc Lang

Explore spatial, temporal and spectral dimensions from space

Need to identify a trade-off satisfying application-specific requirements

- **Spatial resolution**
  - Very high spatial resolution
  - Medium / high spatial resolution
  - Moderate resolution



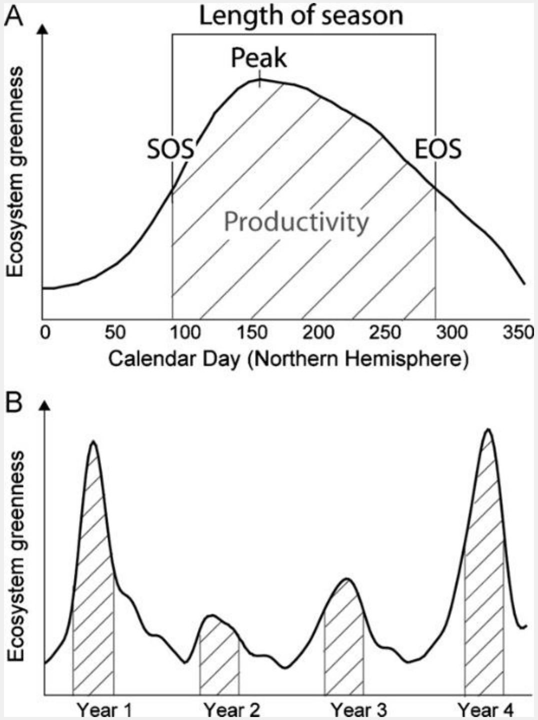
https://apps.sentinel-hub.com/eo-browser/

Explore spatial, temporal and spectral dimensions from space

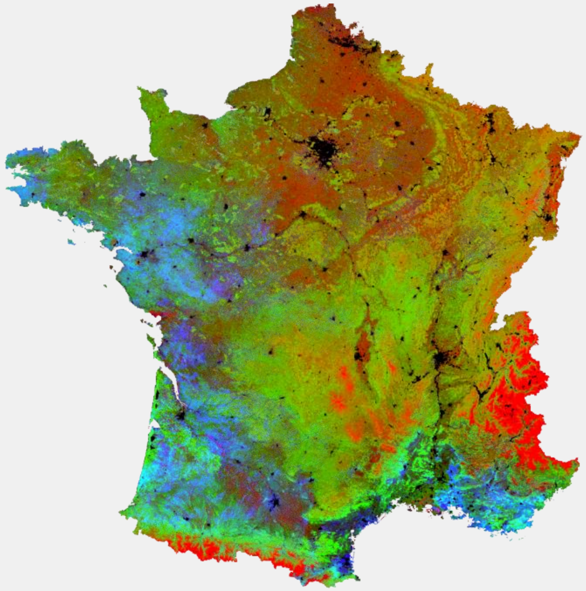
Need to identify a trade-off satisfying application-specific requirements

- **Temporal resolution / revisit period**
  - Vegetation phenology, Time series analysis & Intra / Interseasonal change detection
  - High temporal revisit = higher probability of acquisition with low cloud cover (tropics)
  - High temporal revisit + high spatial resolution = high volume of data

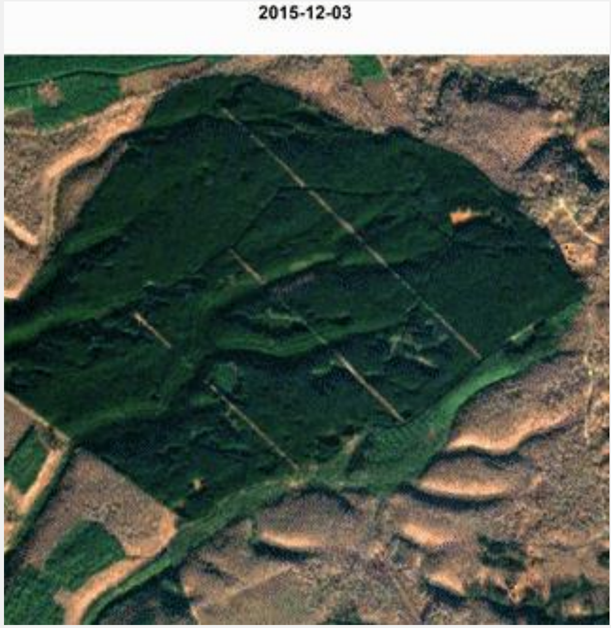
→ See next presentation from David Sheeren



Phenological metrics
Bradley et al., 2012



Dynamic Habitat Index

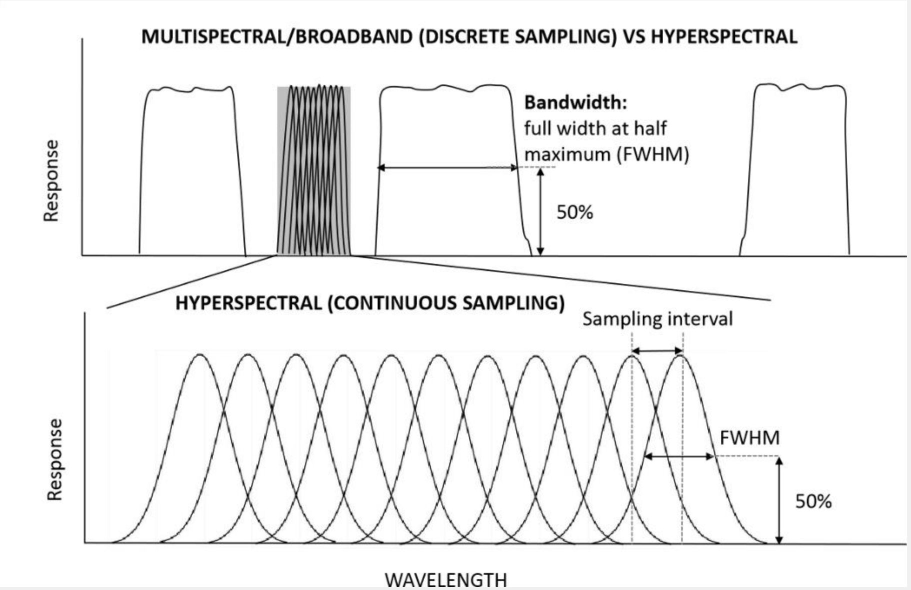


FORDEAD package
For bark beetle detection

Explore spatial, temporal and spectral dimensions from space

Need to identify a trade-off satisfying application-specific requirements

- **Spectral characteristics**
  - Spectral information is linked to chemical & structural properties of vegetation
  - Possibility to assess various vegetation properties remotely (absorption & scattering)
    - Pigment content (chlorophylls, carotenoids, anthocyanins)
    - Water content
    - Dry matter content (== Leaf Mass per Area)
    - Protein content
  - Requirements in terms of spectral sampling and resolution to assess these properties



[Porcar-Castell et al., 2015]

Explore spatial, temporal and spectral dimensions from space

Need to identify a trade-off satisfying application-specific requirements

- **Spatial characteristics**
- **Temporal revisit**
- **Spectral characteristics**

→ **‘More’ does not necessarily mean ‘Better’**

→ **Need to identify appropriate methods corresponding to RS image type**

High resolution satellite imagery for tropical biodiversity studies: the devil is in the detail

Harini Nagendra · Duccio Rocchini

Biodivers Conserv (2008) 17:3431–3442
DOI 10.1007/s10531-008-9479-0

- Introduction
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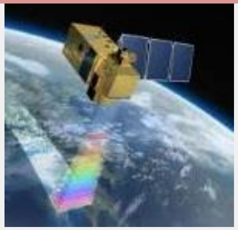
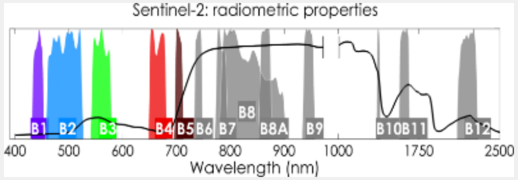
What do optical measurements tell us about vegetation ?



