EO AFRICA EXPLORERS

PRISMA 4 AFRICA

Illustration of the variables object of the validation activities. Theory and practice of the measurement methodologies

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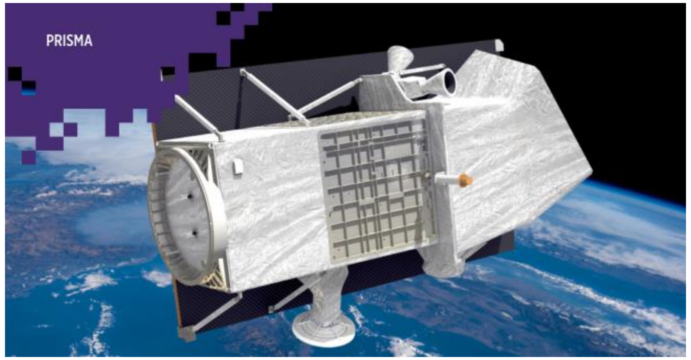
Spaceborne hyperspectral sensing for agricultural monitoring

There is a range of agricultural applications that *potentially* can be supported by **spaceborne hyperspectral remote sensing**:



- Monitoring of vegetation status and dynamics
- Nutrient and water status
- Crop evapotranspiration
- Pest and disease infestation
- Crop yield and production forecasting
- Precision agriculture

While few of these applications already are beginning to become operational, we are still far away from some.

For all these purposes, **crop characteristics or functional vegetation traits** need to be inferred from hyperspectral data.

Credits:

Berger et al. 2021

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Crop characteristics

- What are the most relevant agricultural traits that can be predicted from remote sensing observations, in particular from (spaceborne) hyperspectral mapping?
- Information of interest consists of *functional traits* or *variables* or *features* of the agricultural systems, and especially how these vary in space and time. Note that the term "*variable*" is something that is measurable and has a physical or agronomical meaning. A parameter is something resulting from an empirical fitting. Hence, we prefer the term variable or trait in these contexts.
- Nature of these agronomic traits can be:
  - *typological (e.g. crop type),*
  - *biophysical (e.g. soil moisture),*
  - *morphological (e.g. foliage height diversity, leaf dry mass per leaf area)*
  - *biochemical (e.g. leaf nitrogen content),*
  - *biological (e.g. crop phenology),*
  - *structural-geometrical (e.g. leaf inclination, LAI).*

- Some variables of interest, such as *crop productivity*, *irrigation needs* or *phenology*, result from a series of intertwined biophysical processes within the soil-plant-atmosphere continuum. These secondary variables are not directly related to the radiative transfer mechanisms and thus cannot be inferred directly from imaging spectroscopy data. They can, however, be accessed from remote sensing data in combination with process modelling using data assimilation strategies (Weiss et al. 2020).

Credits:
Berger et al. 2021

Classification of variables

Hereby, we distinguish between variables that are directly involved in radiative transfer mechanisms!

Vegetation traits & radiative transfer

Directly drive radiative transfer:
Primary variables

Leaf level traits

- Pigment content (chlorophyll, carotenoid, & anthocyanin contents)
- Leaf mesophyll structure
- Leaf water

Canopy level traits

- LAI (green LAI, brown LAI)
- Leaf inclination
- Green cover fraction
- fAPAR
- Albedo
- Soil moisture?

Indirectly drive radiative transfer:
Secondary variables

- Evapotranspiration
- Nitrogen content
- Phenology
- Crop yield
- Water stress
- Irrigation needs
- Crop coefficient

The quantitative crop traits included in the PRISMA 4Africa validation activities are:

- Leaf chlorophyll content (LCC)
- Canopy nitrogen content (CNC)
- Leaf nitrogen content (LNC)
- Leaf Area Index (LAI)
- Fractional Vegetation Cover (Fcover) [-]
- Fraction of Absorbed Photosyntetically Active Radiation (FAPAR) [-]

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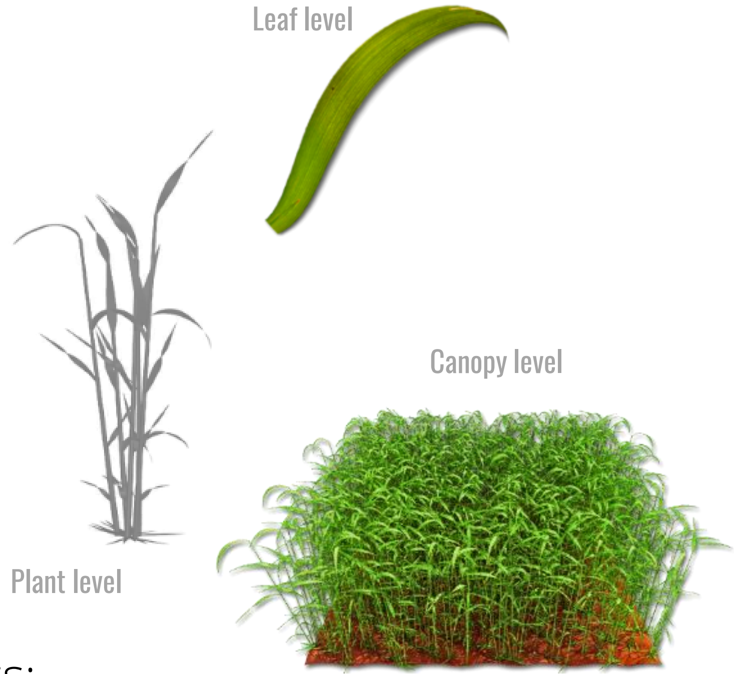
Radiance Regime of Vegetation

Effects on 3 scales



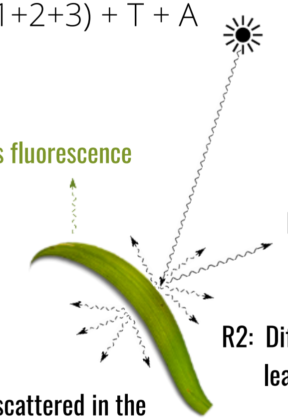
Credits:

Berger et al. 2021

Adapted from Kuester et al. (2014) with permission from IEEE

At leaf level

- Leaves are radiation receivers!
  80% - 90% of the absorbed radiation occurs in the leaves
- Radiation interaction:
  I = R(1+2+3) + T + A



