CIHEAM

LAND and WATER
Resource Management

APPLICATION OF REMOTE SENSING IN DSS FOR LAND AND WATER MANAGEMENT

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Soil – Crop – Atmosphere Continuum

REMOTE SENSING
IMAGES/INDICES

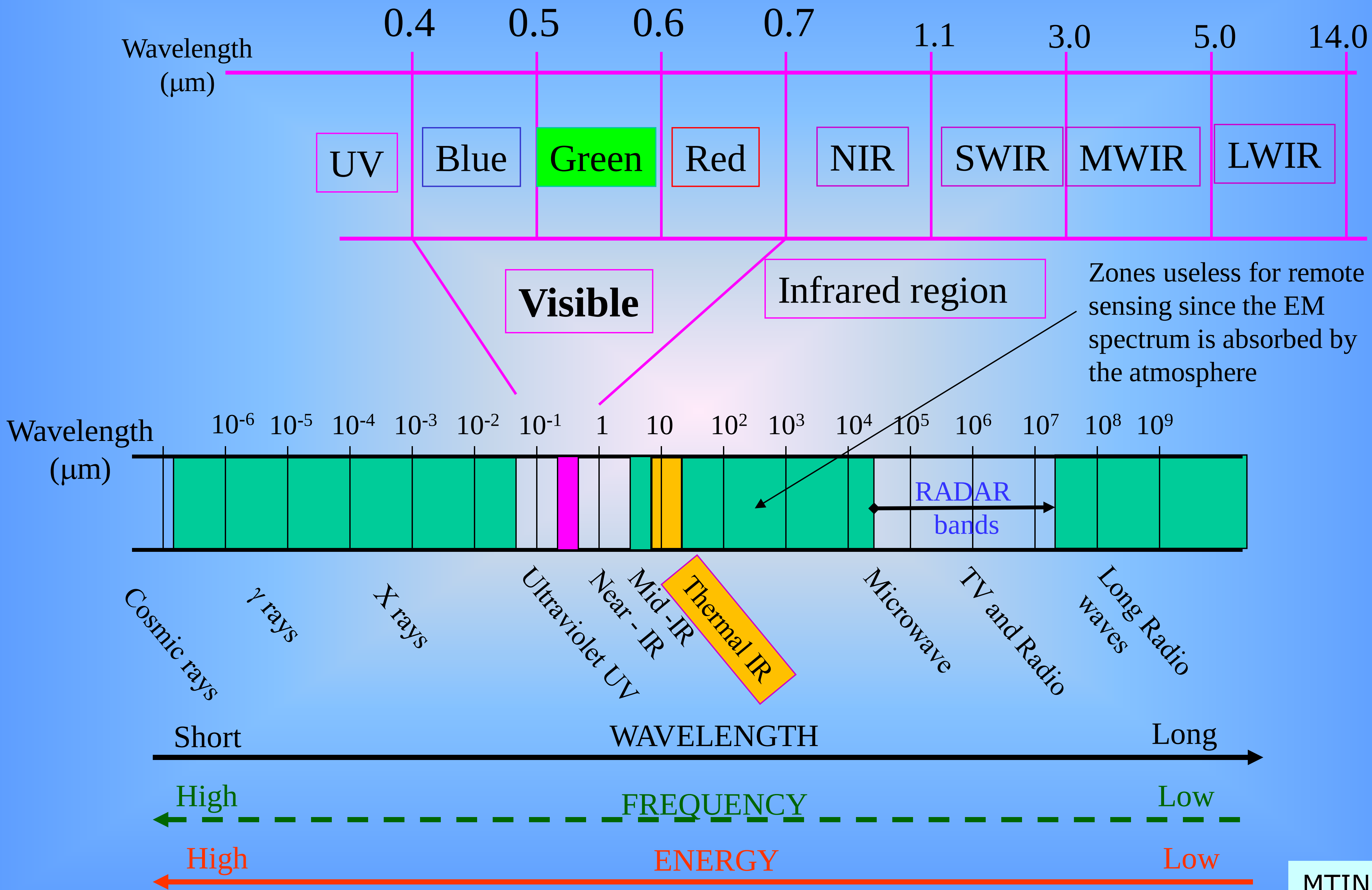
CROP/CANOPY
PARAMETERS
(Biometric & physiological)
SOIL (water & N content)

MANAGEMENT
(water & N inputs,
use of pesticides, herbicides, etc.)

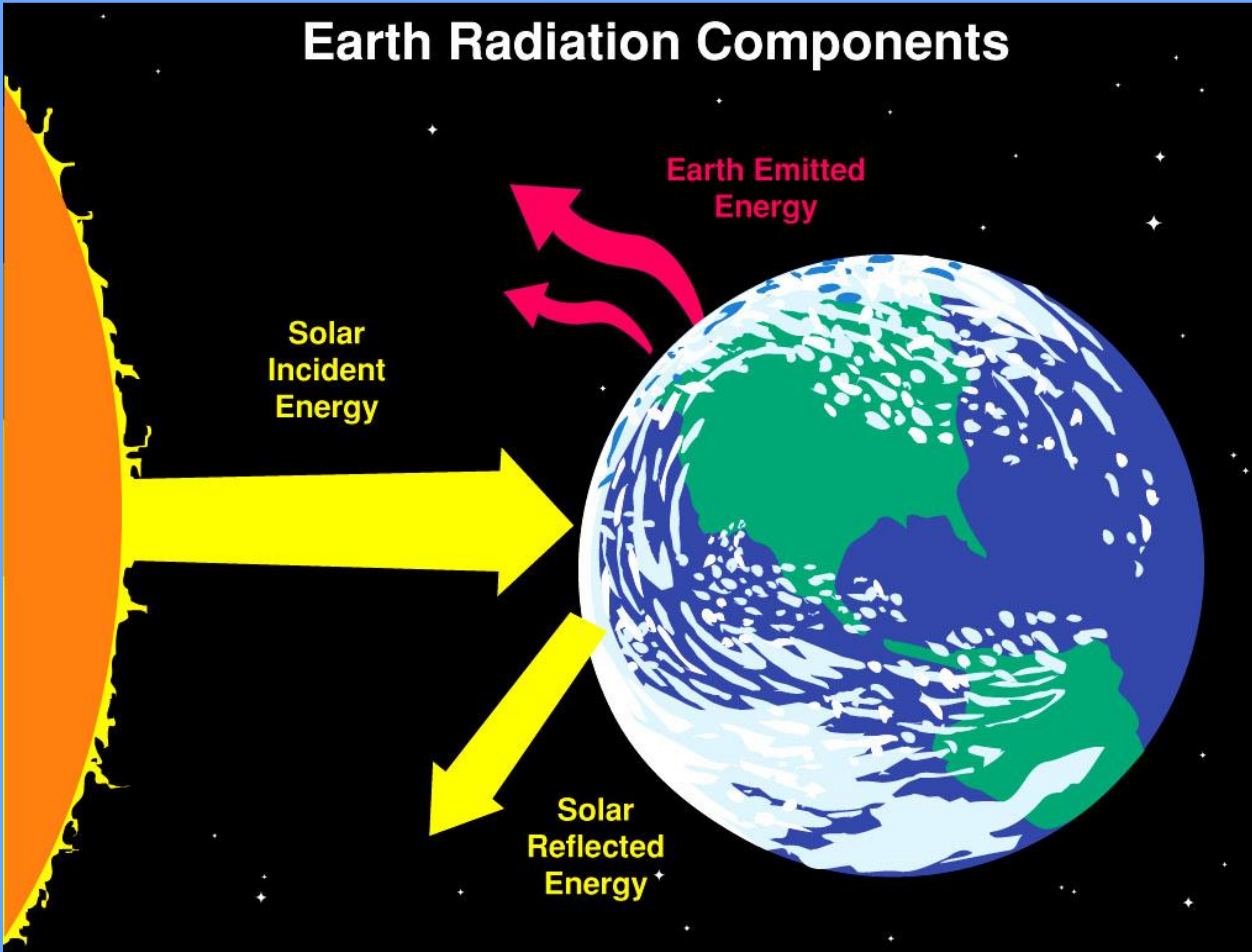
Remote sensing

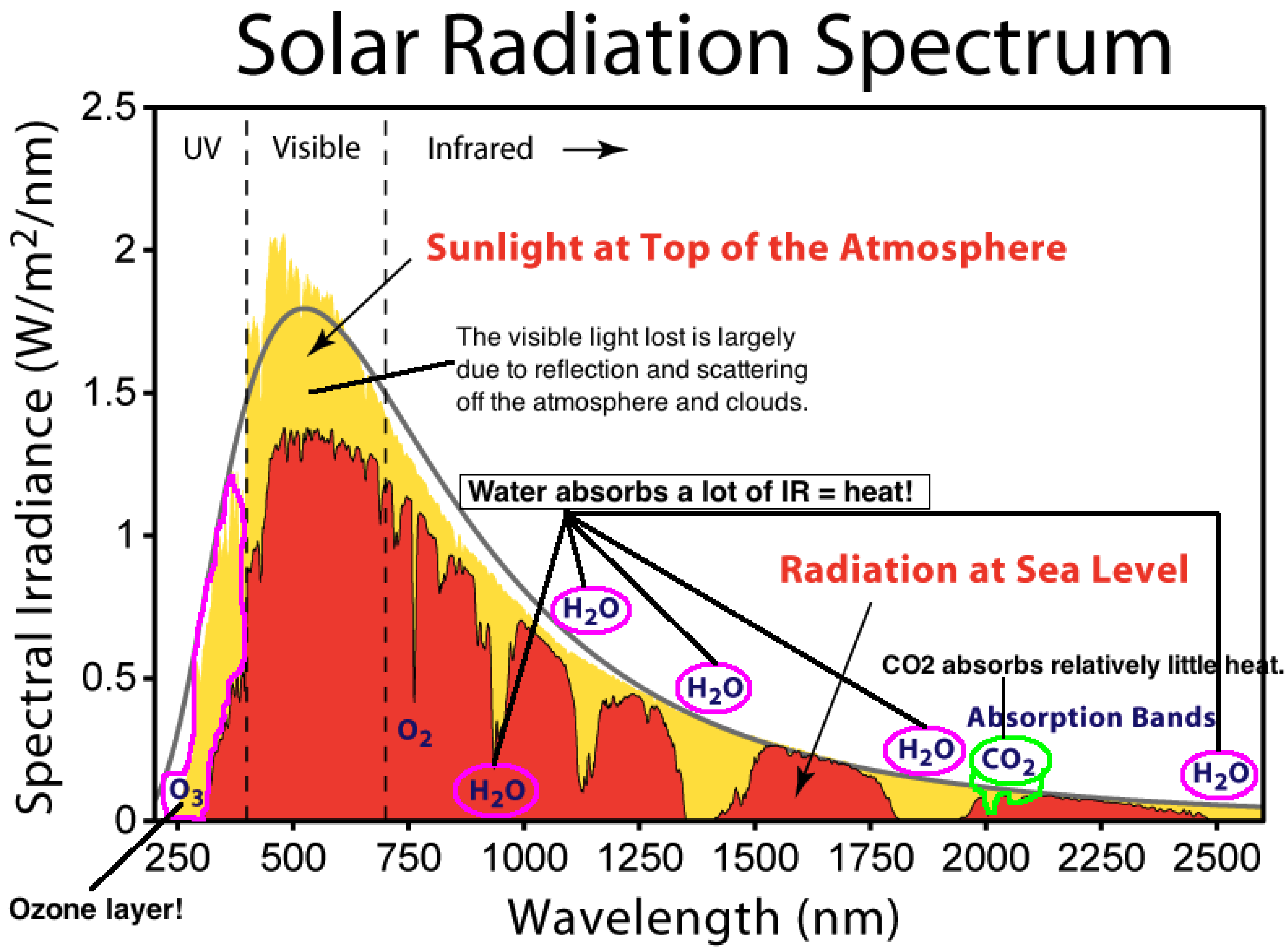
- **Definition:**
  - Remote sensing is a measurement or acquisition of information of some property of an object or phenomena, by a recording device that is not in physical or intimate contact with the object or phenomena under study.
- **Acquisition platforms and methods:**
  - flying observation platforms (satellites, aircrafts, helicopters, Unmanned Aerial Vehicles (UAV) – e.g. drones)
  - ground observation platforms (towers, vehicles, masts…)
  - Ground-based handheld – proximal sensing
- **Principles:**
  - make use of electromagnetic energy to capture information by sampling radiation from selected wavebands (“regions”, “windows”)
  - the spectrum of visible light, some infra-red frequencies and a wide spectrum of radio and microwave frequencies are commonly used