Sensor & acquisition characteristics

Spectral properties, spatial resolution, revisit period, geometry of acquisition…



EnMAP Hyperspectral Imager

From images to pixels

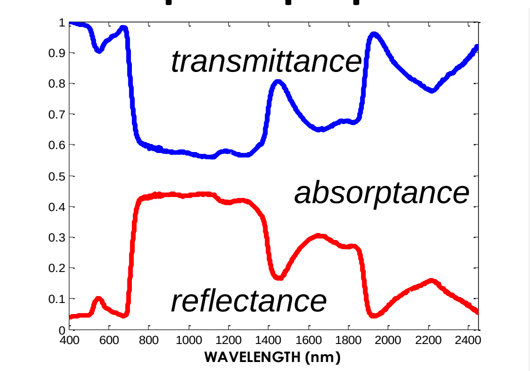
Vegetation, soil, topography, atmosphere…

lidR package

Canopy structural & chemical properties

LAI, leaf orientation, clumping,
Leaf optical properties …

Leaf optical properties



Foliar anatomy

Surface properties, thickness, internal structure, …

Foliar chemistry

Pigments, water, proteins, cellulose, …

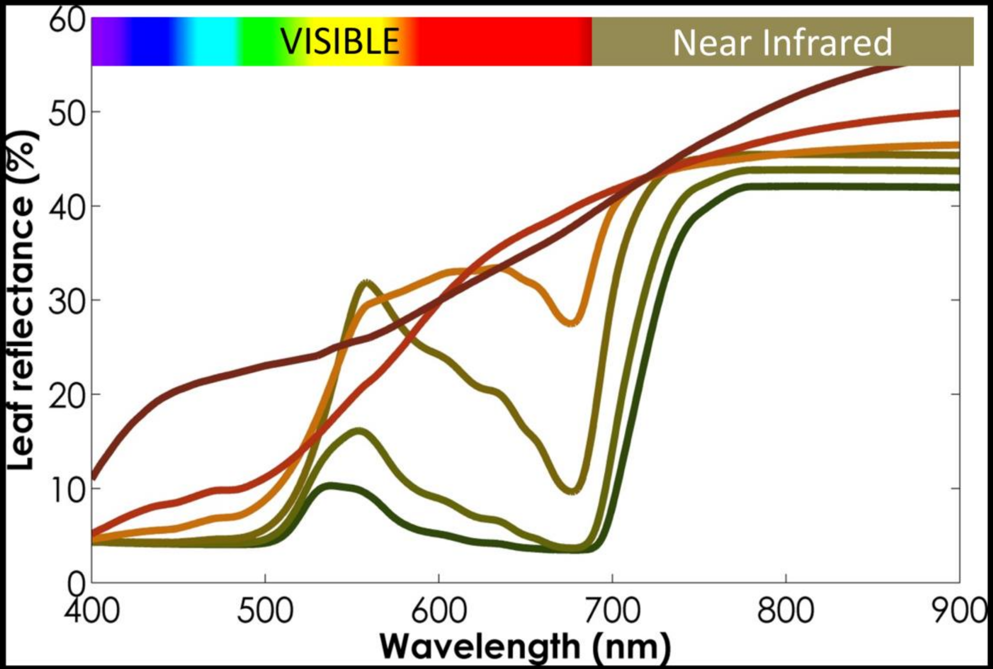
Optical signal (reflectance) results from interactions between light and matter (absorption & scattering from soil, vegetation & atmosphere)

What do optical measurements tell us about vegetation ?

- **Leaf optical properties depend on biochemical and structural properties**
  - Chemical and structural properties result from physiological, phenological & ecological response of plants to environment
  - Models based on physical description of light/matter interactions link leaf optical properties to chemical/structural properties

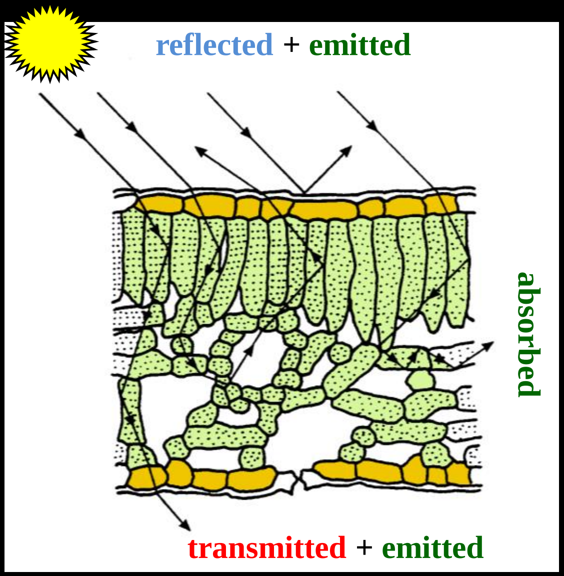
Evolution of visual aspect of a leaf
(mature → senescent)

Evolution of leaf optical properties
(foliar reflectance VNIR)



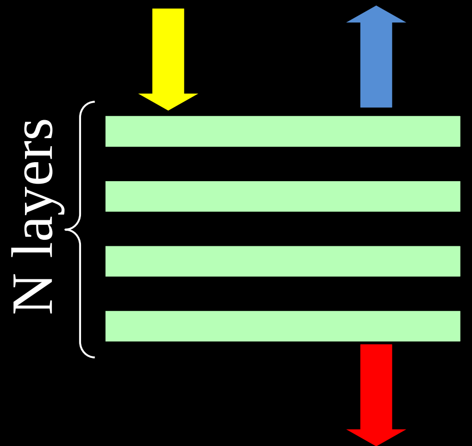
Quick introduction to physical modeling (illustrative purpose)

Leaf



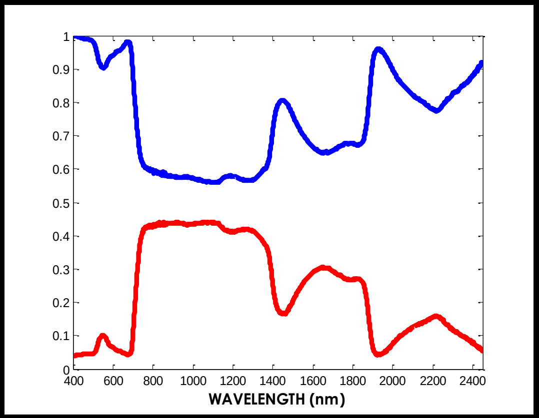
T.R. Sinclair, M.M. Schreiber & R.M. Hoffer, 1973, Diffuse reflectance hypothesis for the pathway of Solar radiation through leaves, *Agronomy Journal*, 65:276-283

… seen by PROSPECT



$$\begin{cases} \rho = R(N) = R(m) + \dfrac{T(m)^2 R(n)}{1 - R(m)R(n)} \\ \tau = T(N) = \dfrac{T(m)T(n)}{1 - R(m)R(n)} \end{cases}$$

Leaf optical properties



Input variables :