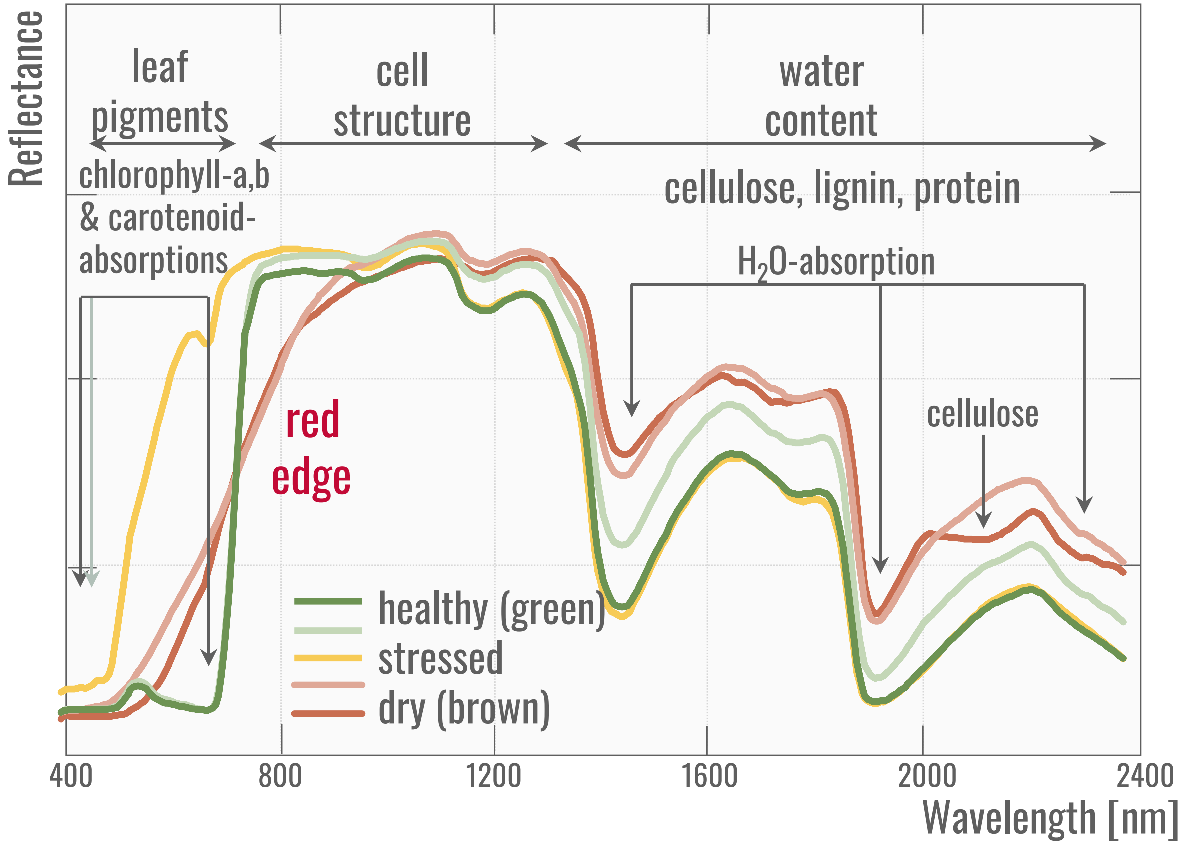
- Leaf level traits describe the biochemical and morphological properties of leaves, including pigments (chlorophyll a + b, carotenoids, anthocyanins), nitrogen, phosphorus, leaf mass per area, leaf water content, carbon and nonstructural carbohydrates (sugars, starches).

→ *These traits are mainly involved in photosynthetic processes and carbon uptake.*

- Leaf structural compounds include cellulose, fiber, lignin and hemicellulose.
- Typically, leaf traits are given in area-based (µg / cm²) or mass-based units (% or mg/g).

Factors controlling Leaf Reflectance

measured at leafs of Prunus plant



Ustin and Jacquemoud (2020)

Shape of the leaf spectra is characterized by:

- Low reflectance across visible wavelengths (due to absorption by photosynthetic pigments).
- High reflectance in the NIR, with only ~ 10% of absorbed radiation.
- Intermediate reflectance in the SWIR, where energy is mainly absorbed by water or plant residues in case of dry/stressed leaves. Cell wall compounds (cellulose, lignin, proteins and sugars) lead to overlapping absorption features.

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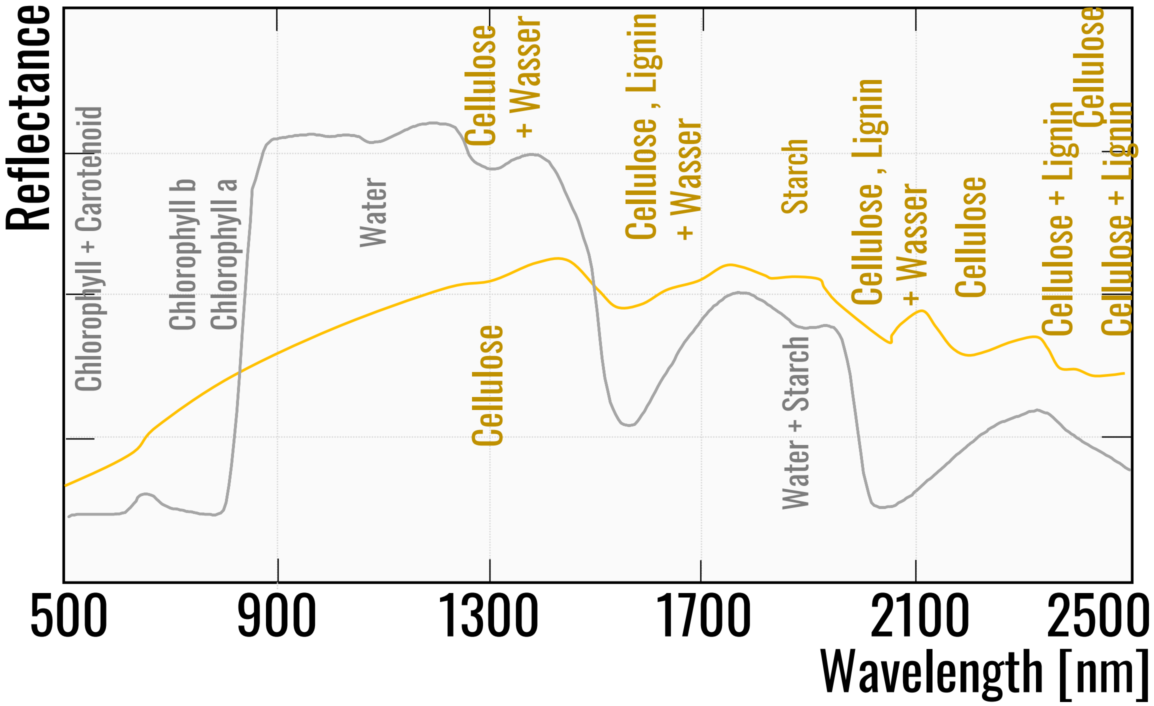
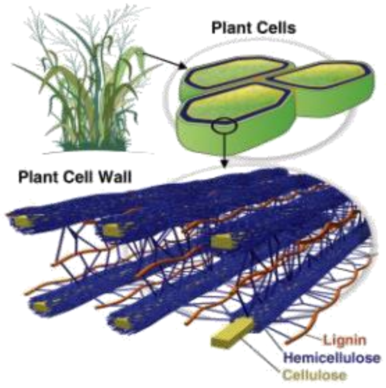
Leaf Biochemical Composition

- Main compounds: Water, cellulose, hemicellulose, lignin
- plant nutrients: e.g. Nitrogen, Phosphorous, substances produced by the plant for energy storage (e.g. starch)