ELECTROMAGNETIC SPECTRUM

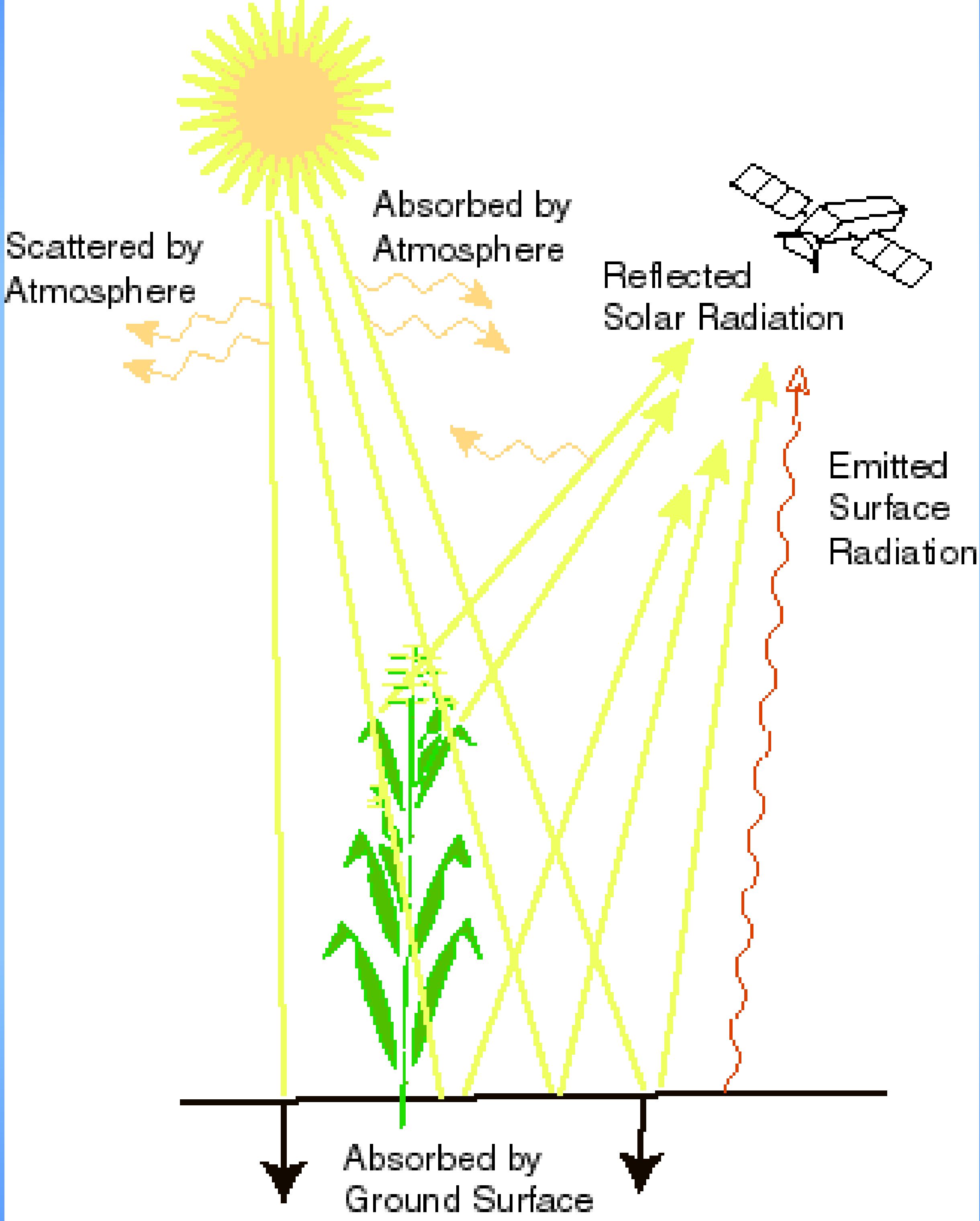


MTING


Earth Radiation Components
Earth Emitted Energy
Solar Incident Energy
Solar Reflected Energy



Source: adapted from www.wikipedia.org



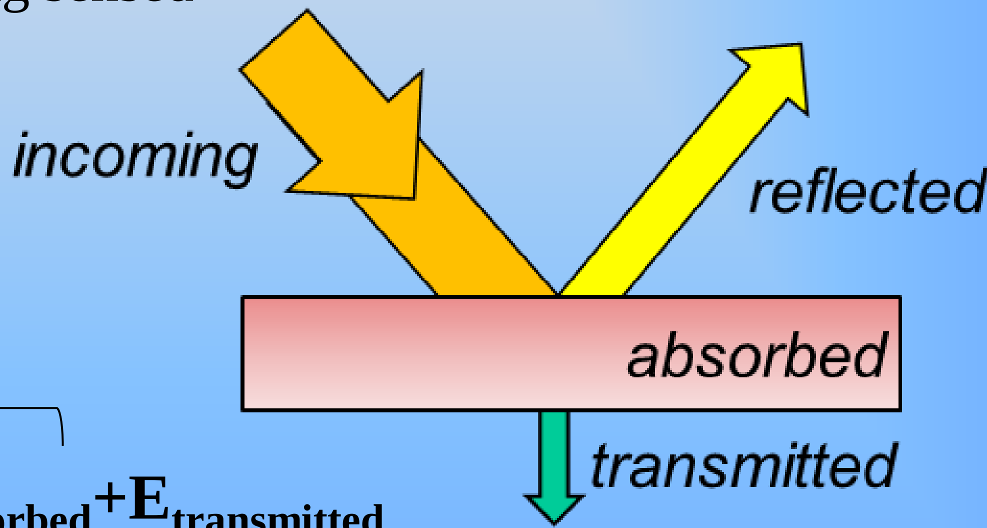
Scattered by Atmosphere
Absorbed by Atmosphere
Reflected Solar Radiation
Emitted Surface Radiation
Absorbed by Ground Surface

Remote sensing - sensors

- **Passive sensors:**
  - use some existing ("natural") source of energy (e.g. the sun) in data acquisition
  - mounted on satellite platforms, robust and do not require special maintenance, long-life
  - application is limited under cloudy conditions and during the night
- **Active sensors:**
  - RADAR (RAdio Detection And Ranging) – emits energy in microwave (radio) region to detect surface characteristics
  - LIDAR (LIght Detection And Ranging) – emits LASER (Light (optical) Amplification by Stimulated Emission of Radiation) in UV, visible and NIR regions
  - mounted on the ground platform, on the aircraft, or on the satellites (ERS, JERS, RADARSAT)
  - can be used at night, in any atmospheric conditions (clouds, rain) and can penetrate the land surface (for studying subsurface conditions)
  - Synthetic Aperture Radar (SAR) - high resolution radar imagery

Remote sensing - data acquisition

- **Principles:**
  - the radiation measured by sensors is reflected or emitted energy generated from molecular interactions between incoming radiation and the object (material) on the earth being sensed



intercepted

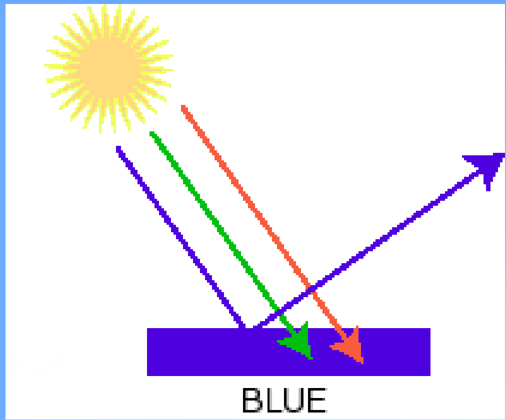
$$E_{incoming} = \underbrace{E_{reflected} + E_{absorbed}}_{\text{intercepted}} + E_{transmitted}$$

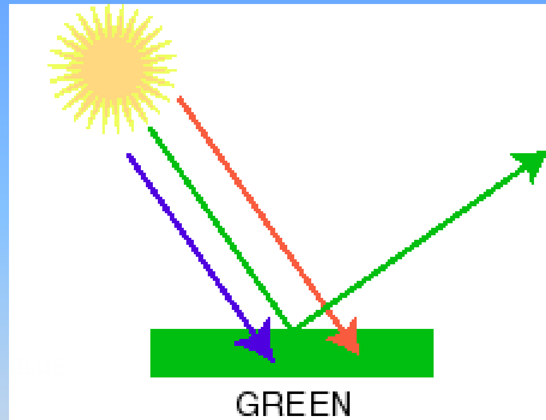
  - The reflection and transmission depends on the wavelength
  - In the visible part of the spectrum about 10% is reflected and 10% is transmitted – therefore, about 80% of visible spectrum represents the absorbed energy (available for photosynthesis)

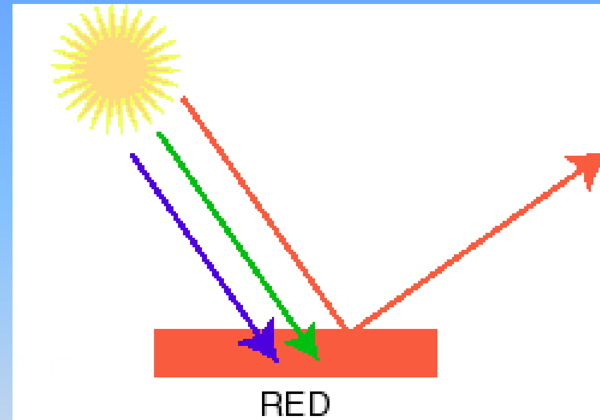
Spectral signature

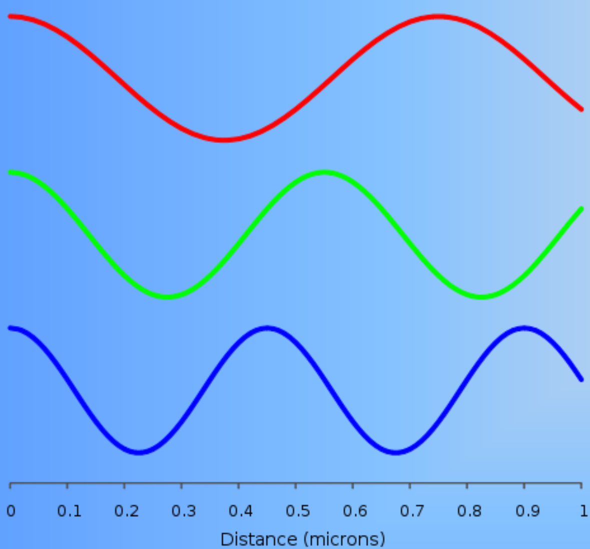
- the energy detected by sensors represent ***the spectral signature*** of the sensed surface - *the intensity of power variations of the reflected signal as a function of wavelength*

- **It is possible to define classes, objects or features of sensed surface:**
  - because the same material has varying values of reflectance (or emittance) in different spectral regions - different materials produce different spectral signatures