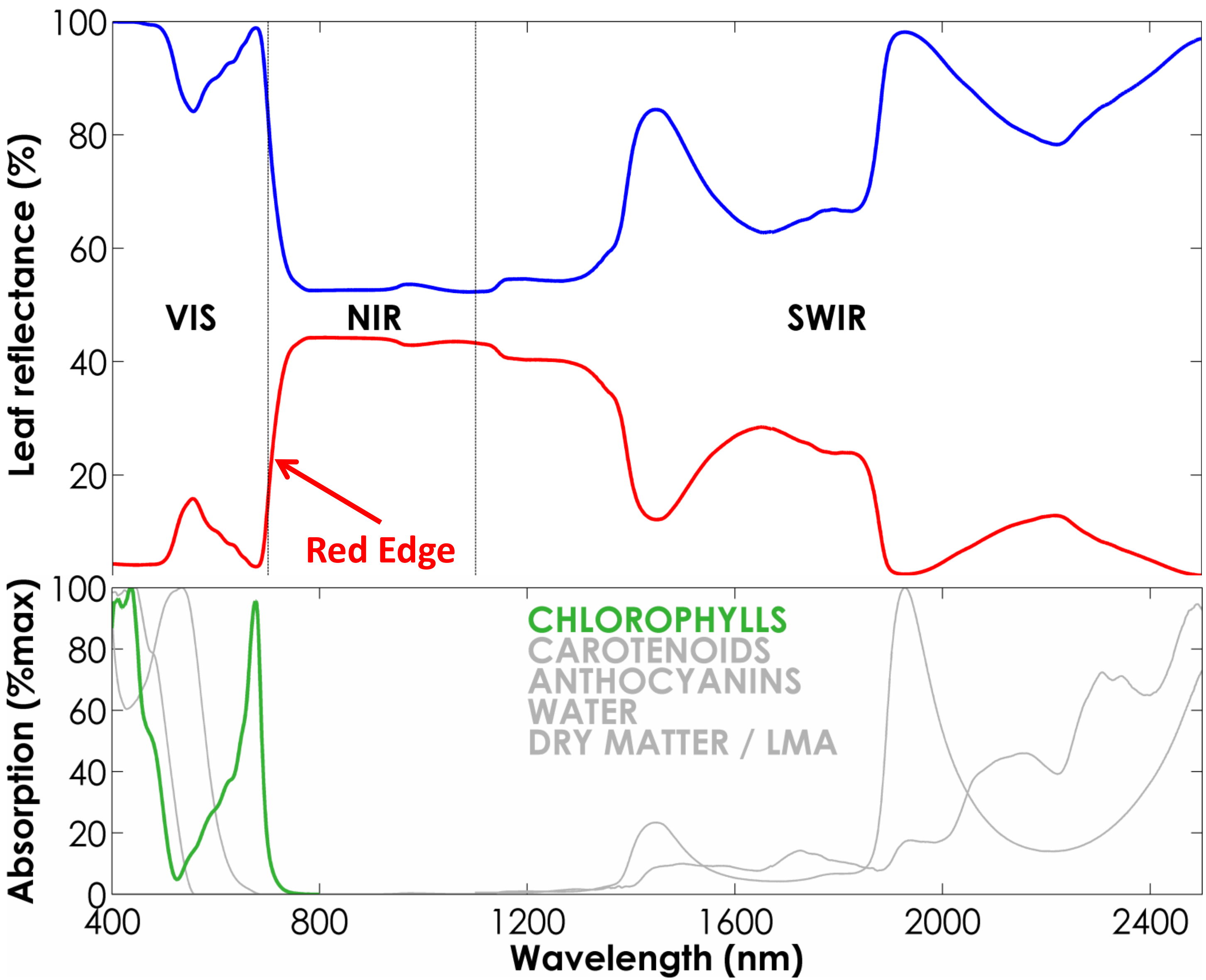
- **Chemical constituents**
- **Foliar structure**

Direct mode

PROSPECT

Directional hemispherical Reflectance & transmittance

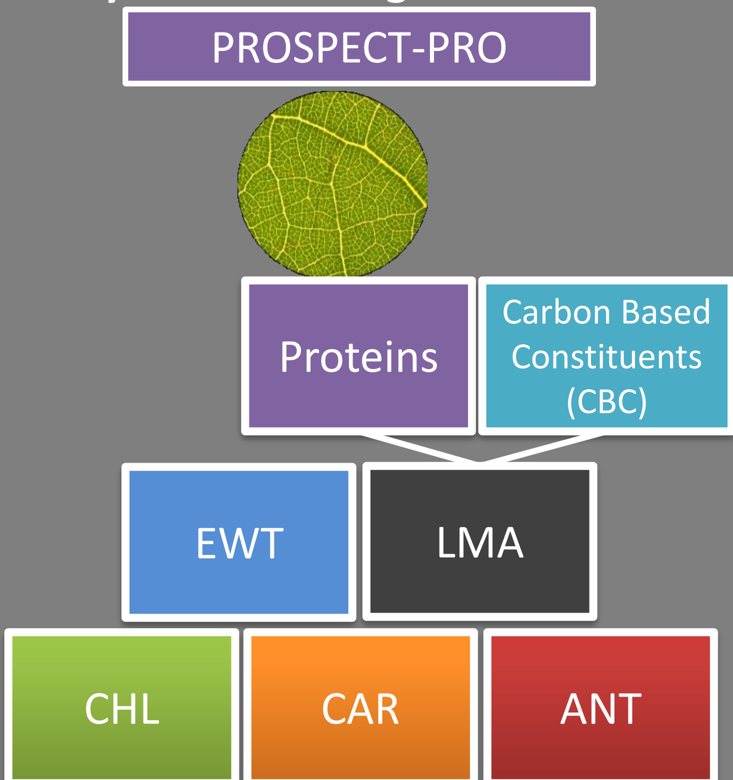
Main leaf chemical constituents absorbing light



Evolution of PROSPECT model and integration into canopy models

- Successive versions of PROSPECT account for increasing nb of chemical constituents
- PROSPECT coupled with most canopy radiative transfer models (SAIL, SCOPE, DART…)

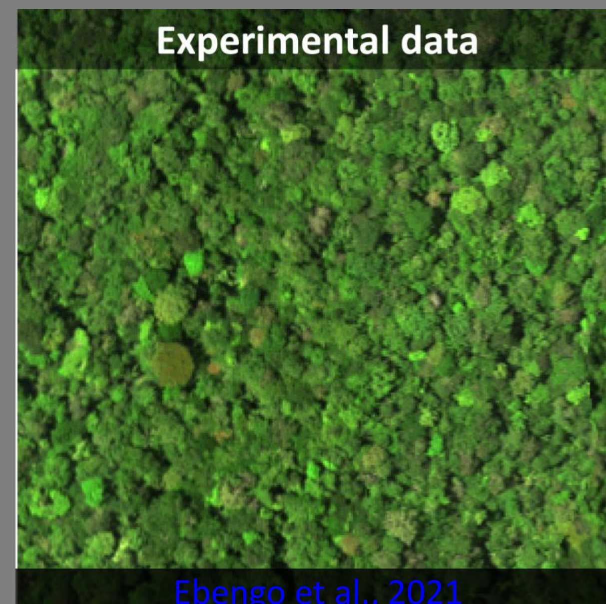
Physical modeling at leaf scale



https://jbferet.gitlab.io/prospect/

Physical modeling at canopy scale

… to realistic simulation of RS acquisitions over complex canopies (3D model DART)