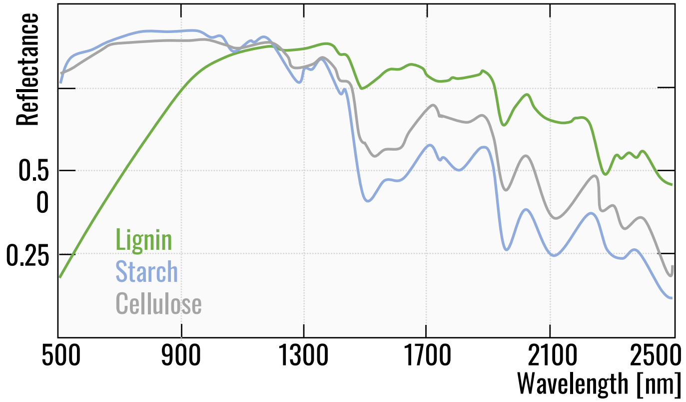


Lignin: 3D Macromolecule

Starch: $(C_6H_{12}O_5)_n$, spiral-shaped macromolecule, short-chain

Cellulose: $(C_6H_{12}O_5)_n$, linear macromolecule, long-chain

Hemicellulose: $(C_5H_{10}O_5)_n$, branched macromolecule



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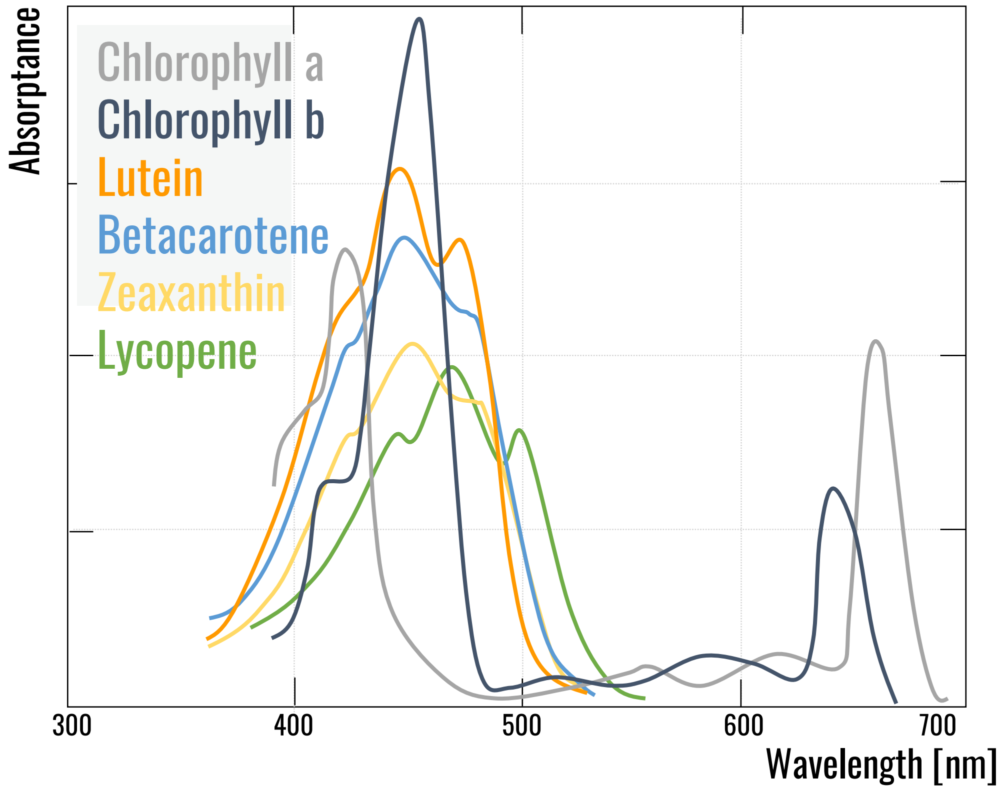
Leaf Pigments



Credits:

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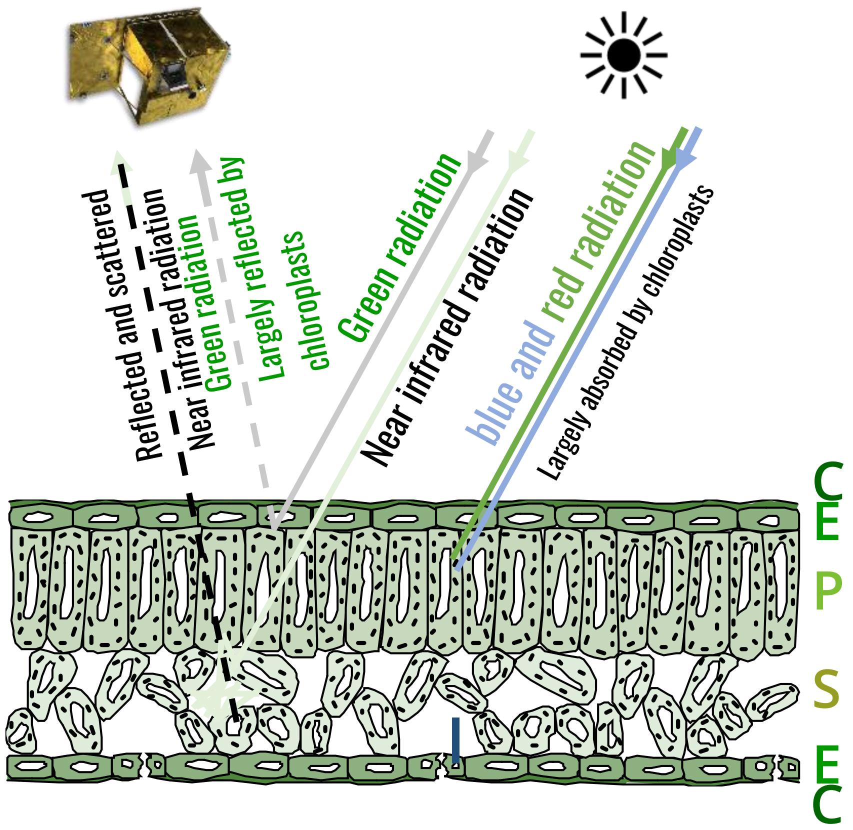
- Light absorption by pigments in the chloroplast produces a unique absorption pattern in the visible spectrum, with higher absorption in the blue and red wavelengths than in the green wavelengths
- Photosynthetic pigments, primarily chlorophylls and carotenoids (e.g. lutein, betacarotene, zeaxanthin, lycopene) strongly absorb light.
- Other non-photosynthetic pigments also absorb in this wavelength region, such as anthocyanins (large diverse group of flavonoids creating leaf, flowers and fruit color).