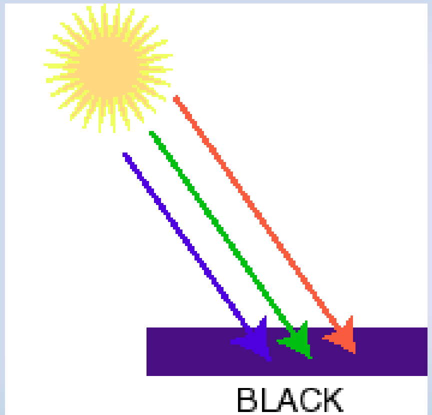


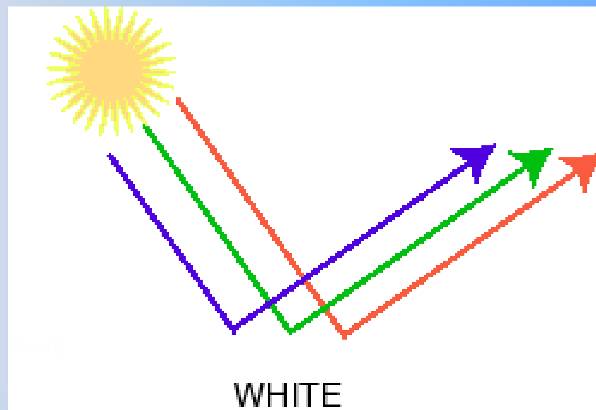


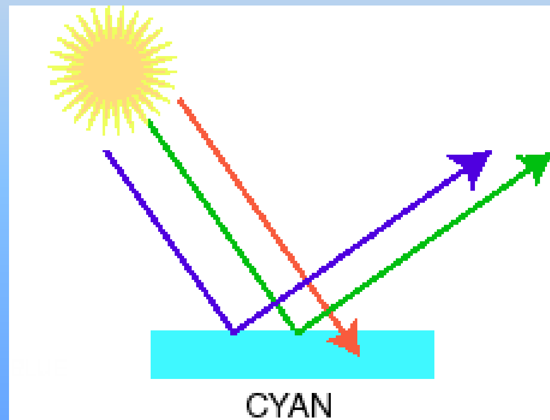


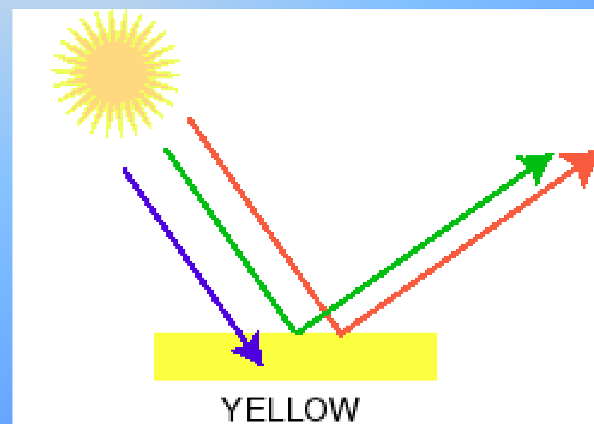


Visible wavelengths

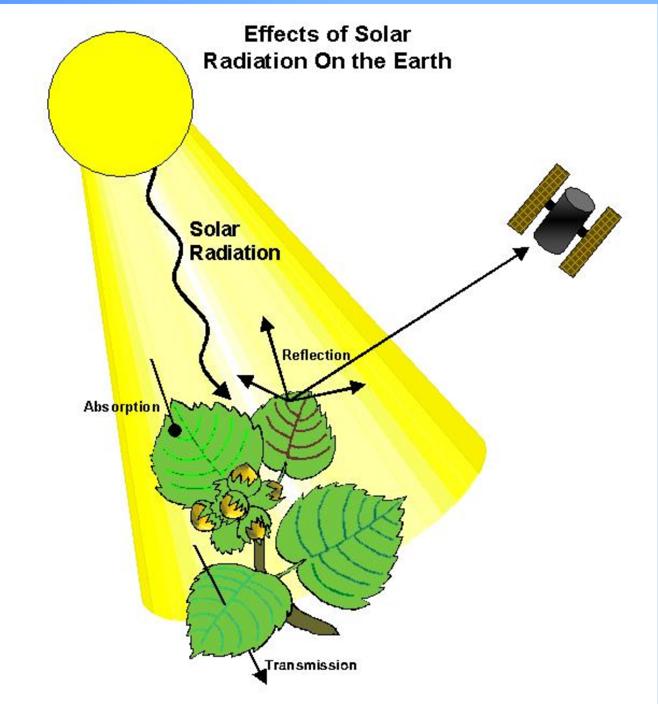




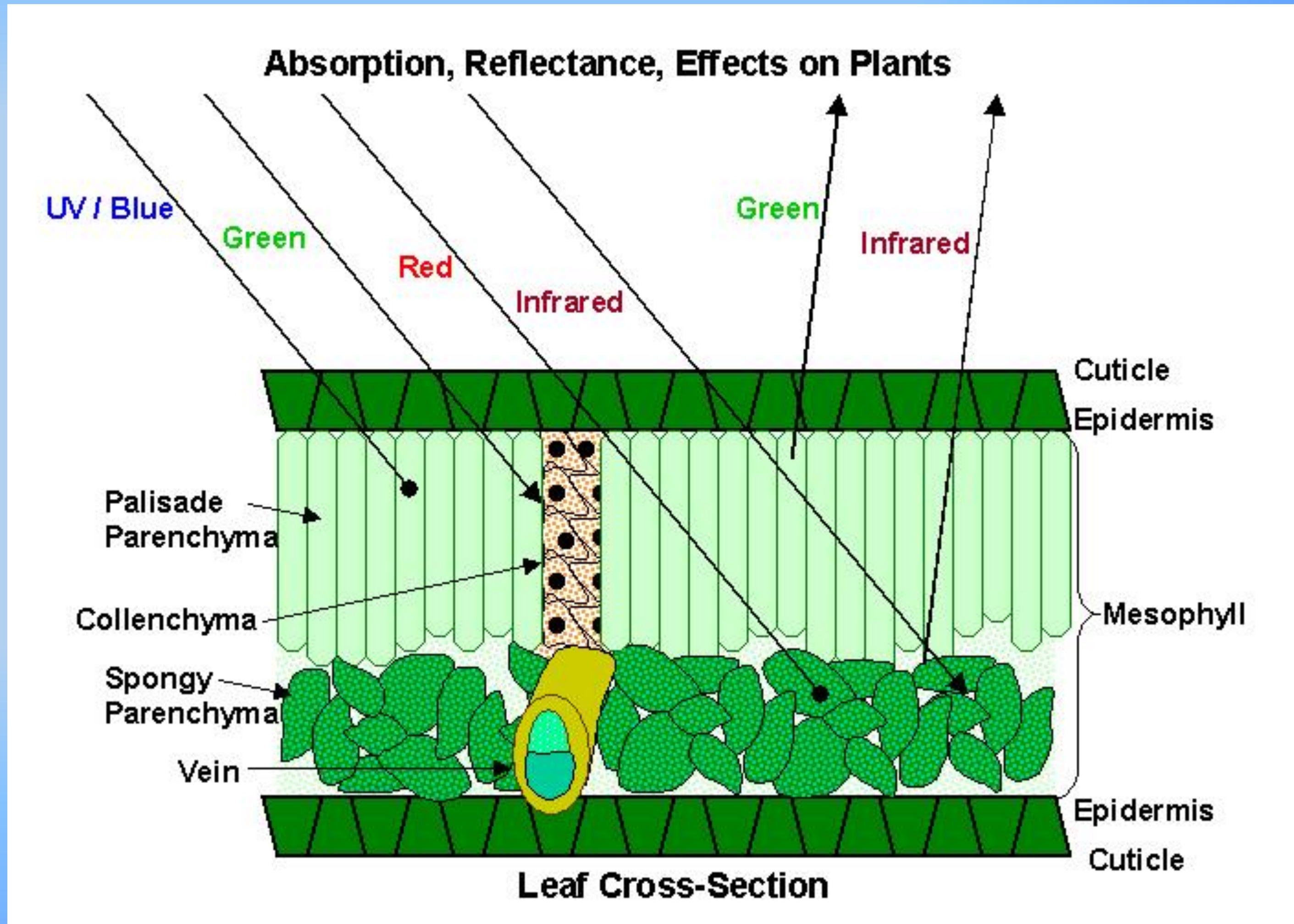




How plant leaves reflect light



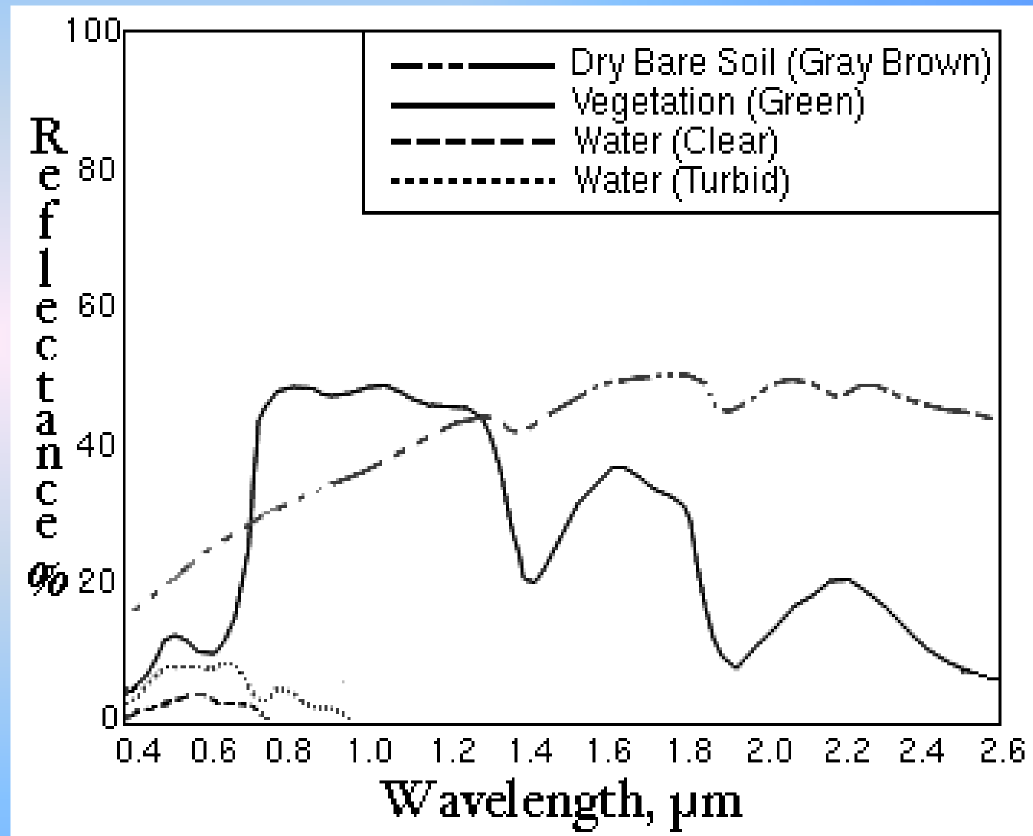
chlorophyll in leaves absorbs red and blue, but reflects green



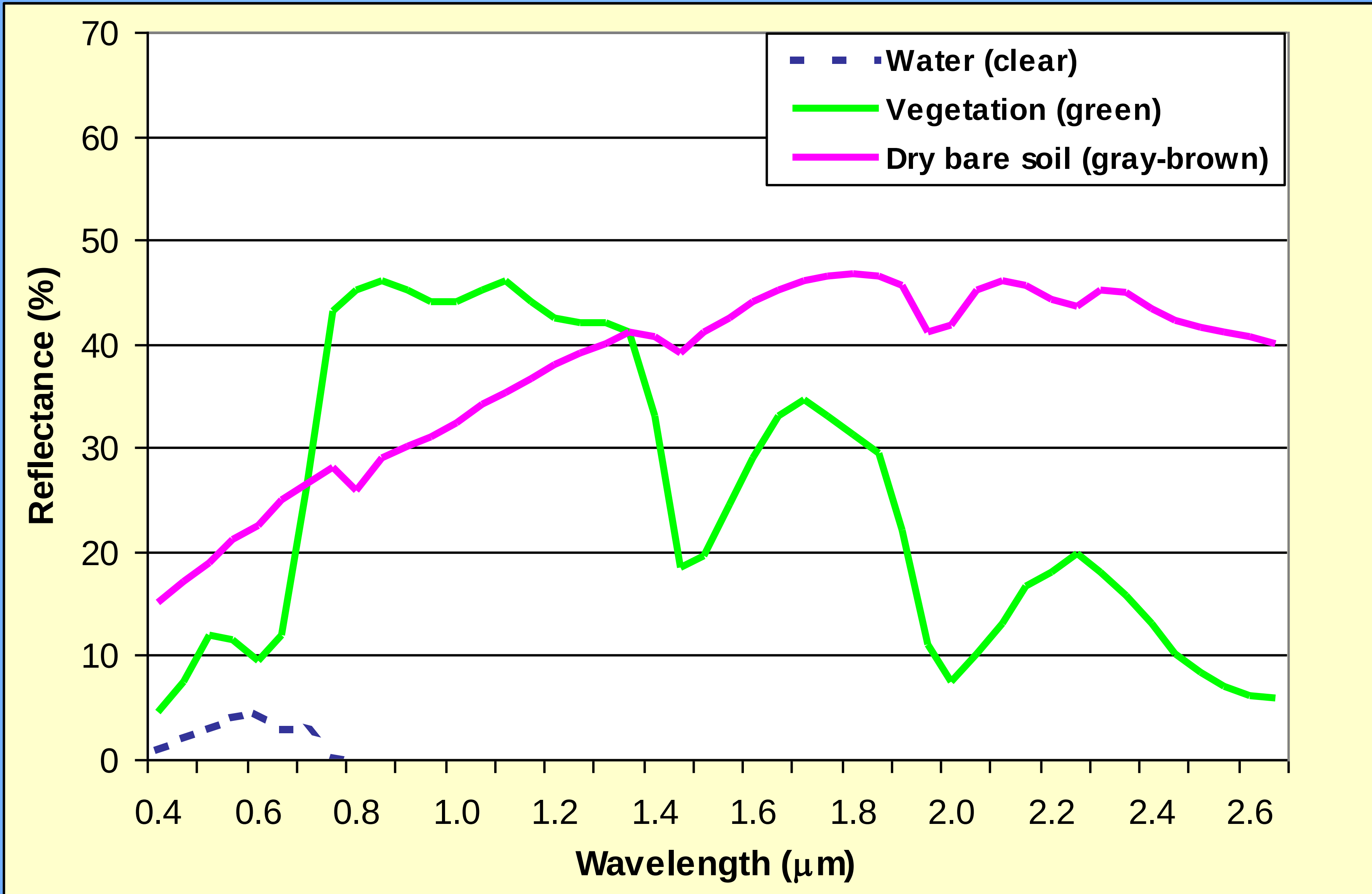
Graphics from http://landsat7.usgs.gov/resources/remote_sensing/radiation.php