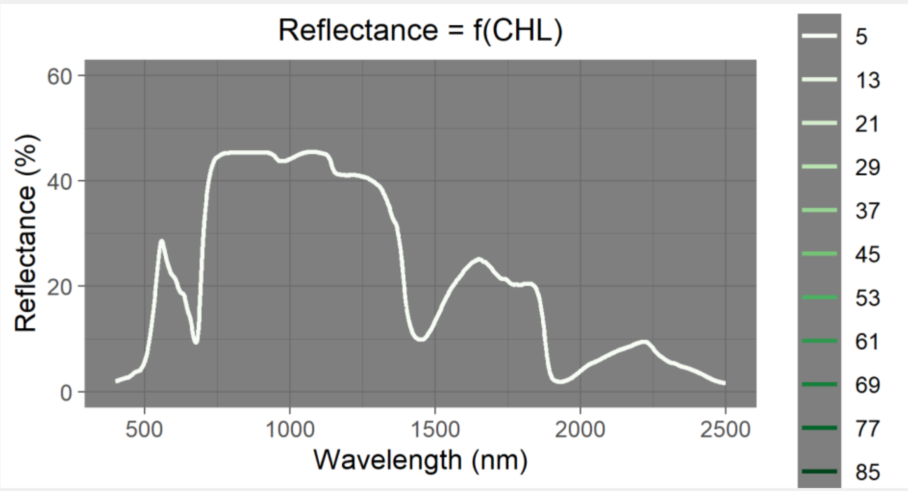


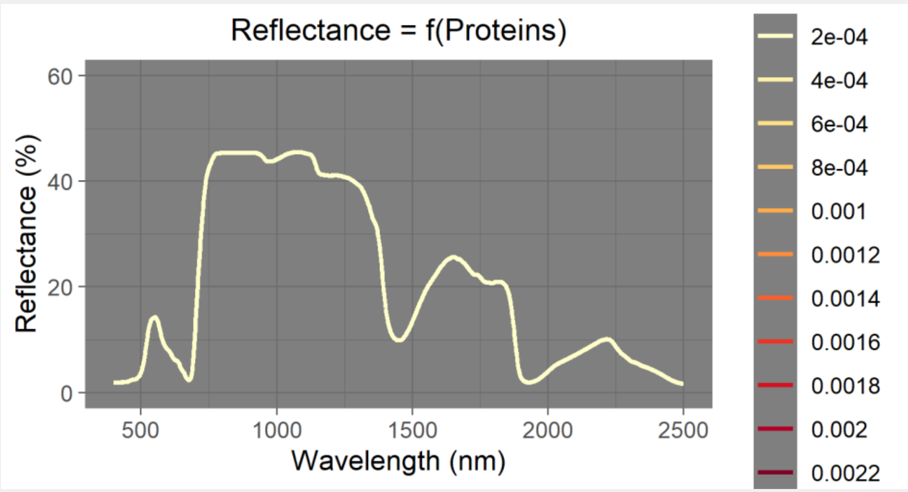
https://pytools4dart.gitlab.io/pytools4dart/

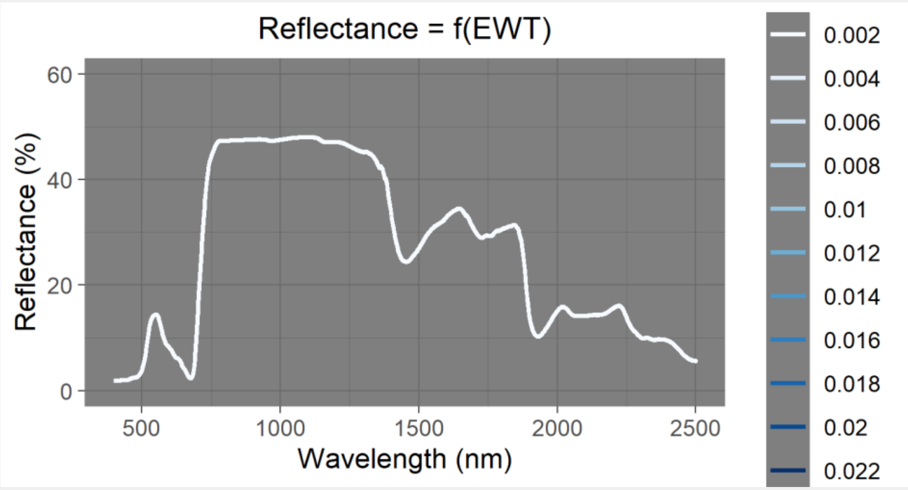
Increasing possibilities to integrate a variety of leaf traits and canopy structural properties (e.g. LiDAR) into realistic simulations for complex vegetation layer

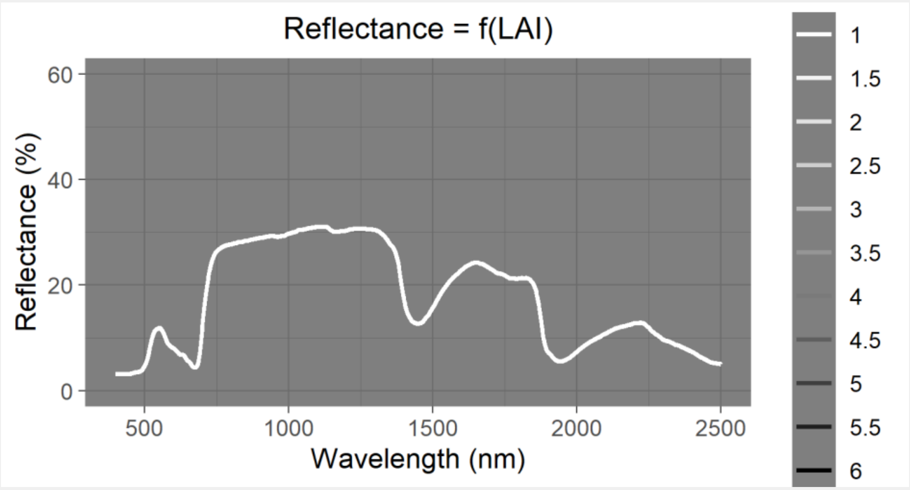
Physical modeling as a tool to understand and predict from RS data

- **Understand the link between vegetation biophysical and optical properties**
  - Influence of vegetation properties on canopy reflectance can be analyzed
  - Illustration: sensitivity of **hyperspectral** reflectance to CHL, PROT, EWT, LAI