Leaf Cell Structure



Cell structur of a broadleaf

C = Cuticule
E = Epidermis
P = Pallisade tissue
S = Spongy tissue
I = Intercellularia

The radiation penetrating into the leaf is subject to numerous processes:

- Multiple scattering and refraction on the cell walls within the cells, but especially in the air-filled intercellular spaces.
- Multiple scattering and refraction at chloroplasts and other cell organelles in cells
- Absorption by leaf pigments in chloroplasts, cell water and other leaf constituents

Credits:

Berger et al. 2021

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Leaf chlorophyll content (LCC)

- *"In agricultural systems, the accurate spatial mapping of leaf chlorophyll content is important for monitoring vegetation health and plant stress, which can be used to guide fertilizer application in order to optimise crop yield and reduce excessive nutrient loss."* (Croft and Chen 2020)
- Chlorophyll molecules allow the conversion of absorbed solar irradiance into stored chemical energy, through harvesting light energy and supplying electrons to the electron transport chain, leading to the production of NADPH for the reactions of the Calvin–Benson Cycle (Croft and Chen 2020). The amount of solar radiation absorbed by a leaf is largely a function of foliar concentration of photosynthetic pigments. Hence, low leaf chlorophyll content (LCC) limits the photosynthetic capacity and reduces primary productivity of the crops (plants).
- LCC is usually quantified in units of µg chlorophyll per cm^2 (leaf area), or µmol m^{-2} or µg g^{-1} .
- *In situ* measurements of LCC are usually performed non-destructively via the Konica Minolta device Chlorophyll Meter SPAD-502Plus:

SPAD-502Plus

DUALEX

MC-100

atLEAF CHL

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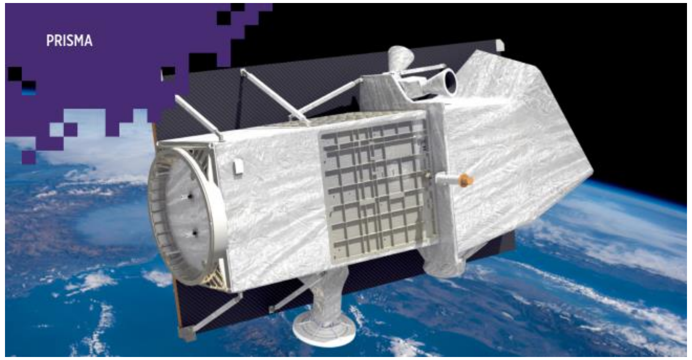
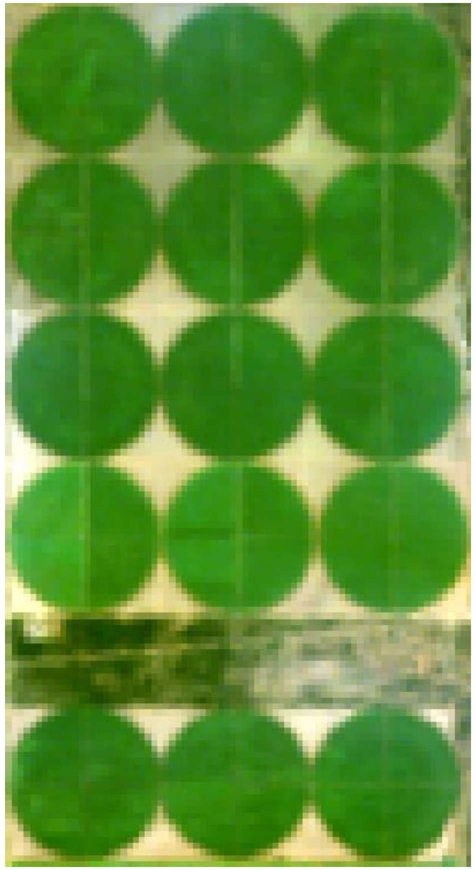
LCC mapping example

Rupisi (Zimbabwe)



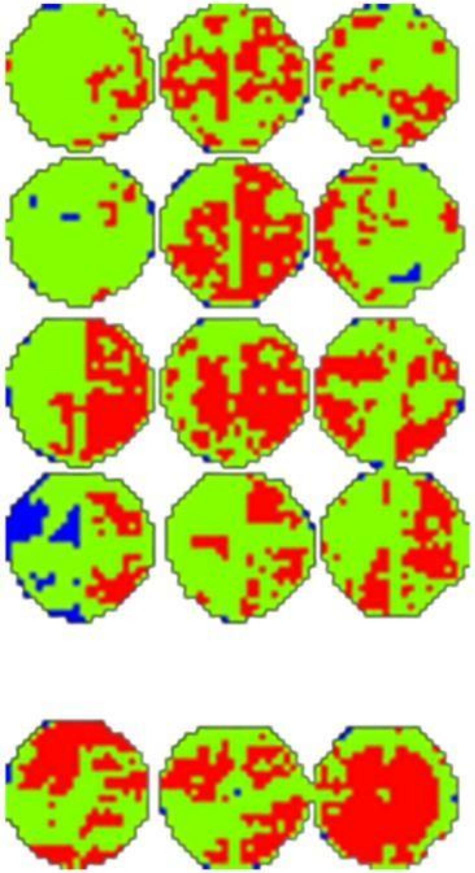


PRISMA RGB (32 21 9)

May 15, 2023

LCC (g/m^2)

28 40 52



- High Stress
- Moderate Stress
- No Stress

Credits:
Mirzaei et al.2024 IGARSS

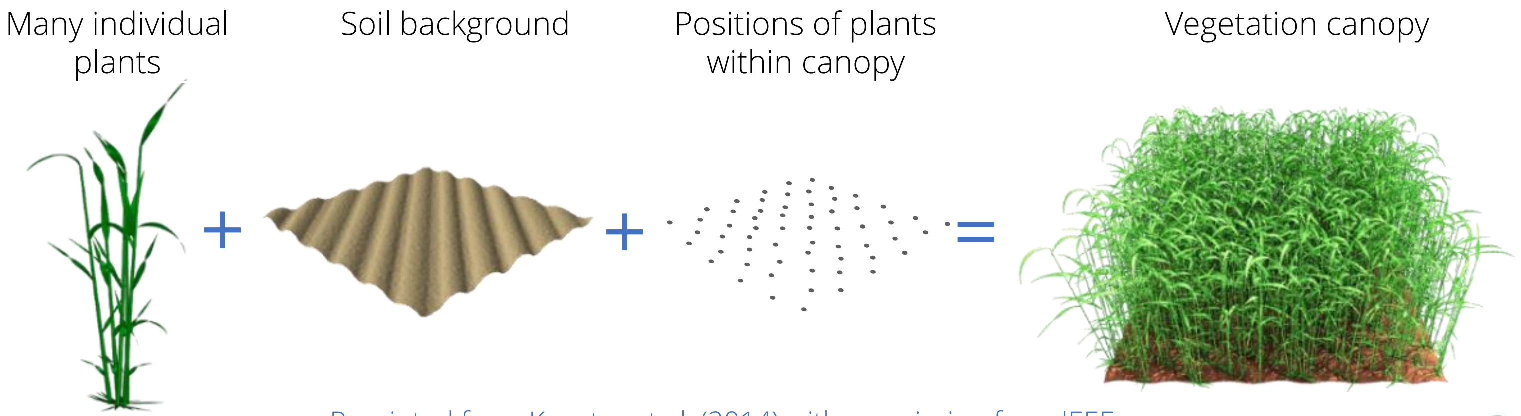
agenzia spaziale italiana

Canopy level traits: structure of a vegetation stand

- Canopy level variables or traits mainly describe the structural properties of a vegetation stand.
- In contrast to leaf biochemicals and leaf structural compounds, the added value of hyperspectral data compared to multi-spectral data for retrieval of canopy – level traits is less obvious.
- Nonetheless, these traits are of essential importance for agriculture due to their *strong link to crop status and yield potential* (Atzberger 2013).