Reflectance from green plant leaves

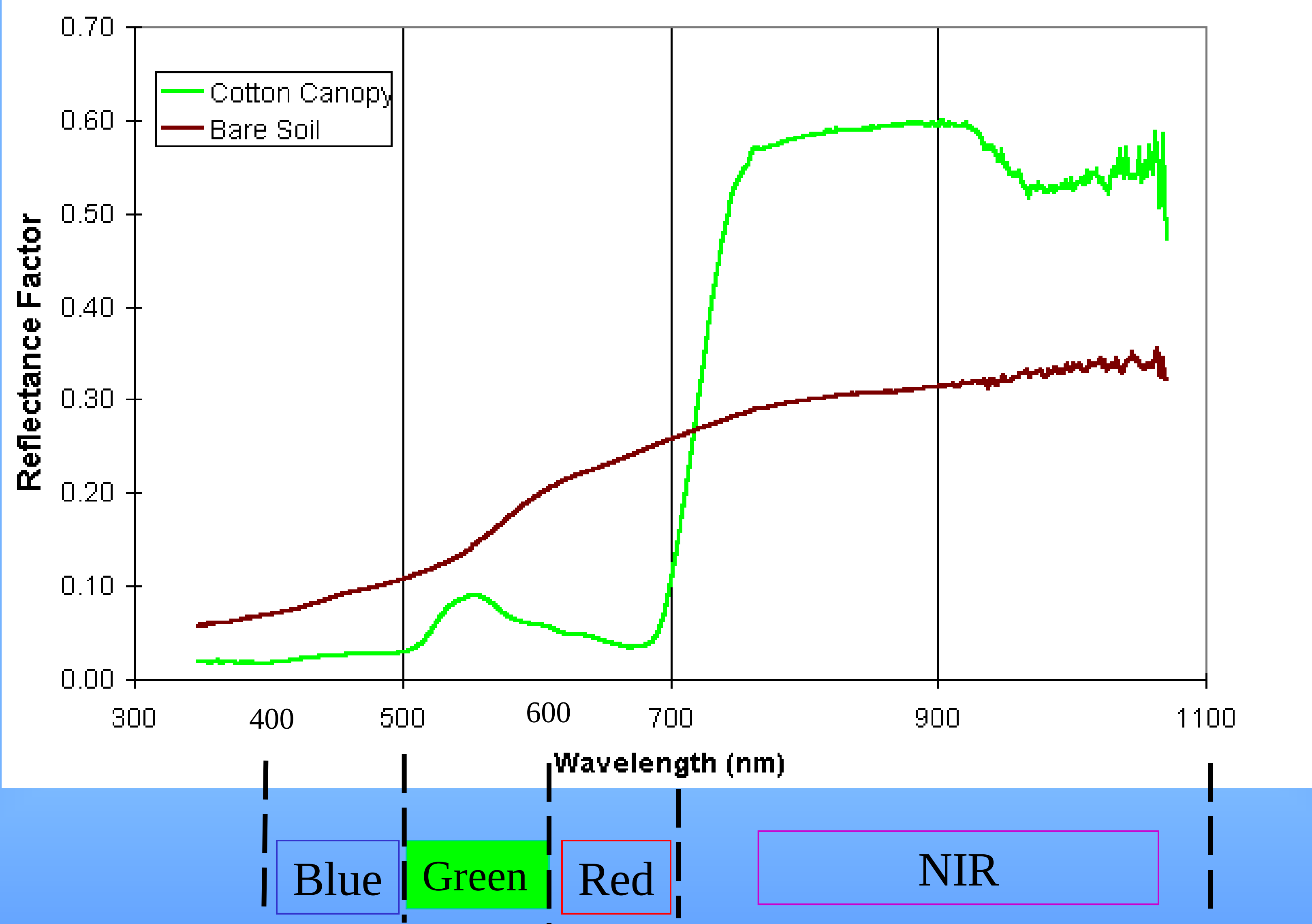
- Chlorophyll absorbs in the wavelengths between 430-450 and 650-680nm. The blue region overlaps with carotenoid absorption, so it should focus on the red region response (650-680nm).
- Peak reflectance in leaves in near infrared (700-1200 nm) up to 60% of infrared energy per leaf is scattered up or down due to cell wall size, shape, leaf condition (age, stress, disease), etc.
- Reflectance in Mid IR (2000-4000nm) influenced by water content-water absorbs IR energy, so live leaves reduce mid IR return



Typical signatures (spectral reflectance curves) for bare soil, green vegetation and clear water

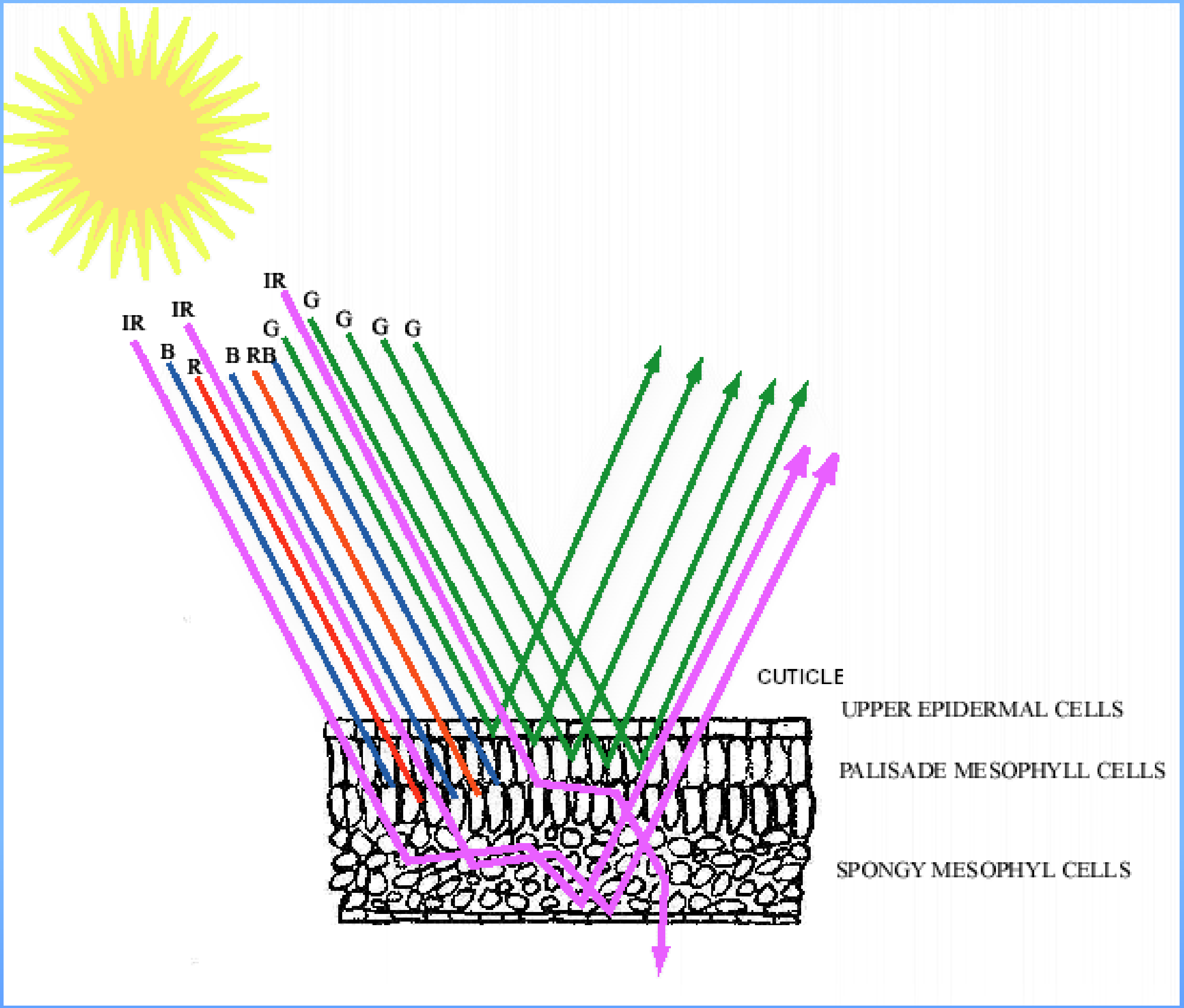


Typical signatures (spectral reflectance curves) for cotton canopy and bare soil in blue, green, red & NIR bands



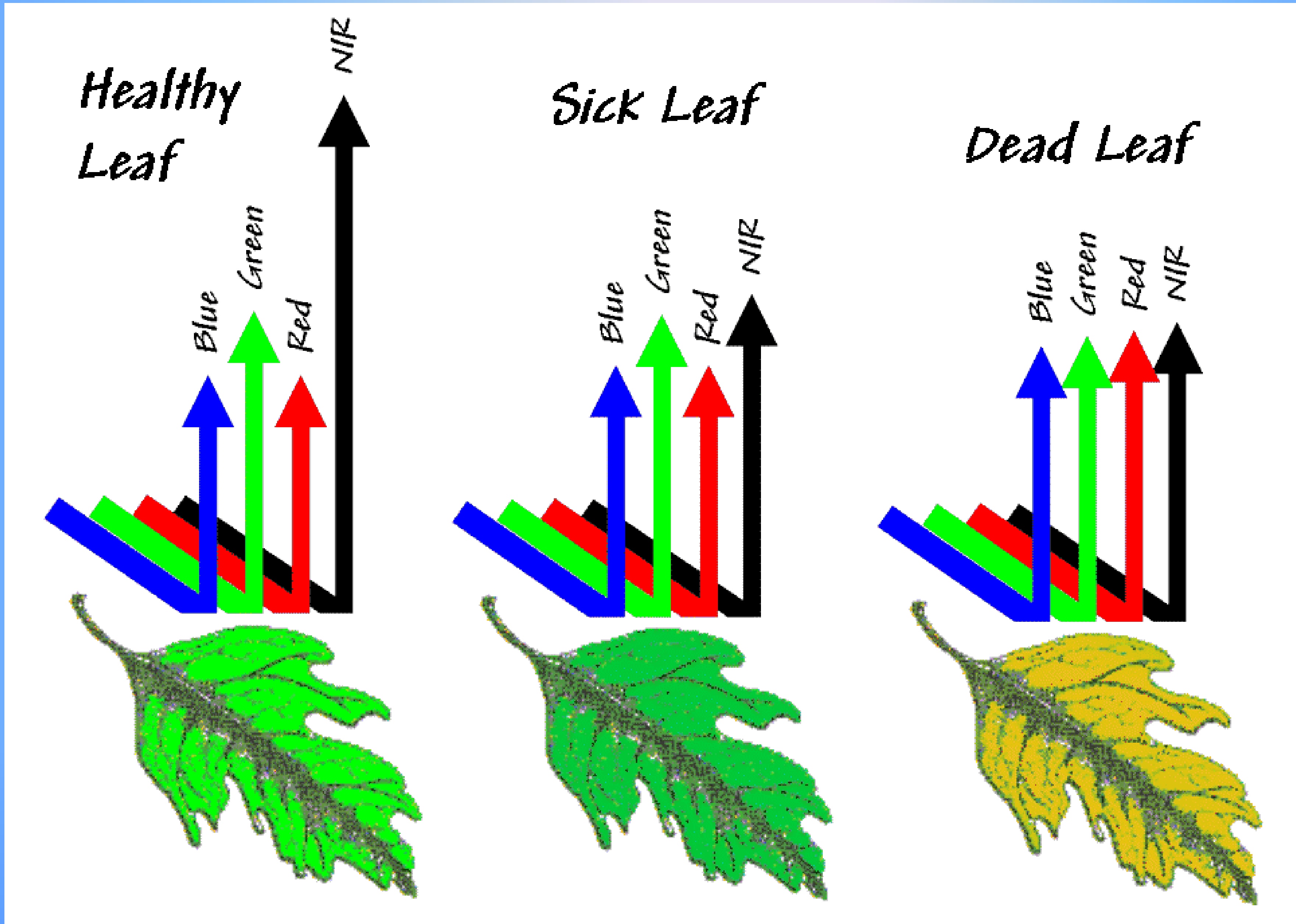
APPLICATIONS IN AGRICULTURE

reflectance of B/G/R/IR from a leaf



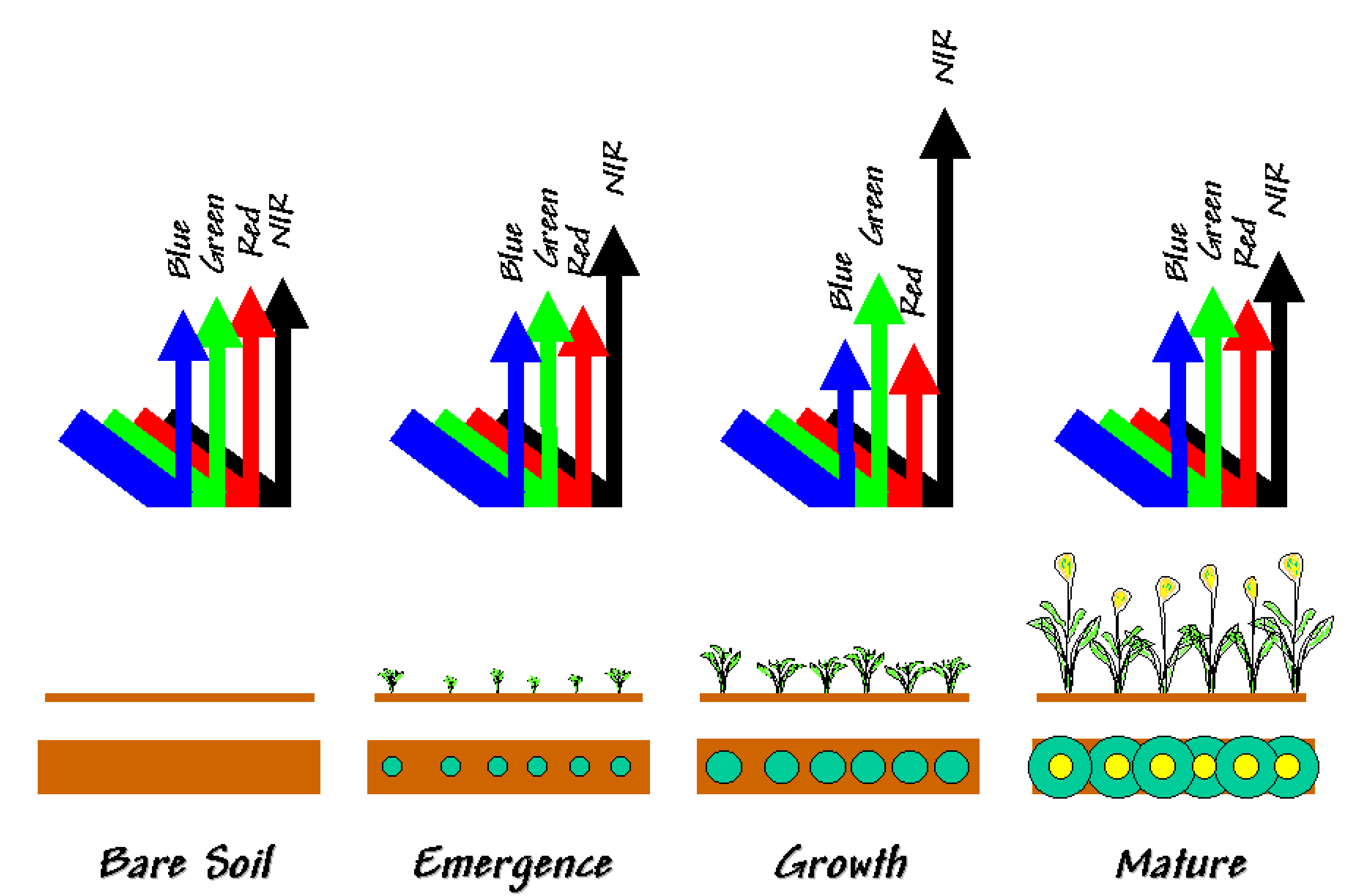
APPLICATIONS IN AGRICULTURE

Plant physiology determines the quality (color) of reflected light from a leaf



APPLICATIONS IN AGRICULTURE

Reflectance from vegetation during the growing cycle



Typical signatures (spectral reflectance curves)
for healthy and stressed sugar beets