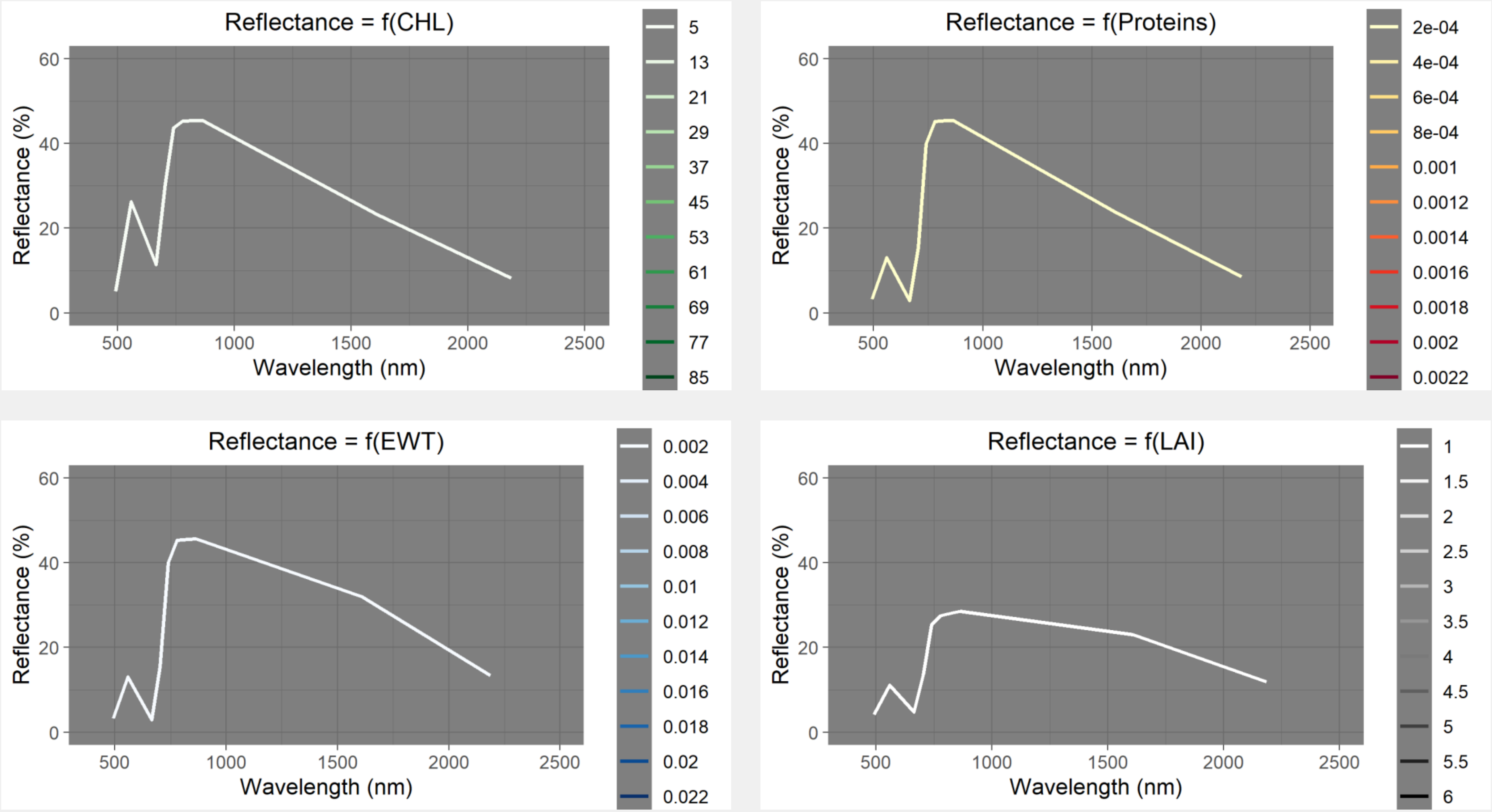






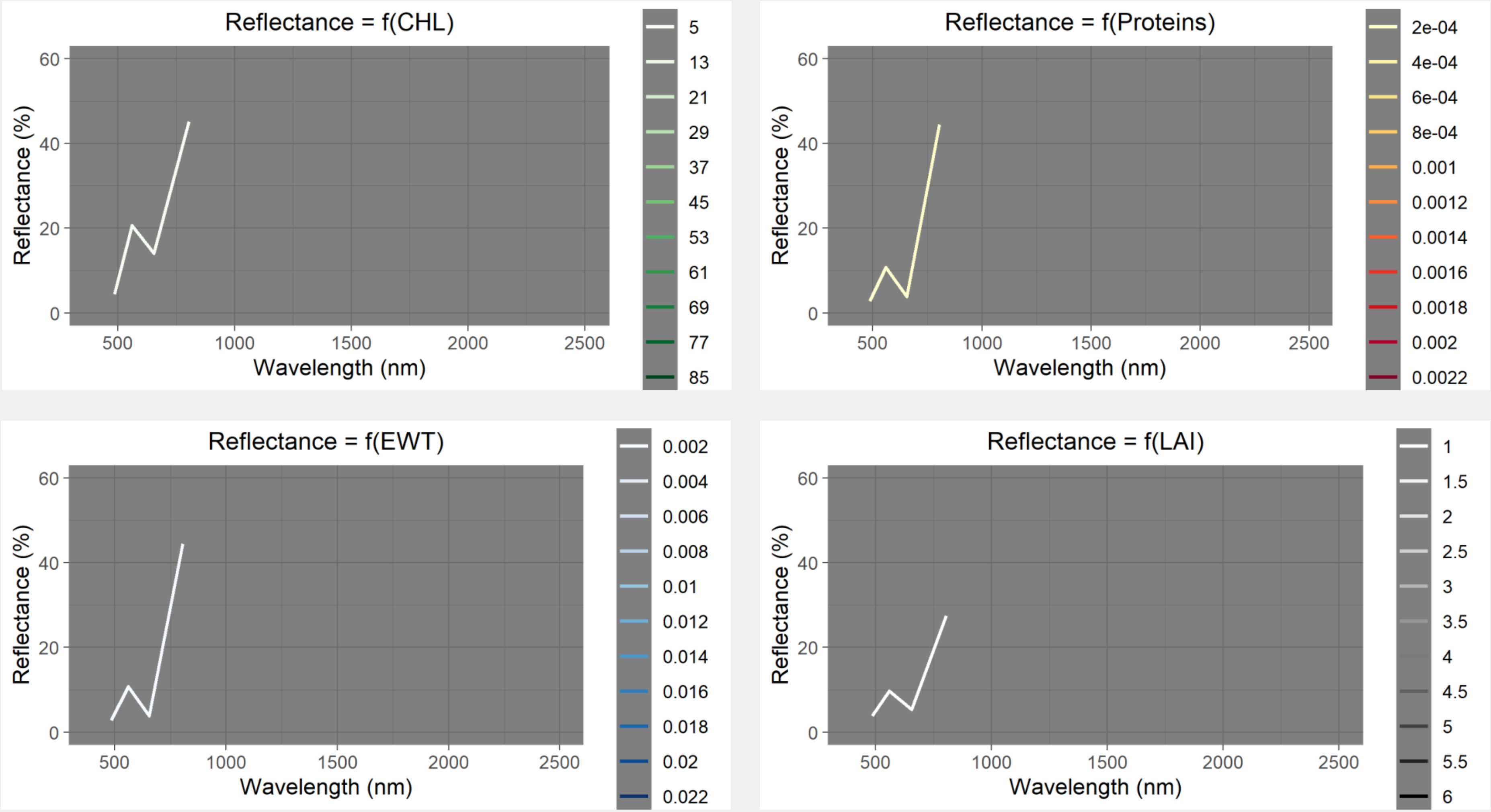
Physical modeling as a tool to understand and predict from RS data

- **Understand the link between vegetation biophysical and optical properties**
  - Influence of vegetation properties on canopy reflectance can be analyzed
  - Illustration: sensitivity of **Sentinel-2** reflectance to CHL, PROT, EWT, LAI



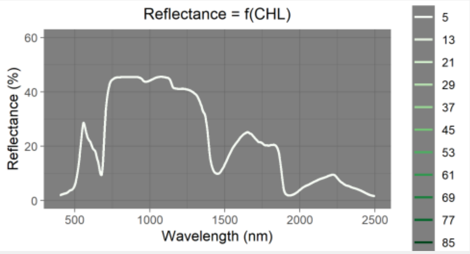
Physical modeling as a tool to understand and predict from RS data

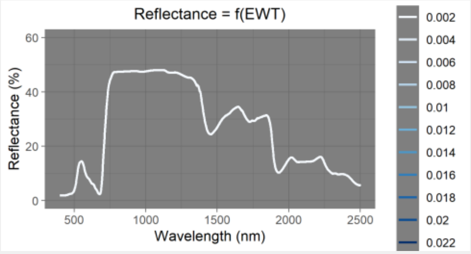
- **Understand the link between vegetation biophysical and optical properties**
  - Influence of vegetation properties on canopy reflectance can be analyzed
  - Illustration: sensitivity of **SPOT-6** reflectance to CHL, PROT, EWT, LAI

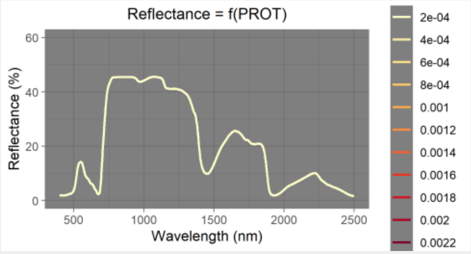


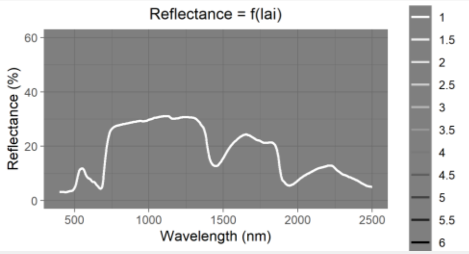
Physical modeling as a tool to understand and predict from RS data

- **Understand the link between vegetation biophysical and optical properties**
  - Influence of an individual property of vegetation
  - Sensitivity analysis of part or all properties of vegetation