Canopy is characterized through:

- Morphology of plants and phytoelements
- Phenology of individual plants
- Vitality of individual plants
- Arrangement and density of the plants
- Composition of plant species (natural vegetation vs. cultivated vegetation)
- Geometry and reflectivity of soil background



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Berger et al. 2021

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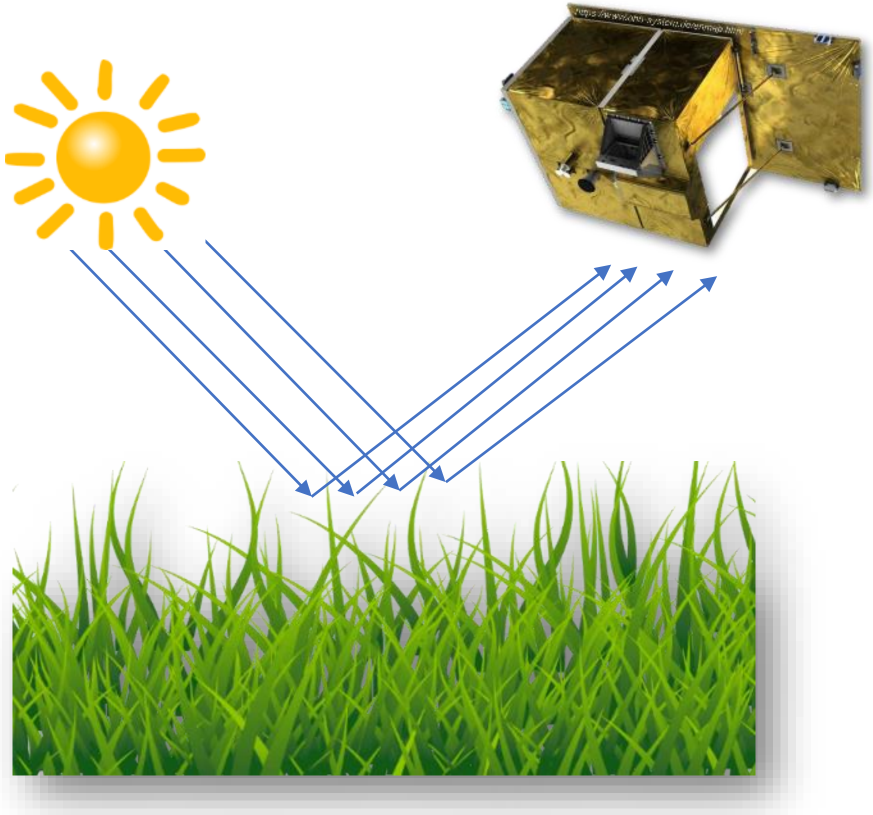
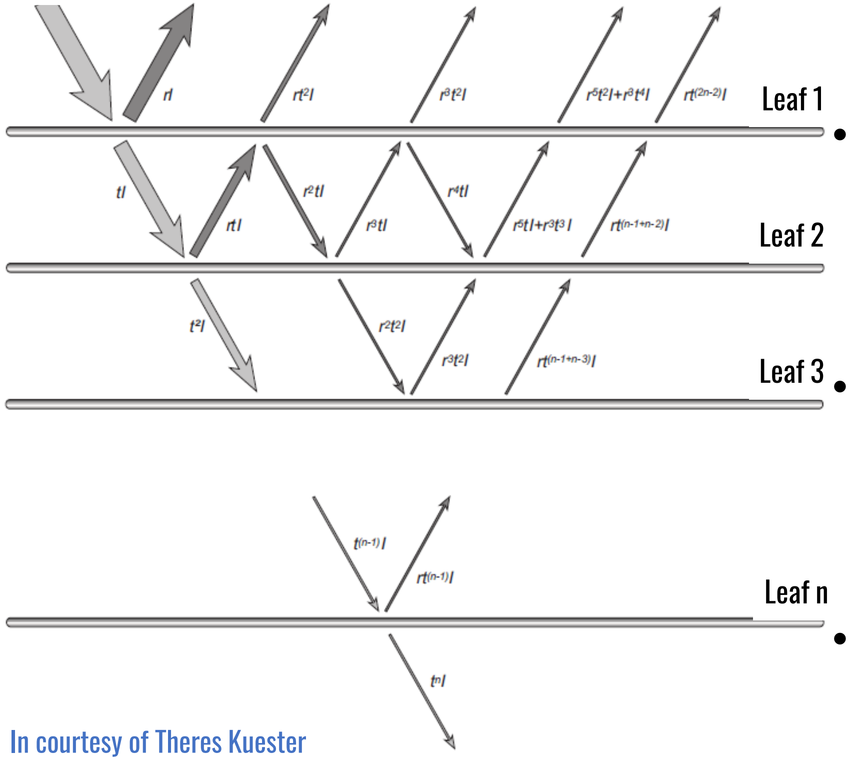
Effect of several Leaf Layers

$r \in]0;1[\ ;\ t \in]0;1[\ ;\ r + t < 1$





In courtesy of Theres Kuester

- Leaf surface is decisive size (LAI)
- Reflectance decreases in the visual wavelength range with increasing LAI due to absorption of leaf pigments
- Reflectance increases in the NIR wavelength range with increasing LAI due to scattering within leaf intercellulars
- Passing through the radiation of several leaf layers causes additive effect on absorptance, reflectance and transmittance
- Above a certain number of leaf layers saturation occurs, that is a limitation for the derivation of LAI from remote sensing data

Credits:

Berger et al. 2021

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Leaf Area Index (LAI)

- LAI is the biophysical vegetation trait that attracted most interest in optical remote sensing studies related to agriculture. “*Many applications, including crop growth and yield monitoring, require accurate long-term time series of leaf area index (LAI) at high spatiotemporal resolution with a quantification of the associated uncertainties*” (Yin et al. 2019)
- In general, LAI is defined as half the total leaf area per unit horizontal ground area (Jonckheere et al. 2004), though different LAI definitions exist:
  - Plant Area Index (PAI), accounting for non-green plant elements during the measurements. Note that most indirect methods used to estimate LAI from upward looking canopy transmittance corresponds to PAI rather than LAI!
  - Green Area Index (GAI): accounts for the functioning of the aboveground parts of the plants (crops), which are photosynthetically active during a significant fraction of the growth cycle (Boegh et al. 2002; Duveiller et al. 2012). Very important variable for agriculture & nitrogen content (Verrelst et al. 2014; Amin et al. 2021).
  - True GAI: half the developed area of green elements per unit horizontal ground area (destructive measurements).
  - Apparent GAI (effective LAI, or PAI): the value retrieved from remote sensing observations that depends on the (turbid medium) assumptions associated to the estimation algorithm. Effective LAI only considers random positions of leaves, and is referred to the value retrieved from green fraction (gap fraction) measurements based on turbid medium assumption (DHP, LAI2200) (Jonckheere et al.,2004; Richter et al. 2009).