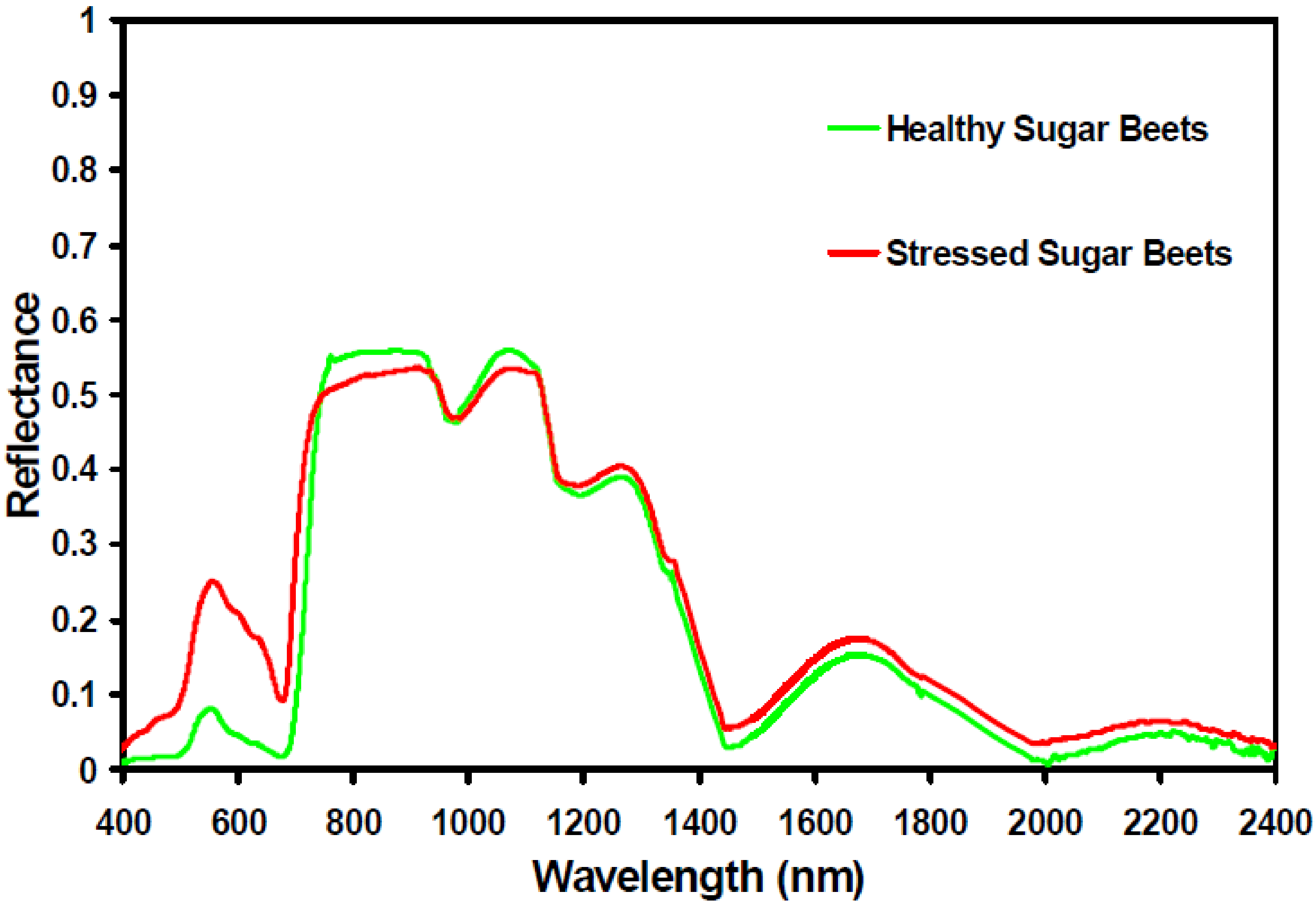
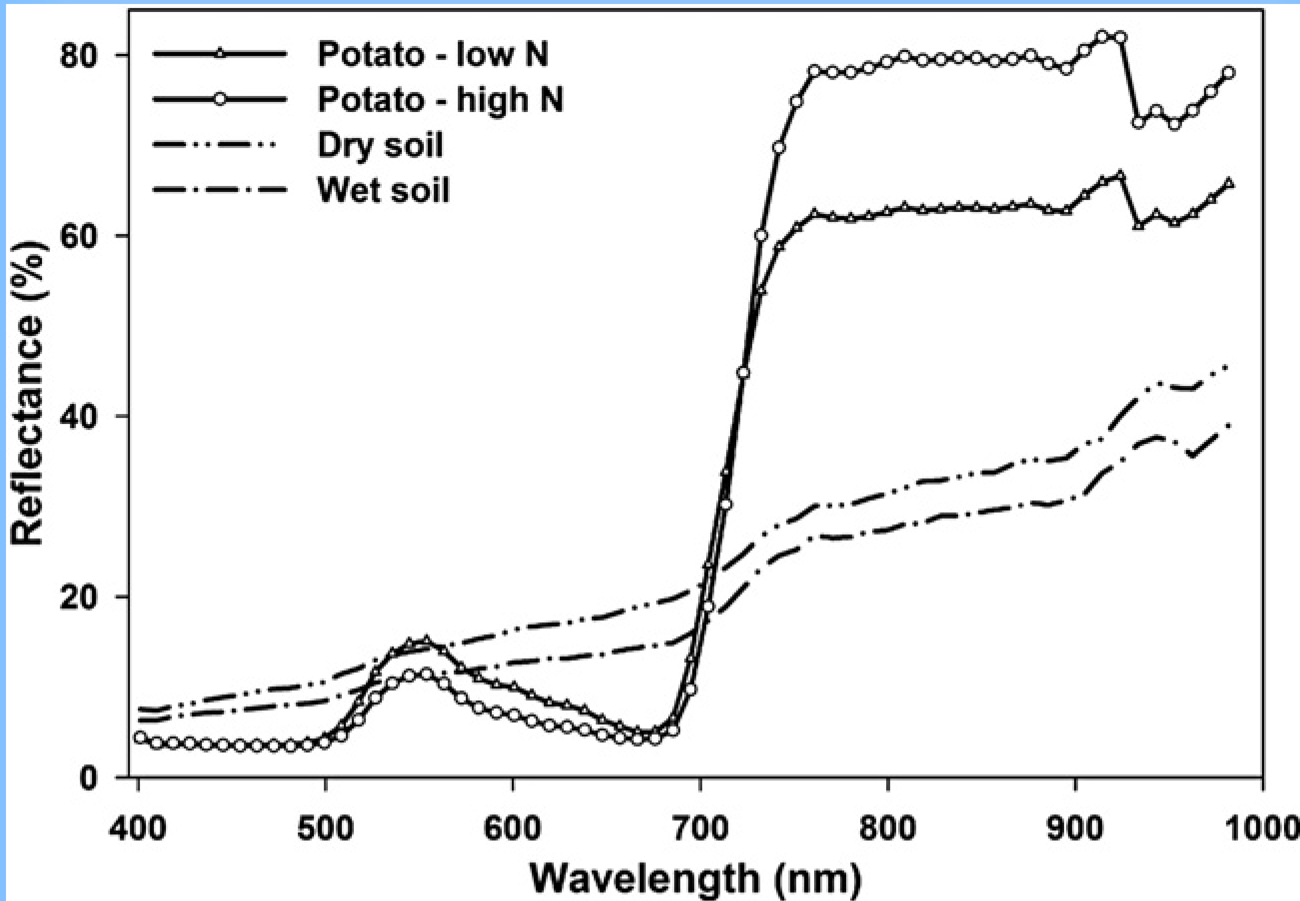


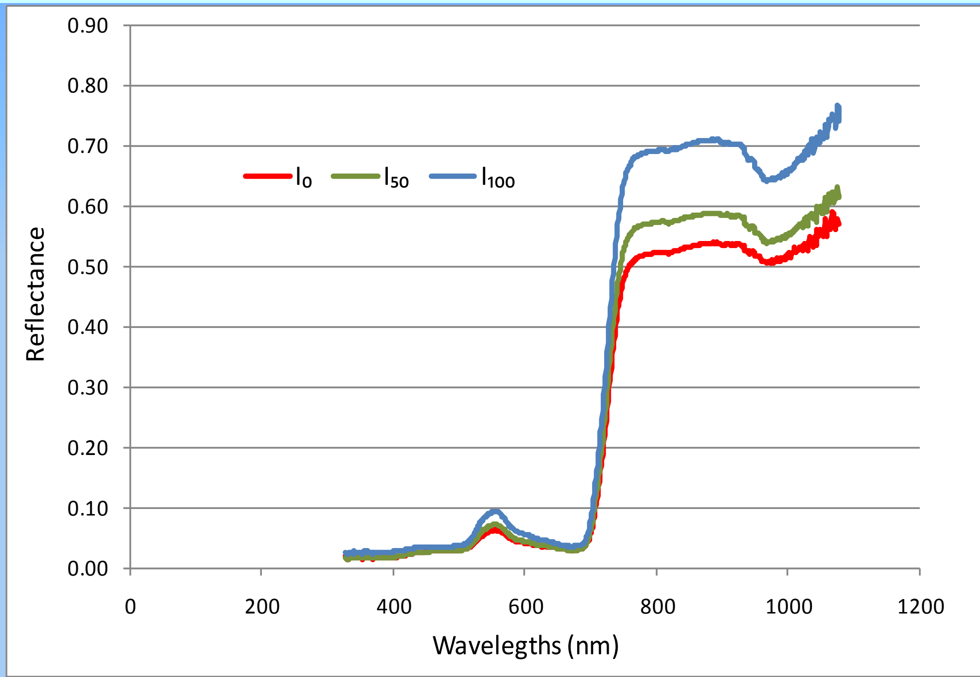
Figure 3. Spectral signatures of healthy and stressed sugarbeets (Kyllo, 2003).

Typical signatures (spectral reflectance curves)
for low and high N potato fields and dry and wet soil

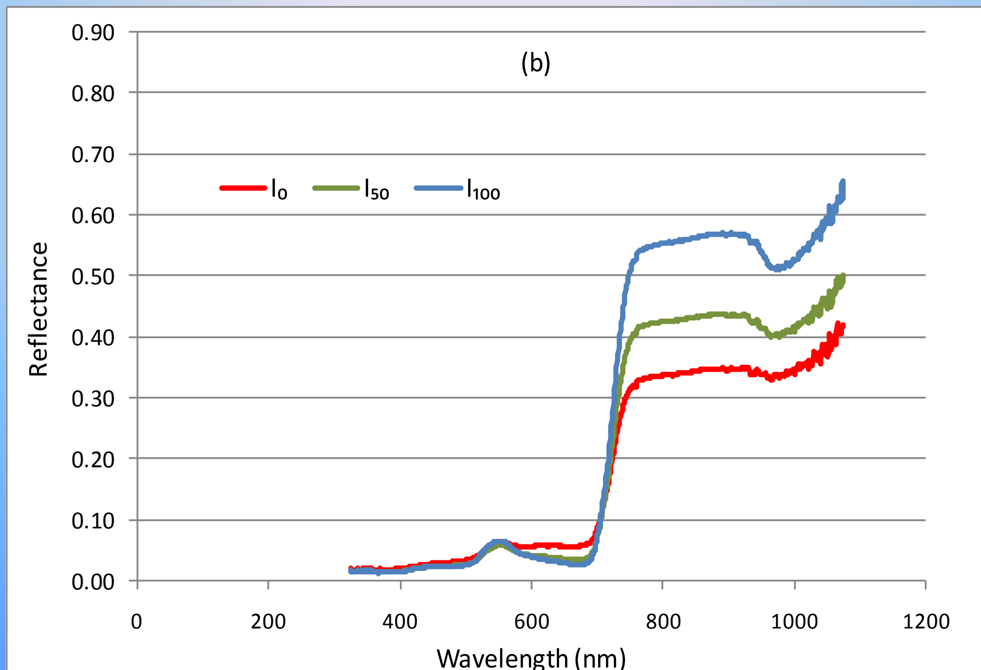


Source: Mulla, 2013

Typical signatures (spectral reflectance curves)
for different water regimes (rainfed, 50% and 100% irrigation)



Leaf scale



Canopy scale

Source: Hammaoui, 2013

Commonly used vegetation indices

- **Normalized Difference Vegetation Index (NDVI)**

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

  - ranges from 0.1 (bare soil) to near 1 (dense canopy)
  - classes are derived from the data and then the user has to determine what each class means

- **(Simple) Ratio Vegetation Index (SRVI)**

$$RVI = \frac{NIR}{RED}$$

  - Ranges from 1 (bare soil) to more than 20 (dense canopy)

- **Soil Adjusted Vegetation Index (SAVI)**

$$SAVI = \frac{NIR - RED}{NIR + RED + L}(1 + L)$$

  - Resembles NDVI to adjust for different brightness of background soil
  - L can vary from 0 to 1 depending on amount of visible soil
  - L default value is 0.5

Multispectral broad-band vegetation indices

Table 2 – Multi-spectral broad-band vegetation indices available for use in precision agriculture. G refers to green reflectance, NIR to near infrared, and R to red reflectance.