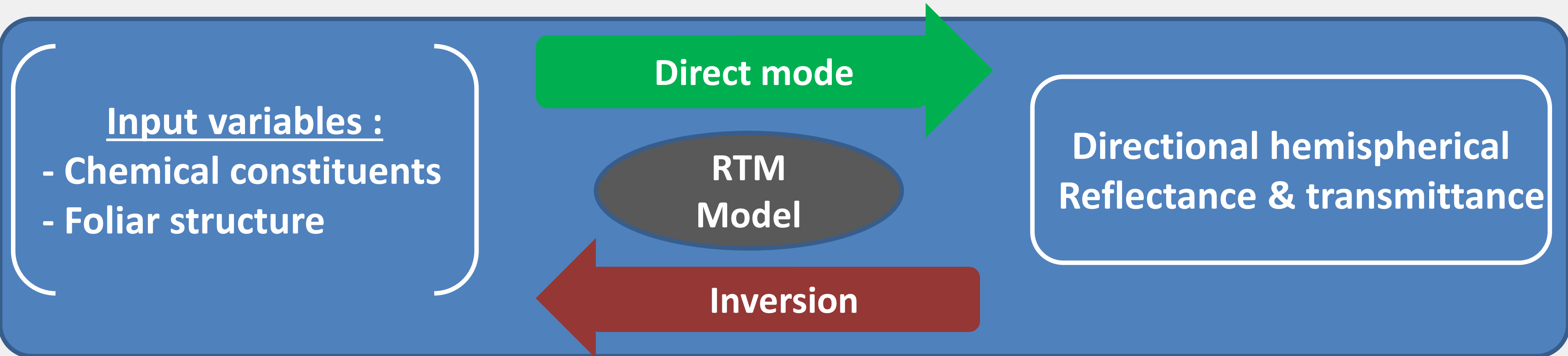




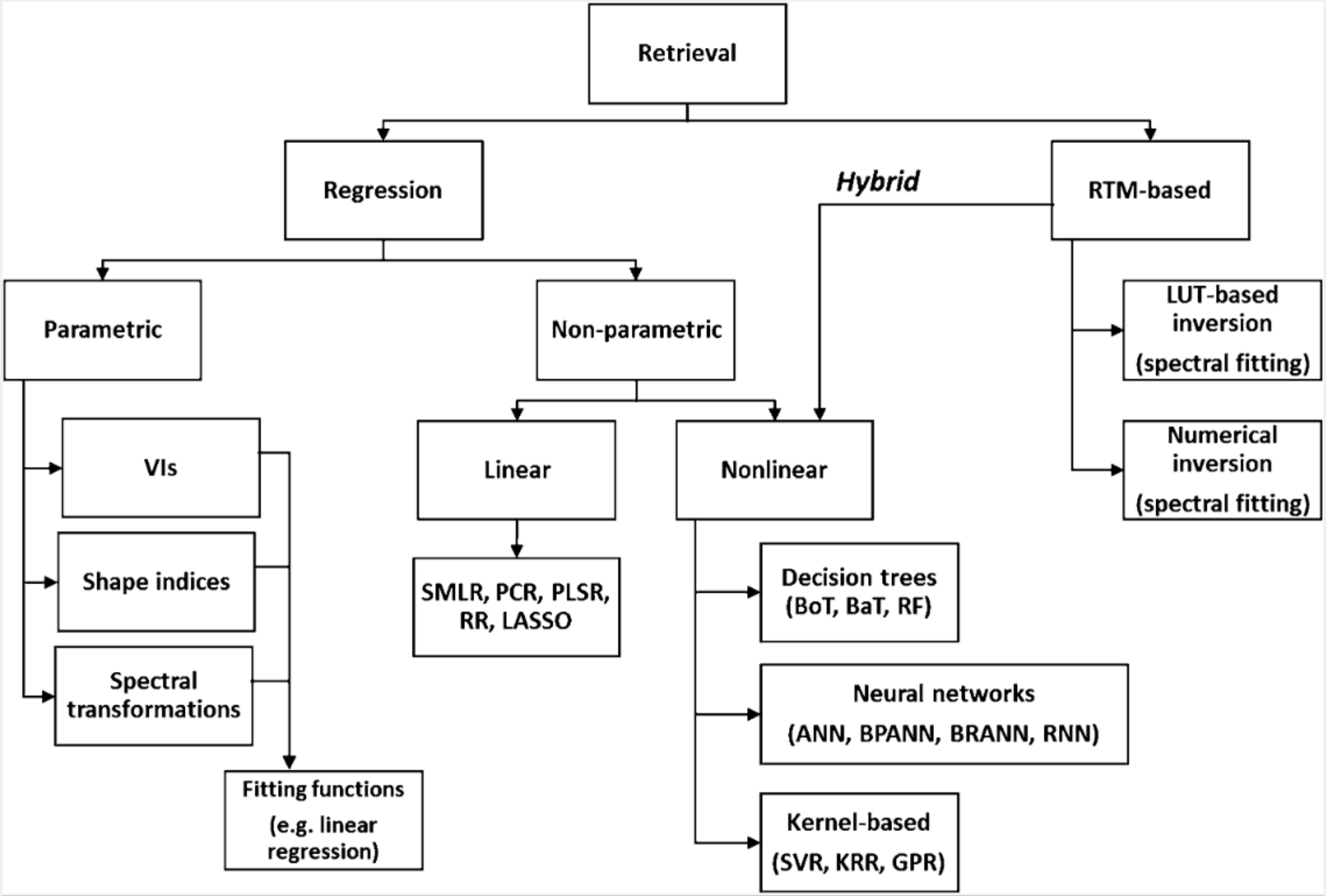




- **Predict vegetation biophysical properties from optical measurements**
  - Model inversion : iterative optimization or hybrid inversion
    - *Leaf scale:* iterative optimization usually more accurate
    - *Canopy scale:* hybrid inversion or LUT more appropriate for image processing



Retrieving vegetation properties from canopy reflectance



See Verrelst et al. (2019) for a comprehensive overview of the techniques available to estimate vegetation properties with remote sensing data

Verrelst et al. (2019) Quantifying Vegetation Biophysical Variables from Imaging Spectroscopy Data: A Review on Retrieval Methods. *Surveys in Geophysics* 40, 589–629 https://doi.org/10.1007/s10712-018-9478-y

Retrieving vegetation properties from canopy reflectance

Application of physical model inversion needs to account for computational efficiency in the context of big data processing