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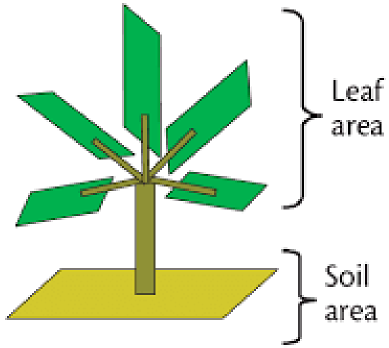
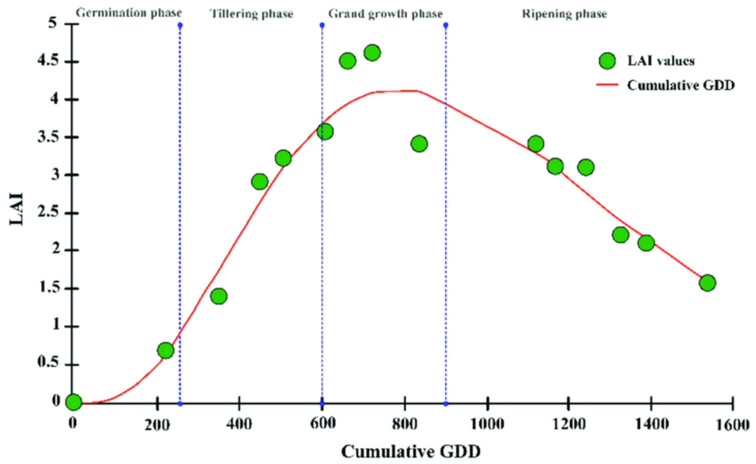
Leaf Area Index (LAI)



$$LAI = \frac{\text{Leaf area}}{\text{Soil area}}$$

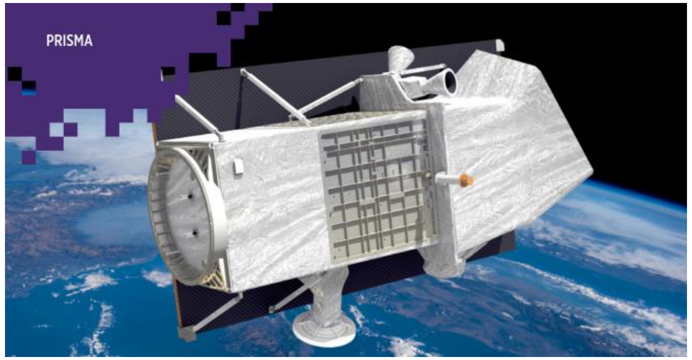
GROUND AREA = 1m²
LEAF AREA = 1m²
LAI = LEAF AREA: GROUND AREA = 1:1 = 1

GROUND AREA = 1m²
LEAF AREA = 3m²
LAI = LEAF AREA: GROUND AREA = 3:1 = 3

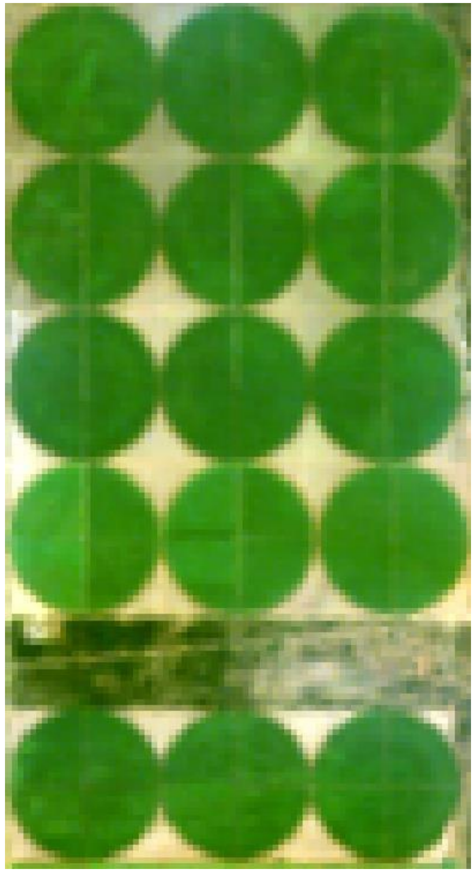


DOI: 10.3390/rs13204040

Rupisi (Zimbabwe)



Credits:
Mirzaei et al.2024 IGARSS



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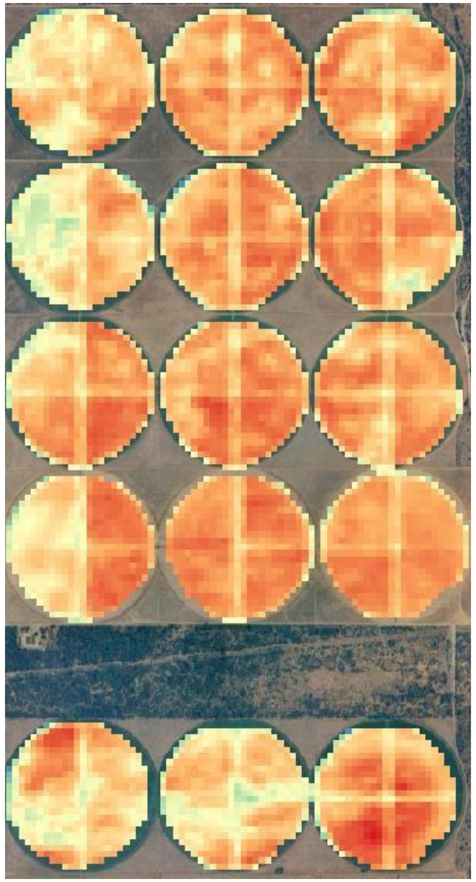
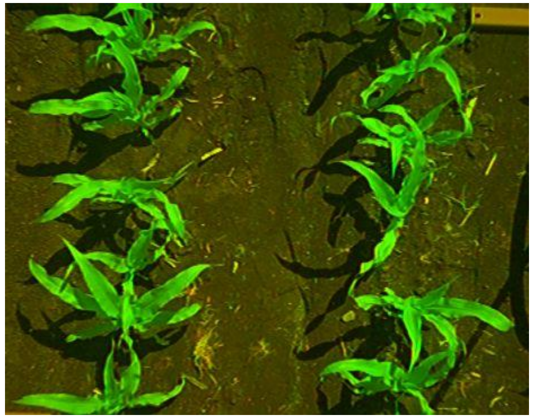


LAI (m²/m²)
1.5 2.5 5.5

Fractional vegetation cover (fCOVER or FVC)



- *Fractional vegetation cover (fCOVER or FVC) is useful for various applications in the field of agriculture - ranging from irrigation and crop residues management to yield estimations.*
- Green fCOVER is an important biophysical variable describing the Earth's surface system. *"Fractional vegetation cover is generally defined as the ratio of the vertical projection area of above-ground vegetation organs on the ground to the total vegetation area."*
- fCOVER in [%], the fraction of the green vegetation in the nadir direction, is used to separate vegetation and soil in energy balance processes, including temperature and evapotranspiration.
- fCOVER is also know as green ground cover (GGC%).