Index	Definition	Reference
NG	G/(NIR + R + G)	Sripada et al., 2006
NR	R/(NIR + R + G)	Sripada et al., 2006
RVI	NIR/R	Jordan, 1969
GRVI	NIR/G	Sripada et al., 2006
DVI	NIR – R	Tucker, 1979
GDVI	NIR – G	Tucker, 1979
NDVI	(NIR – R)/(NIR + R)	Rouse et al., 1973
GNDVI	(NIR – G)/(NIR + G)	Gitelson et al., 1996
SAVI	1.5*[(NIR – R)/(NIR + R + 0.5)]	Huete, 1988
GSAVI	1.5*[(NIR – G)/(NIR + G + 0.5)]	Sripada et al., 2006
OSAVI	(NIR – R)/(NIR + R + 0.16)	Rondeaux, Steven, & Baret, 1996
GOSAVI	(NIR – G)/(NIR + G + 0.16)	Sripada et al., 2006
MSAVI2	$0.5*[2*(NIR + 1) - SQRT((2*NIR + 1)^2 - 8*(NIR - R))]$	Qi, Chehbouni, Huete, Keer, & Sorooshian, 1994

Source: Mulla, 2013

Multispectral broad-band vegetation indices features

- The **normalised red (NR)** index focuses on the portion of the spectrum where chlorophyll strongly absorbs radiation.
- In contrast, the **normalised green (NG)** index focuses on the portion of the spectrum where pigments other than chlorophyll (carotenoids, anthocyanins, xanthophylls) absorb radiation.
- There are *two forms* of the **ratio vegetation index (RVI)**, one that consists of the ratio of NIR to R reflectance, the other **green red vegetation index (GRVI)** that consists of the ratio of NIR to G reflectance.
- *Two forms* of the **NDVI** exist, one that involves NIR and R reflectance, the other **green normalized difference vegetation index (GNDVI)** involves NIR and G reflectance.
- The **difference vegetative index (DVI)** was developed using the difference between reflectance in the NIR and R bands to *compensate for effects of soil reflectance*.
- Economically optimum N rate in corn was better correlated with **green difference vegetation index (GDVI)** (NIR G) than DVI (NIR R), and these *indices that compensated for soil effects performed better than NIR and R ratio indices such as NDVI and RVI that did not compensate for soil effects*.
- A wide range of other indices have been developed to **compensate for soil effects**, including soil adjusted vegetation index (**SAVI**), green soil adjusted vegetation index (**GSAVI)**, optimised soil adjusted vegetation index (**OSAVI**), green optimised soil adjusted vegetation index (**GOSAVI**) and modified soil adjusted vegetation index (**MSAVI**).

Hyperspectral remote sensing for precision agriculture

- **Multispectral** imaging that traditionally collects reflectance data in broad bands (greater than 40 nm wide) centred in the B, G, R and NIR regions of the spectrum.
- **Hyperspectral** images investigate spectral response of soils and vegetated surfaces in narrow spectral bands (10 nm wide) across a wide spectral range.
- *Hyperspectral imaging differs from multispectral imaging in the continuity, range and spectral resolution of bands*. In theory, it offers the capability of sensing a wide variety of soil and crop characteristics simultaneously, including moisture status, organic matter, nutrients, chlorophyll, carotenoids, cellulose, leaf area index and crop biomass.
- **Three general categories of predictive spectral indices**, including:

  1) Optimal Multiple Narrow Band Reflectance indices (OMNBR),

  2) narrow band NDVI,

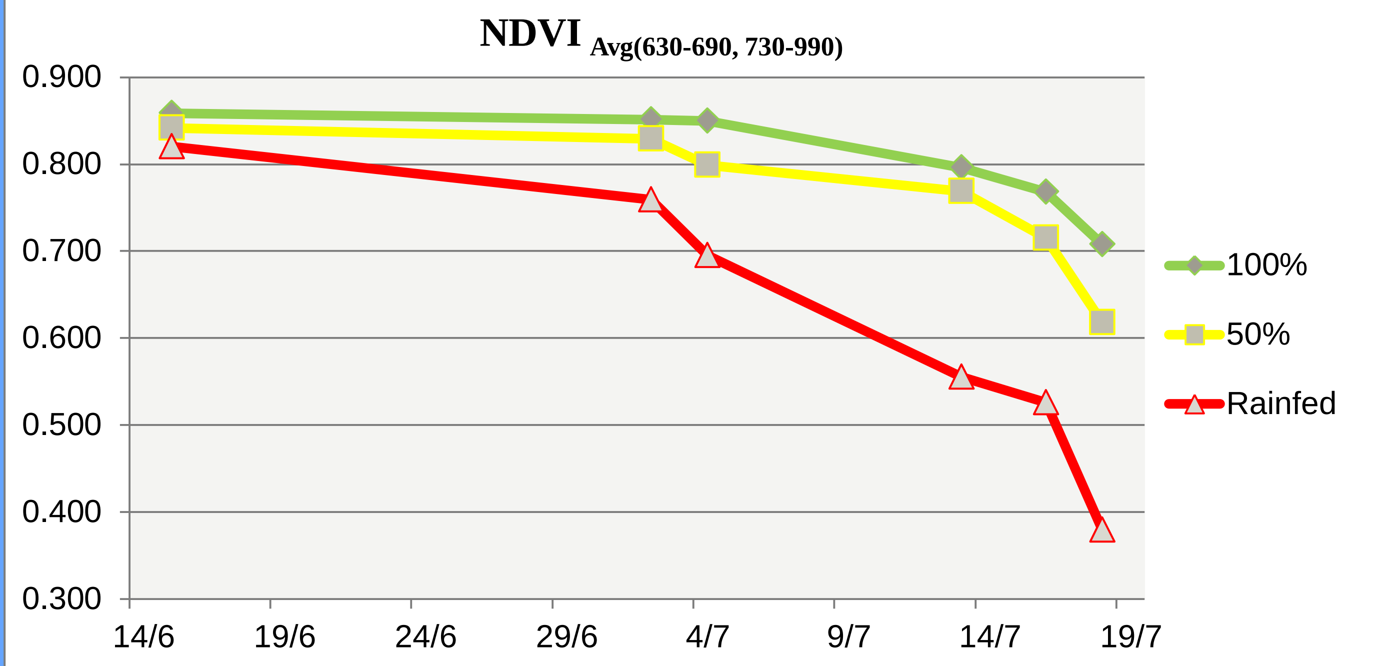
  3) narrow band SAVI.
- *The greatest information about plant characteristics in OMNBR* includes the longer red wavelengths (650-700 nm), shorter green wavelengths (500-550 nm), red-edge (720 nm), and two NIR (900-940 nm and 982 nm) spectral bands. The information in these bands is only available in narrow increments of 10-20 nm, and is easily obscured in broad multispectral bands that are available with older satellite imaging systems.
- **The best combination of two narrow bands in NDVI-like indices was centred in the red (682 nm) and NIR (920 nm) wavelengths, but varied depending on the type of crop (corn, soybean, cotton or potato) as well as the plant characteristic of interest (LAI, biomass, etc.).**

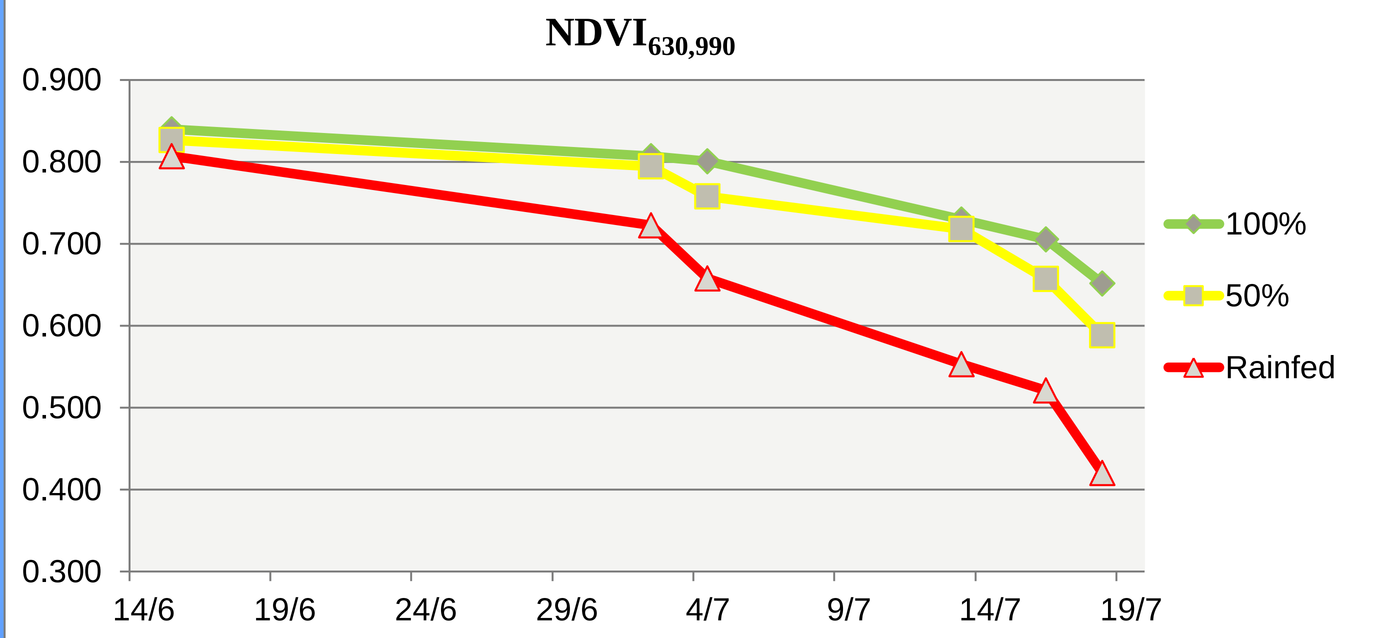
Table 4 – Hyperspectral narrow-band vegetation indices available for use in precision agriculture. R refers to reflectance at the wavelength (nm) in subscript. NIR refers to near infrared reflectance.