Various approaches applicable to estimate vegetation properties from RS data

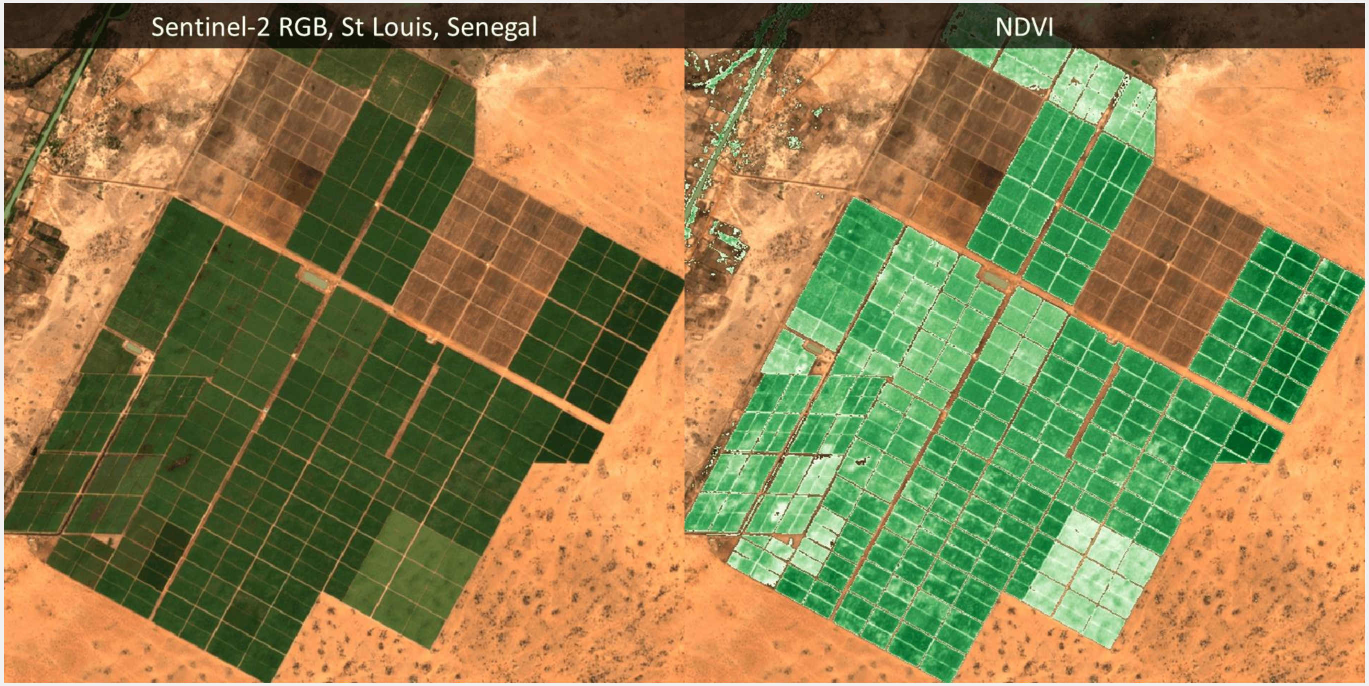
- **Regression / data-driven approaches**
  - From spectral indices to machine learning & multivariate statistical algorithms
  - Computationally efficient
  - Data demanding (training + independent validation data)

- **Inversion of radiative transfer models**
  - Brut force inversion (iterative optimization) can be computationally demanding
  - No training stage, but validation requires data

- **Hybrid approaches**
  - Physical model: production of simulated training data
  - ML / statistical method: estimation from regression algorithm
  - Best of both worlds :
    - Requires experimental data for validation only
    - Computationally efficient

Retrieving vegetation properties from canopy reflectance

- **Estimation of canopy properties (PROSAIL inversion)**
  - PROSAIL: vegetation described as turbid layer
    - Theoretical domain of validity of the model : homogeneous canopies (agriculture, forestry)
    - Some versions of PROSAIL allow accounting for limited heterogeneity (clumping, layers…)
    - Application to heterogeneous vegetation can be explored with caution (uncertainty ↗)
  - Properties accessible from Sentinel-2 : **LAI, CHL, EWT, LMA** (uncertainty tbd)
  - Properties accessible from spectroscopy: **LAI, CHL, CAR, ANT, EWT, LMA, PROT** …



https://jbferet.gitlab.io/prosail/index.html

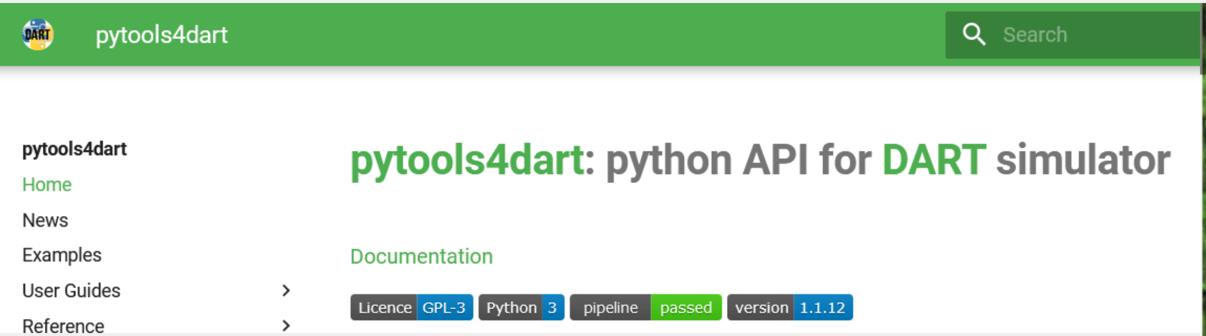
Retrieving vegetation properties from canopy reflectance

- **Simulating complex canopies using 3D modeling with DART**
  - Integration of 3D structure (e.g. derived from LiDAR acquisitions)

    → See next talk from Sylvie Durrieu
  - Simulation of raster data corresponding to exact instrumental specifications

    → Particularly useful for the preparation of future satellite missions

    → Allows simulation of LiDAR data, fluorescence, thermal infrared…



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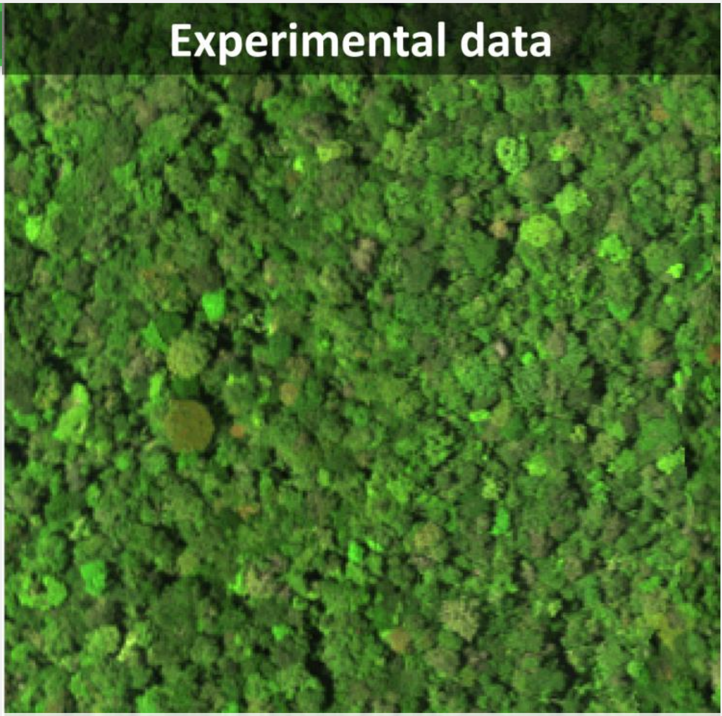

Ebengo et al., 2021

Ebengo et al. (2021). Simulating Imaging Spectroscopy in Tropical Forest with 3D Radiative Transfer Modeling, *Remote Sensing*, 13(11) – 2120 https://doi.org/10.3390/rs13112120

Retrieving vegetation properties from canopy reflectance

- **Various methods applicable to assess vegetation properties from optical images**
- **Available ground observation & capacity to take advantage of existing DB = Key**
- **Physical model inversion: strong potential for estimating optical traits**
  - **Extends possibilities of multi/hyperspectral analysis compared to spectral indices**
  - **Already integrated in commercial decision tools for precision agriculture**
- **Currently lacks maturity for routine global production (e.g. EBV framework)**
  - Extensive, open & documented validation data (ground & RS) to consolidate
  - Spaceborne imaging spectroscopy in its infancy
  - Models and methods are increasingly available
  - Need to work on uncertainty assessment

nature ecology & evolution
PERSPECTIVE
https://doi.org/10.1038/s41559-018-0667-3
OPEN

Towards global data products of Essential Biodiversity Variables on species traits

Kissling et al. (2018) Towards global data products of Essential Biodiversity Variables on species traits. *Nature Ecology & Evolution*, 2 – 1531-1540 https://doi.org/10.1038/s41559-018-0667-3

Current missions and forthcoming opportunities

- Increasing number of Earth observation satellites available
  - Free and open data from operational & forthcoming missions (major space agencies)
    - ESA (Copernicus program): Sentinel satellites, CHIME (hyperspectral, 202x)
    - NASA: Landsat, MODIS, SBG (hyperspectral, 202x)
  - Scientific missions
    - EnMAP, FLEX…
  - Commercial satellites (originally mainly VHSR, expanding to multi & hyperspectral)
    - Airbus (Pleiades, SPOT)
    - Planet
- Imaging spectroscopy (hyperspectral) satellites
  - Operational: DESIS (DLR, 2018), Gaofen 5 (CASC, 2018), PRISMA (ASI, 2019), HISUI (JAXA, 2019), EnMAP (DLR, 2022), EMIT (NASA, 2022)