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Berger et al. 2021

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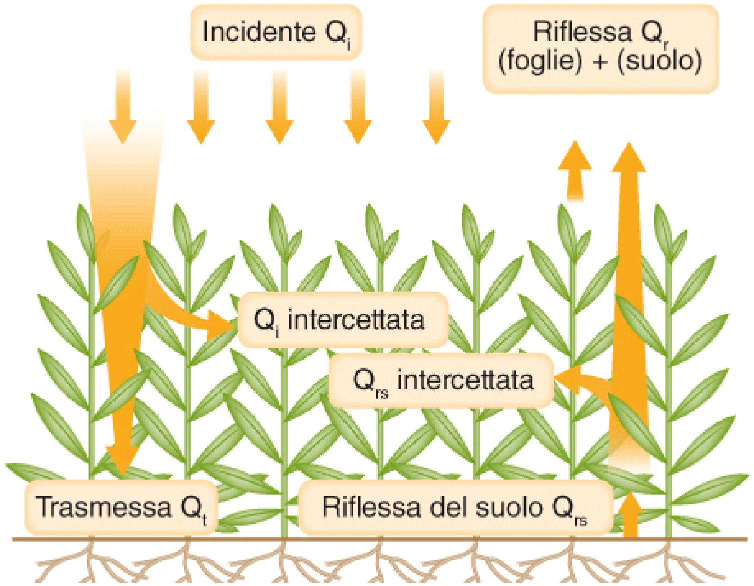
Fraction of absorbed photosynthetically active radiation (FAPAR)



- Remote sensing time-series of fraction of absorbed photosynthetically active radiation (fAPAR) have been "*confirmed to be a reliable tool for regional crop yield forecasting with a strong potential to contribute effectively to operational systems such as those currently running at continental/global level (GIEWS, NASS, FAS, CropWatch or MCYFS).* (López-Lozano et al. 2015)

  Photosynthetically active radiation (**PAR**): corresponds to the incoming solar radiation in the spectral range of 400–700 nm.

  Absorbed photosynthetically active radiation (**APAR**): corresponds to the amount of PAR absorbed by the plant for photosynthesis (Gallo and Daughtry 1986).

  Fraction of absorbed photosynthetically active radiation (**fAPAR**): is the proportion of PAR absorbed by the plant, expressed as fraction.

- fAPAR is an important biophysical variable in models assessing the primary productivity of vegetation and, more generally, in carbon cycle models between the terrestrial boundary layer and the atmosphere (Viña and Gitelson 2005, Rahmann et al. 2014).

Methods for ground measurement of biophysical variables

Methods	Pros	Cons
Direct Methods	more accurate	destructive methods computationally time consuming not adequate for large field campaigns
Scientific grade Commercial Instruments Lai-2000 / 2200, Ceptometer, DHP	Simple, Scientifically validated, versatile, Robust efficient for large field data collection	cost – purchase / maintenance low portability
Smartphone Apps, DHP, PocketLAI	efficient for large field data collection no cost, smartphone – 2 sensors LAI - gap fractions	less accurate as compared to direct methods

Methods for ground measurement of biophysical variables

Pocket LAI

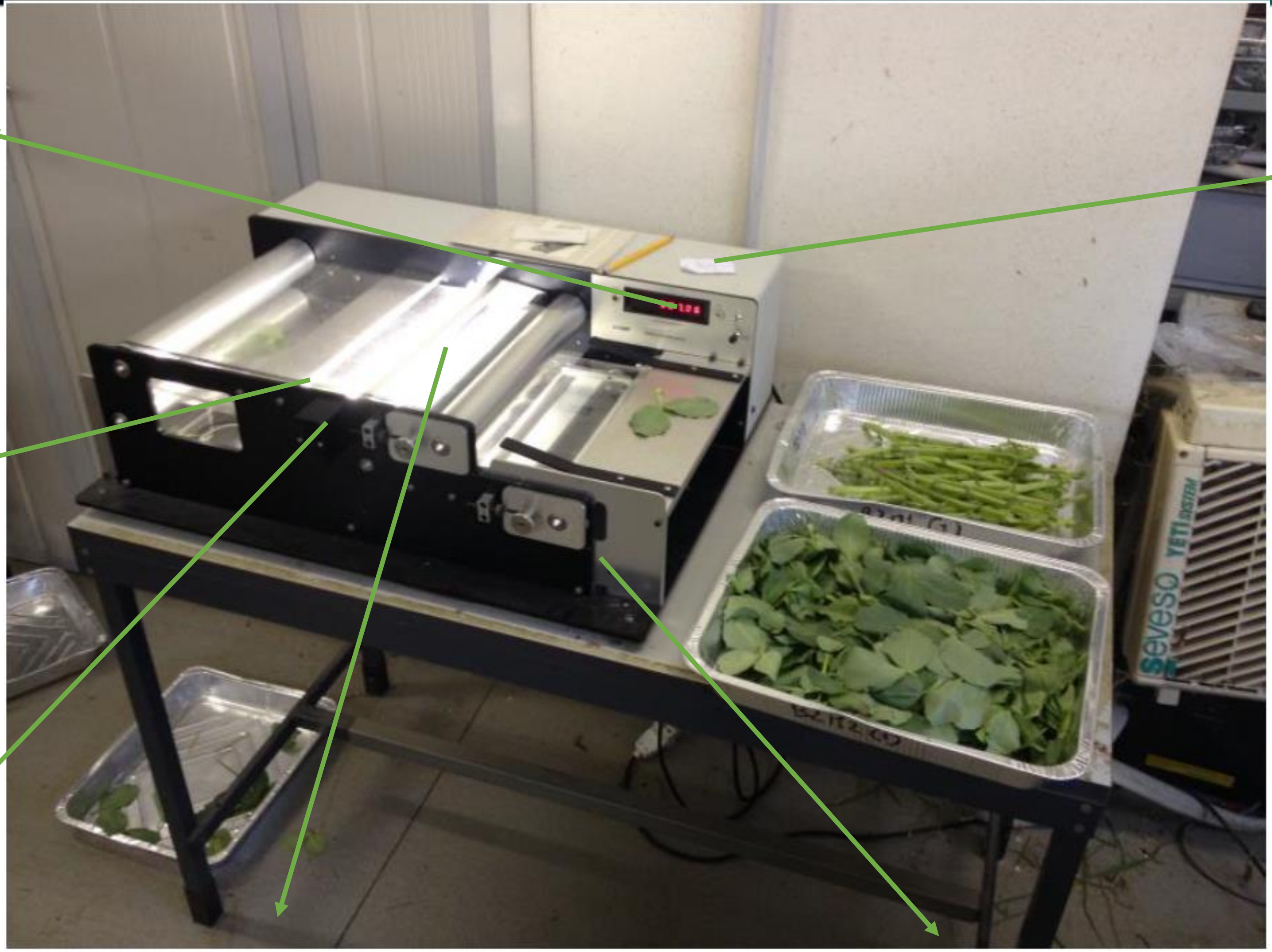
PocketLAI

Direct measurement of Leaf Area Index: Area Meter -

Decimal selector switch in the 1.0 mm^2 operation

25 mm lens in place for 0.1 mm^2 operation

Screws on the outer camera pressure rail



Rear sliding bearing blocks

Main Printed Circuit Board

Sample guides (7.5 cm) for 0.1 mm^2 resolution

Assumptions behind Indirect methods of LAI estimation

- random distribution of leaves within canopy

Less gap fraction

More gap fraction

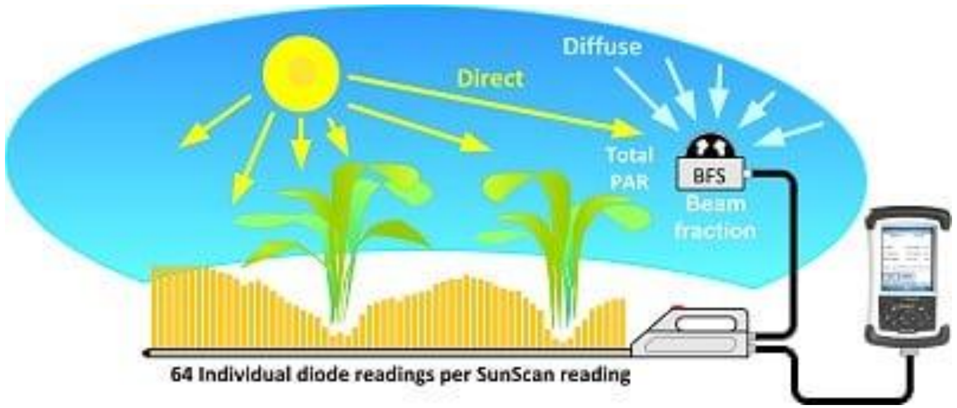
- Estimated LAI (effective LAI) ≠ True LAI (planimeter measured)