Index	Definition	Reference
Greenness index (G)	R_{554}/R_{677}	Smith, Adams, Stephens, & Hick, 1995
SR1	$NIR/red = R_{801}/R_{670}$	Daughtry, Walthall, Kim, de Colstoun, & McMurtrey, 2000
SR2	$NIR/green = R_{800}/R_{550}$	Buschman & Nagel, 1993
SR3	R_{700}/R_{670}	McMurtrey, Chappelle, Kim, Meisinger, & Corp, 1994
SR4	R_{740}/R_{720}	Vogelmann, Rock, & Moss, 1993
SR5	$R_{675}/(R_{700}{}^{*}R_{650})$	Chappelle at al., 1992
SR6	$R_{672}/(R_{550}{}^{*}R_{708})$	Datt, 1998
SR7	$R_{860}/(R_{550}{}^{*}R_{708})$	Datt, 1998
DI1	$R_{800} - R_{550}$	Buschman & Nagel, 1993
NDVI	$(R_{800} - R_{680})/(R_{800} + R_{680})$	Lichtenthaler, Lang, Sowinska, Heisel, & Mieh, 1996
Green NDVI (GNDVI)	$(R_{801} - R_{550})/(R_{800} + R_{550})$	Daughtry et al., 2000
PSSRa	R_{800}/R_{680}	Blackburn, 1998
PSSRb	R_{800}/R_{635}	Blackburn, 1998
NDI1	$(R_{780} - R_{710})/(R_{780} - R_{680})$	Datt, 1999
NDI2	$(R_{850} - R_{710})/(R_{850} - R_{680})$	Datt, 1999
NDI3	$(R_{734} - R_{747})/(R_{715} + R_{726})$	Vogelmann et al., 1993
MCARI	$[(R_{700} - R_{670}) - 0.2(R_{700} - R_{550})](R_{700}/R_{670})$	Daughtry et al., 2000
TCARI	$3^{*}[(R_{700} - R_{670}) - 0.2^{*}(R_{700} - R_{550})(R_{700}/R_{670})]$	Haboudane et al., 2002
OSAVI	$(1 + 0.16)(R_{800} - R_{670})/(R_{800} + R_{670} + 0.16)$	Rondeaux et al., 1996
TCARI/OSAVI		Haboudane et al., 2002
TVI	$0.5^{*}[120^{*}(R_{750} - R_{550}) - 200^{*}(R_{670} - R_{550})]$	Broge & Leblanc, 2000
MCARI/OSAVI		Zarco-Tejada, Miller, Morales, Berjón, & Agüera, 2004
RDVI	$(R_{800} - R_{670})/SQRT(R_{800} + R_{670})$	Rougean & Breon, 1995
MSR	$(R_{800}/R_{670} - 1)/SQRT(R_{800}/R_{670} + 1)$	Chen, 1996
MSAVI	$0.5[2R_{800} + 1 - SQRT((2R_{800} + 1)^2 - 8(R_{800} - R_{670}))]$	Qi et al., 1994
MTVI	$1.2^{*}[1.2^{*}(R_{800} - R_{550}) - 2.5^{*}(R_{670} - R_{550})]$	Haboudane et al., 2004
MCARI2	$\frac{1.5[2.5(R_{800} - R_{670}) - 1.3(R_{800} - R_{550})]}{\sqrt{(2R_{800} + 1)^2 - (6R_{800} - 5\sqrt{R_{670}}) - 0.5}}$	Haboudane et al., 2004

Source: Mulla, 2013

NDVI for different water regimes (rainfed, 50% & 100% irrigation) estimated by two approaches/formulas





$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

$$NDVI = \frac{NIR_{730\text{-}990} - RED_{630\text{-}690}}{NIR_{730\text{-}990} + RED_{630\text{-}690}}$$

$$NDVI = \frac{NIR_{990} - RED_{630}}{NIR_{990} + RED_{630}}$$

Other examples of vegetation indices 1

RNIR=range_NIR
RR=range_R

Vegetation Indices	Index shortcut	Formula
Normalised difference vegetation index	NDVI	(RNIR - RR)/(RNIR + RR)
Corrected and modified Normalised difference vegetation index	NDVIc	NDVI(1-(RSWIR - RSWIRmin)/(RSWIRmax - RSWIRmin))
	GNDVI	(RNIR - Rgreen)/(RNIR+Rgreen)
Water Index	WI	R900/R970
Simple ratio Index	SR or RVI or SRVI	RNIR/RR
Photochemical reflectance index	PRI	(R531 - R570)/(R531 + R570)
Transformed chlorophyll absorption reflectance Index	TCARI	3*{(R700-R670) - 0.2 (R700-R550) R700/R670}
Carotenoid reflectance Index	CRI	(1/R510) - (1/R550)
Normalized pigment chlorophyll index	NPCI	(R680 - R430) / (R680 - R430)
Soil adjusted vegetation Index	SAVI	((RNIR - RR) *(1+L)) / ((RNIR +RR +L))
Vegetation ratio index	VRI	RNIR / RR
Transformed Vegetation Index	TVI	((RNIR - RR)/ (RNIR + RR) +0.5) ^ 0.5
Infrared percentage vegetation	IPVI	RNIR / (RNIR + RR)
Difference vegetation Index	DVI	RNIR - RR

Other examples of vegetation indices 2

Vegetation Indices	Index shortcut	Formula
Chlorophyll based Difference Index	CI	(R850-R710)/(R850-R680)
Nitrogen Index	RN	(R5500-R600)/(R800-(R900)
Water Band Index	WBI	R900/R970
structure-independent pigment index	SIPI	(R800 - R445)/(R800+R680)
Chlorophyll normalized difference index	Chi NDI	(R800 - R445)/(R800 - R680)
Modified soil-adjusted vegetation index	MSAVI	(RNIR + 1) - (1/2)[(2RNIR + 1)^2 - 8(RNIR - RR)]^ 0.5
Transformed soil-adjusted vegetation index	TSAVI	[a(RNIR - aRR- b)]/[aRNIR +RR-ab + X(1 + a^2)]
Perpendicular vegetation index	PVI	(RNIR - aRR - b)/(1 a^2)^0.5
Photosynthesis Index	PI	(R531-R570)/(R531+R570)
Water Moisture Index	WMI	R1600/R820
Corrected Simple Ratio Index	SRc	SR(1-((RSWIR - RSWIRmin)/(RSWIRmax+ RSWIRmin))
Modified Simple Ratio Index	MSR	(RNIR/RR-1)/((RNIR/RR)^0.5 +1)
Ratio Difference Vegetation Index	RDVI	(RNIR-RR)/((RNIR+RR)^0.5)
Optimized Soil Adjusted	OSAVI	(RNIR-RR)/(RNIR+RR+0.16)

Other examples of vegetation indices 3

Vegetation Indices	Index shortcut	Formula
Non-Linear Index	NLI	(RNIR^2-RR)/(RNIR^2+RR)
Modified Triangulation Vegetation Index-1	MTVI1 or MCARI1	1.2{1.2(RNIR -RGREEN)- 2.5(RR-RGREEN)
Modified Triangulation Vegetation Index-2	MTVI2 or MCARI2	[1.5{1.2(RNIR -RGREEN)- 2.5(RR-RGREEN)}] /{(2RNIR+1)^2 -(6RNIR-5(RR^0.5))-0.5}^0.5
Non-conventional ratio and differential	NDII or NDWI	(RNIR-RSWIR)/(RNIR+RSWIR)
Specific Leaf Area Vegetation Index	SLAVI	RNIR/(RR+ RSWIR)
Normalized Canopy Index	NCI	(RSWIR-RGREEN)*(RSWIR+RGREEN)
Red-Edge Inflection Point	REIP	700+40*((R670+R780)/2-R700)/(R740-R700))
Vogelman ratio Index	VOG	(R734 - R747)/(R715 - R726)
Enhanced Vegetation Index	EVI	2.5*(RNIR - RRED/(RNIR+6*RRED-7.5*RBLUE+1))
Atmospherically Resistant Vegetation Index	ARVI	RNIR-(2*RRED-RBLUE/(RNIR+(2RRED-RBLUE))
Normalized Difference Nitrogen Index	NDNI	Log(1/R1510)-log(1/R1680))/((log(1/R1510)+log(1/R1680)

Remotely sensed images can be used to support the large scale estimation of

- Land use and planting/sowing period,
- Nutrient deficiencies,
- Plant diseases,
- Water deficiency (stress) or surplus,
- Pests attack (weed infestations, insect damage),
- Hail damage, wind damage,
- Herbicide damage,
- Crop development – phenological phases,
- Evapotranspiration/irrigation, biomass growth and yield.

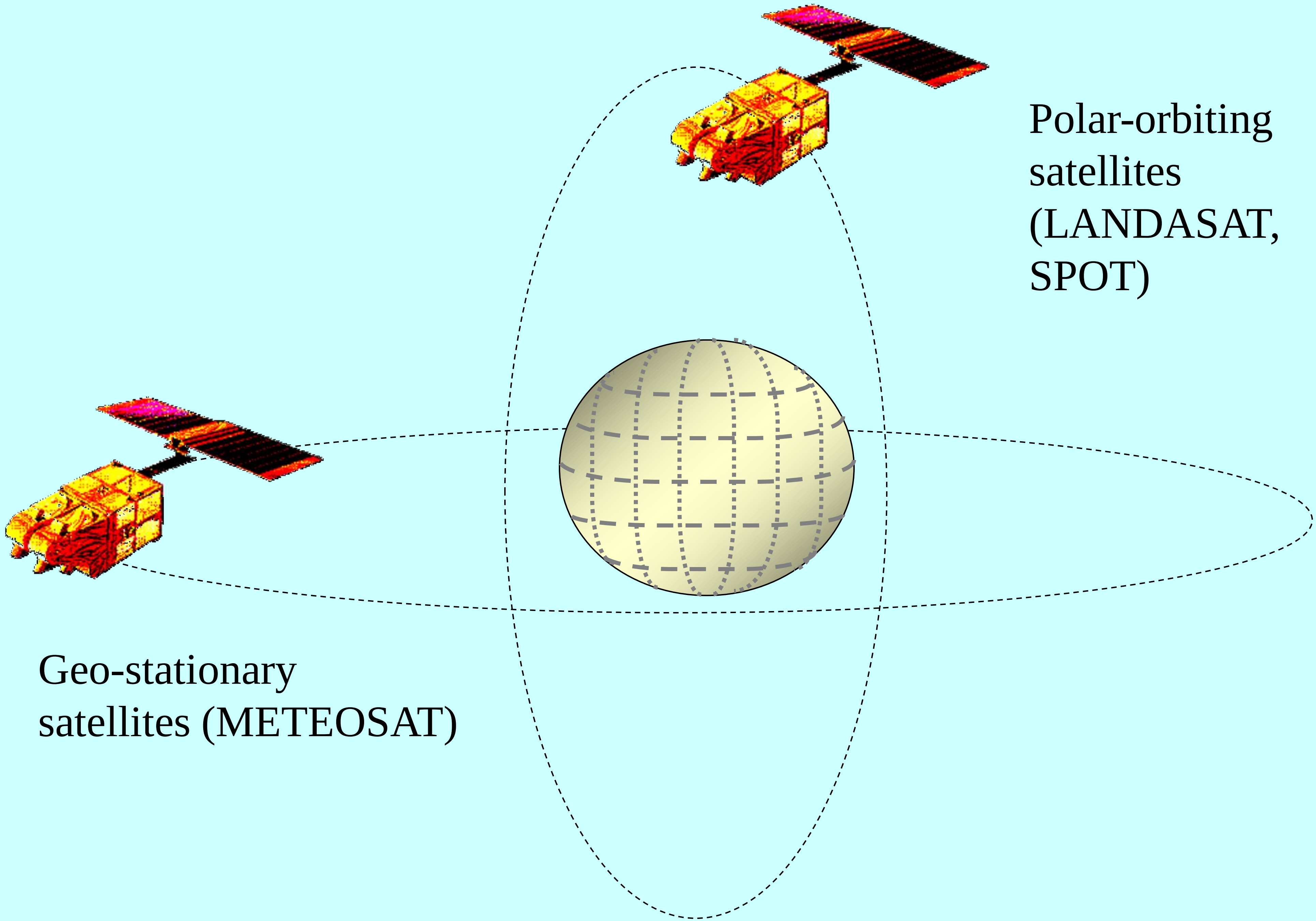
Remote Sensing for Mapping Crop Characteristics: *intermediate remarks*

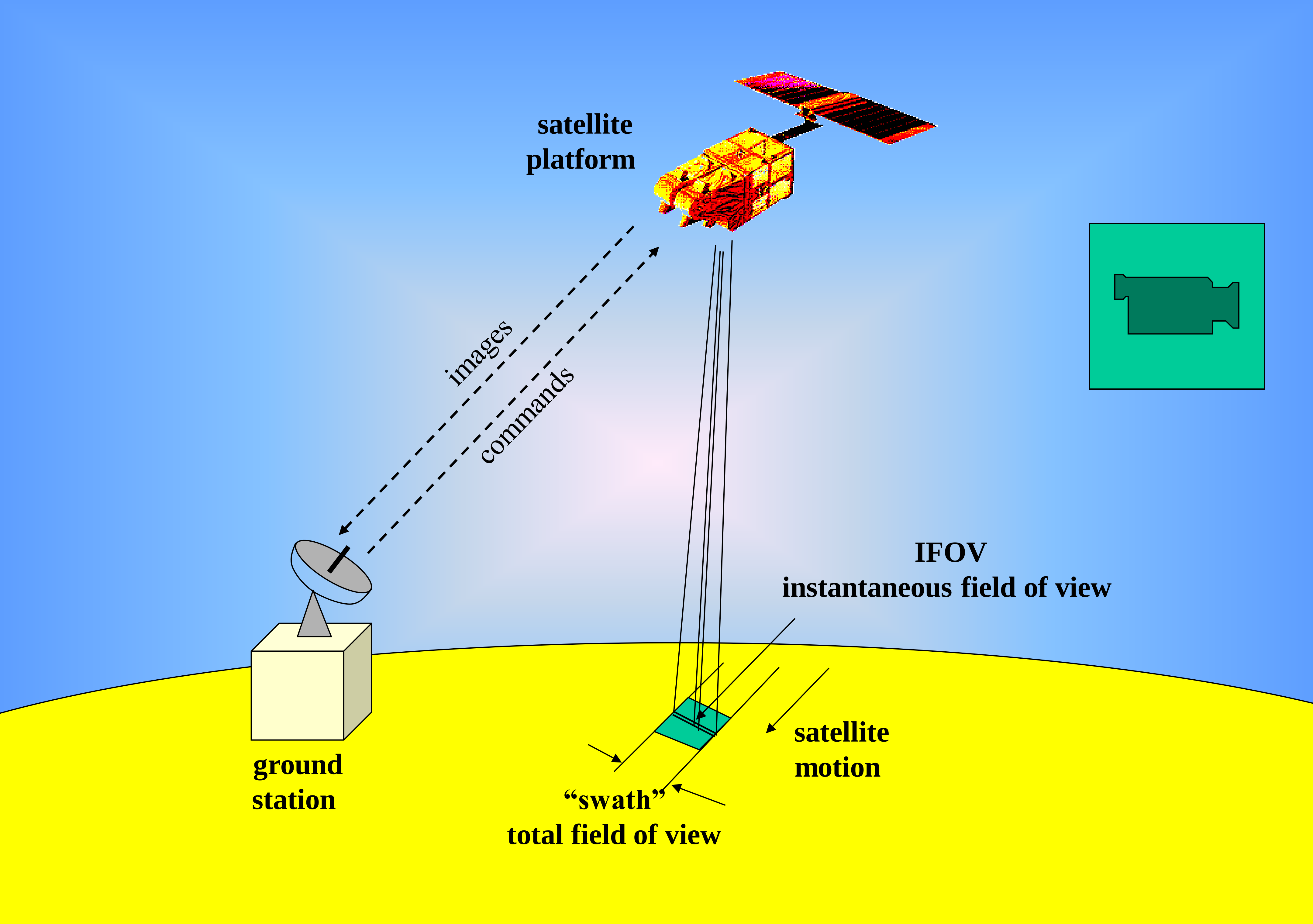
- Canopy reflectance depends on the interaction of many factors:
  - leaf area index, leaf angle distribution, spectral properties of leaves and soil, relative geometry of illumination and observation;
  - influence of atmospheric absorption and scattering at different wavelengths
- Canopy is assumed to behave as Lambertian surface:
  - canopy reflectance is constant with the angle of observation.
- Canopy reflectance is used to estimate:
  - albedo, Leaf Area Index and canopy height from which the Kc values may be calculated (empirical relationship).
  - This analytical approach requires detailed ground-truth in order to calibrate the empirical relationships between the canopy properties and reflectance values.