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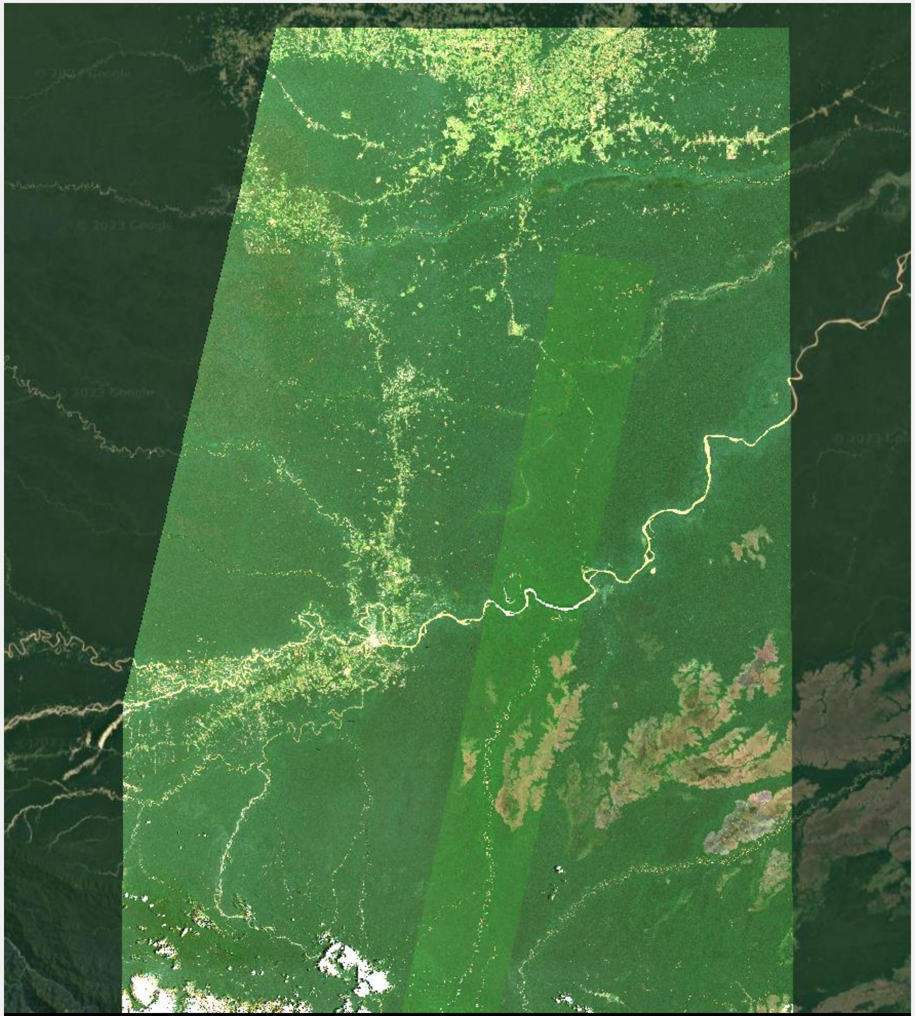
  - **Future missions**
    - **with global coverage & 30 spatial res. : CHIME (ESA, 202x), SBG (NASA, 202x)**
    - **Decametric spatial resolution: Biodiversity (CNES, 202x)**

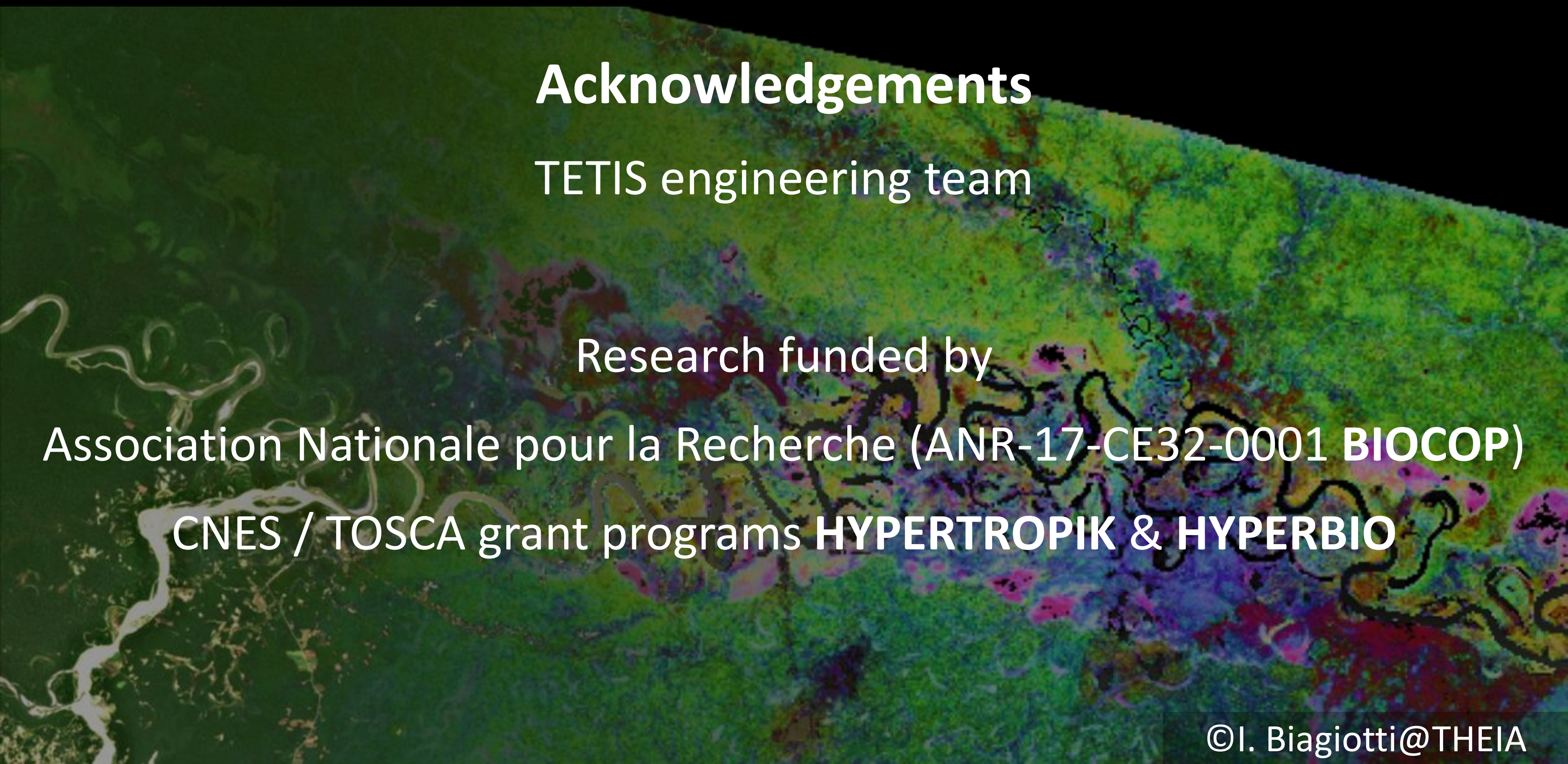
Current missions and forthcoming opportunities

- Current imaging spectroscopy satellites do not compete with MS sensors to cover large areas
  → IS as local source of information to prepare for upscaling



Sentinel-2 acquisition (6 tiles, 200 km x 300 km) vs EnMAP footprint (30 km) over tropical forest in Peru (~12 Gb)

Thank you !



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