$$P(\theta) = exp^{-k(\theta).LAI}$$

K = Extinction Coefficient

Depends on the leaf angle distribution of the canopy

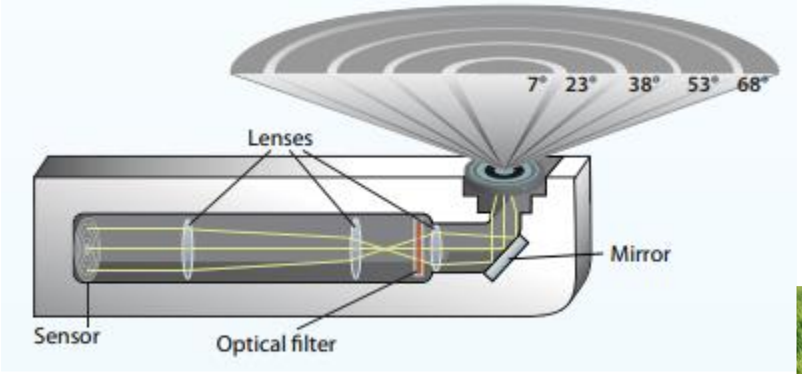
Sun Scan Ceptometer (Decagon)



- Consists of 1m long probe with 64 PAR sensors
- All sensors are scanned and readings are sent to PDA
- Average PAR level is stored
- All PAR readings can be saved for PAR mapping
- Ease of use, robust and can save upto 1 million readings
- Readings can be displayed, reviewed and stored

An estimate of K must be provided
K = Extinction Coefficient

LAI 2000 / 2200 – LiCor

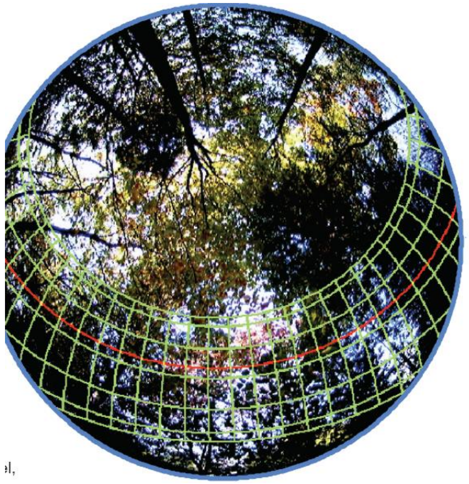


K is directly estimated by using different angles

K = Extinction Coefficient

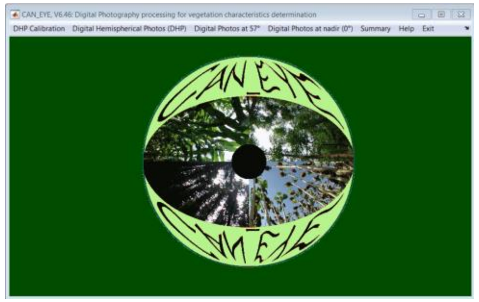
- Readings should be taken in overcast sky conditions
- Diffuser cap is used to block the portion of sky in case of direct sun light
- Gap fractions are estimated based on five zenith angles
- Data stored – gap fractions + raw LAI estimate
- Raw estimates are corrected for scattering
- Allows to estimate LAI in defined number of rings (outer ring excluded)

Digital hemispherical photography

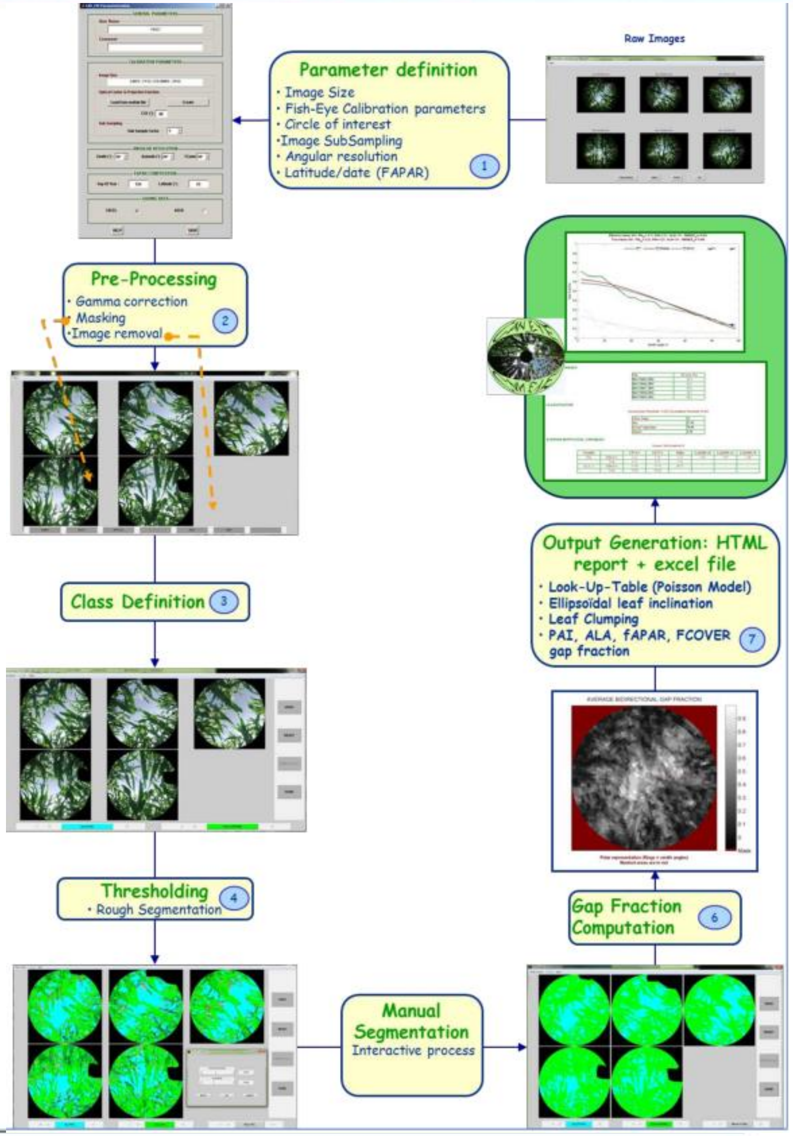


- Computes gap fractions in multiple directions
- Later processing can be performed on dedicated software
- Interactive processing on Can-Eye

K is directly estimated by using different angles
K = Extinction Coefficient



- Can be performed also using a smartphone with a fish-eye lens



Measurement of leaf pigments