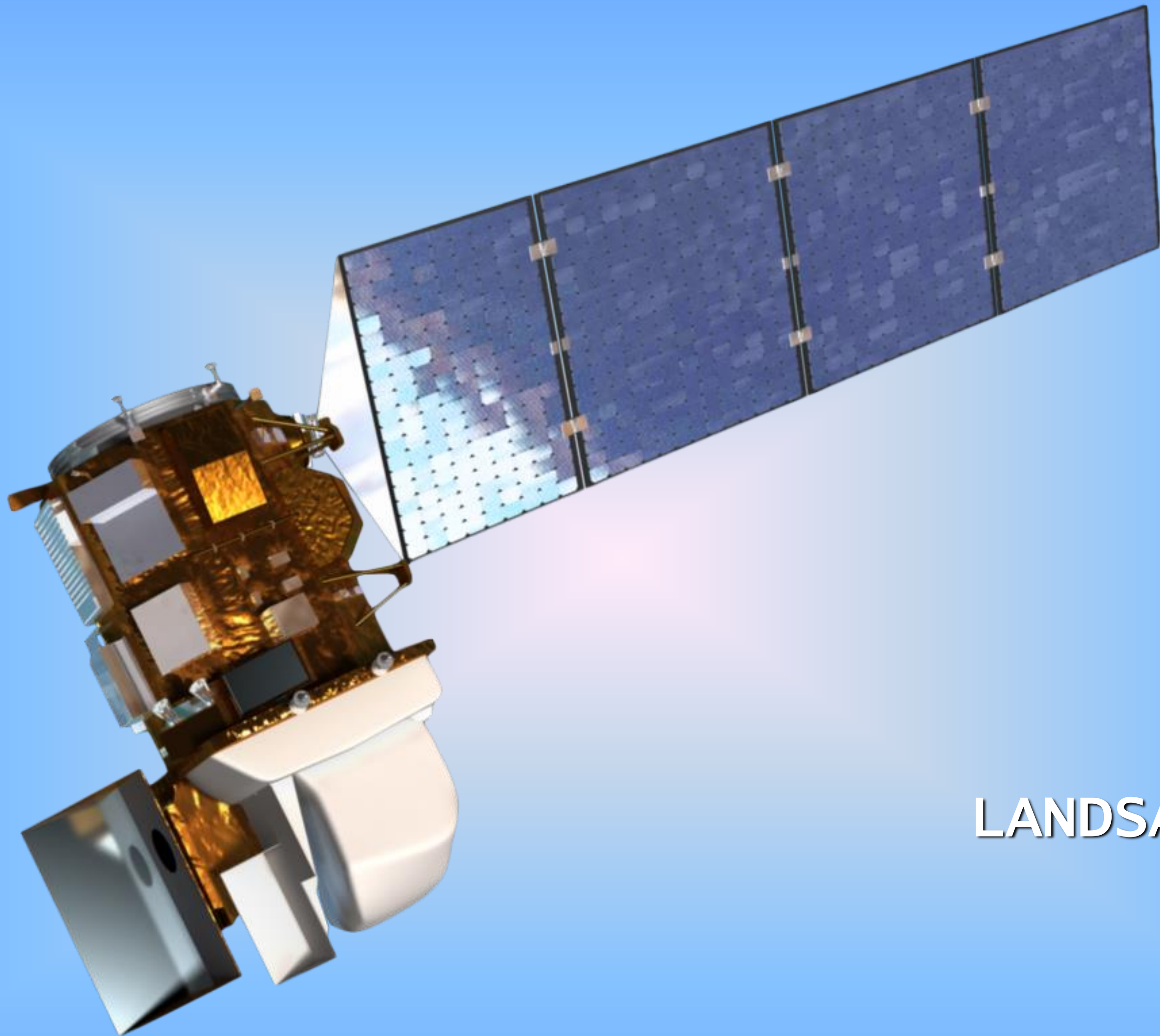
SATELLITES
& IMAGE ELABORATION

Satellites & Image elaboration

- **Why satellites:**
  - provide continuous monitoring
  - cost less than aerial photographs
  - allow rapid integration with GIS
- **Geo-stationary satellites:**
  - orbit in the same speed and in the same direction (34,000-39,000 km)
  - high temporal resolution and low spatial resolution
  - 24 hrs data acquisition on the sensors field of view
- **Polar orbiting satellites:**
  - travel from pole to pole (400-900 km)
  - high spatial and low temporal resolution
  - sun-synchronous satellites - take the images of the same latitude at the same local time - this allows the comparison of images


Polar-orbiting satellites (LANDASAT, SPOT)
Geo-stationary satellites (METEOSAT)


satellite
platform
images
commands
IFOV
instantaneous field of view
satellite
motion
ground
station
"swath"
total field of view

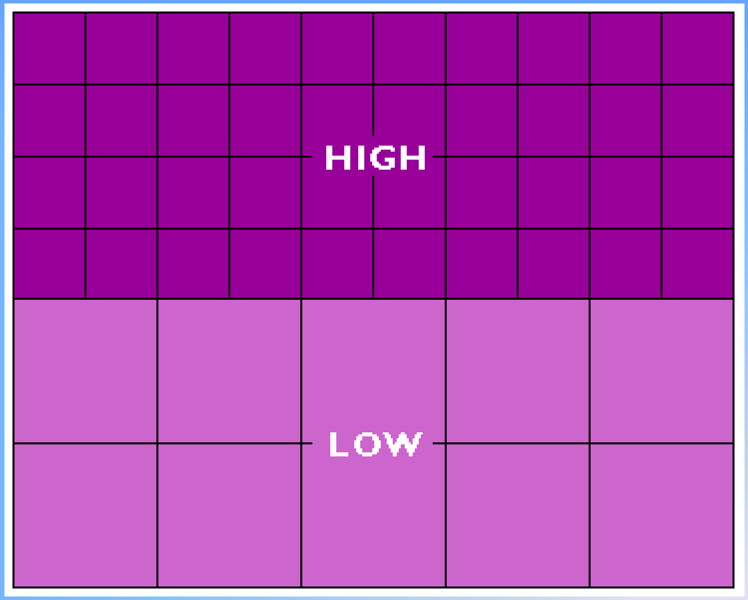


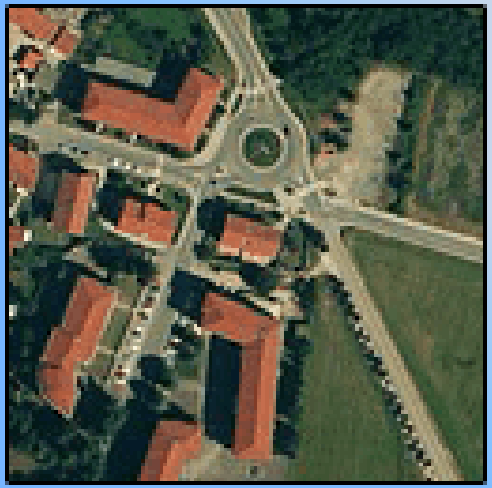
LANDSAT 8

Properties characterizing sensors (RS systems)

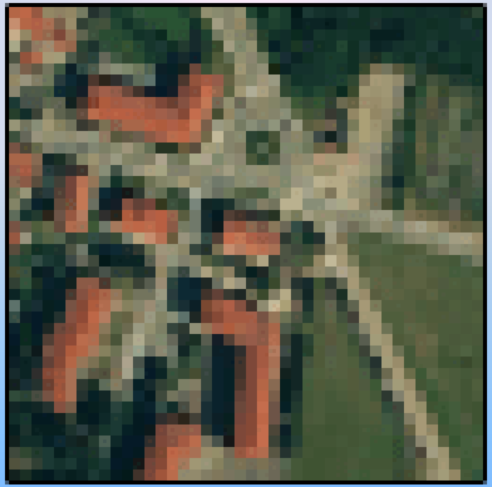
- **Spatial resolution**
  - the size of area on the ground that is summarized by one data value
  - if the feature is smaller than this, it may not be detectable as the average brightness of all features in that resolution cell will be recorded.
- **Radiometric resolution**
  - the minimum intensity difference that can be revealed from the sensor;
  - it is given by the number of discrete levels used to represents a signal;
  - depends on the number of bits used for coding numbers in binary format and goes from 2 (1bit, 0/1) to 256 (1 byte = 8 bits, 0 - 255)
- **Spectral resolution**
  - number and width of spectral bands that sensor detects
  - hyperspectral sensors (e.g. AVIRIS) detect hundreds of very narrow spectral bands – suitable for precision agriculture applications
- **Temporal resolution (revisit time)**
  - time lap between consecutive acquisition of data over the same area on the ground

SPATIAL RESOLUTION





High Spatial Resolution



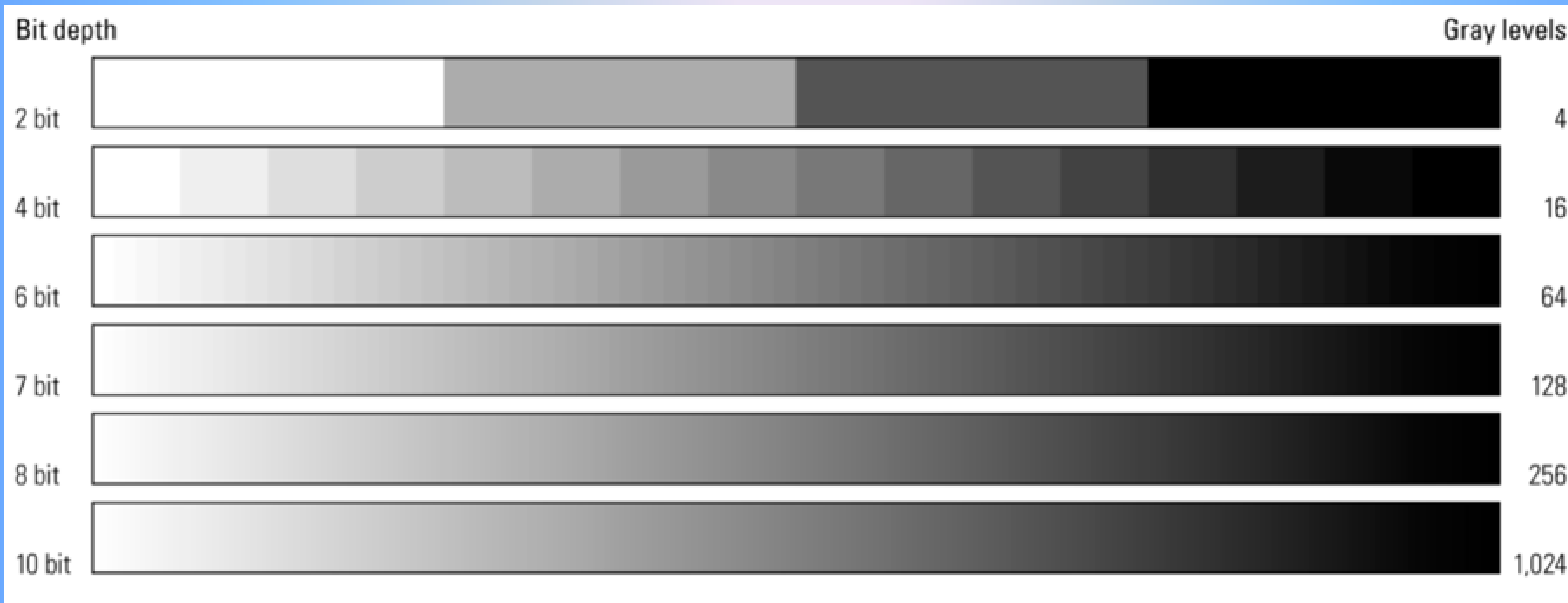
Medium Spatial Resolution

Low Spatial Resolution

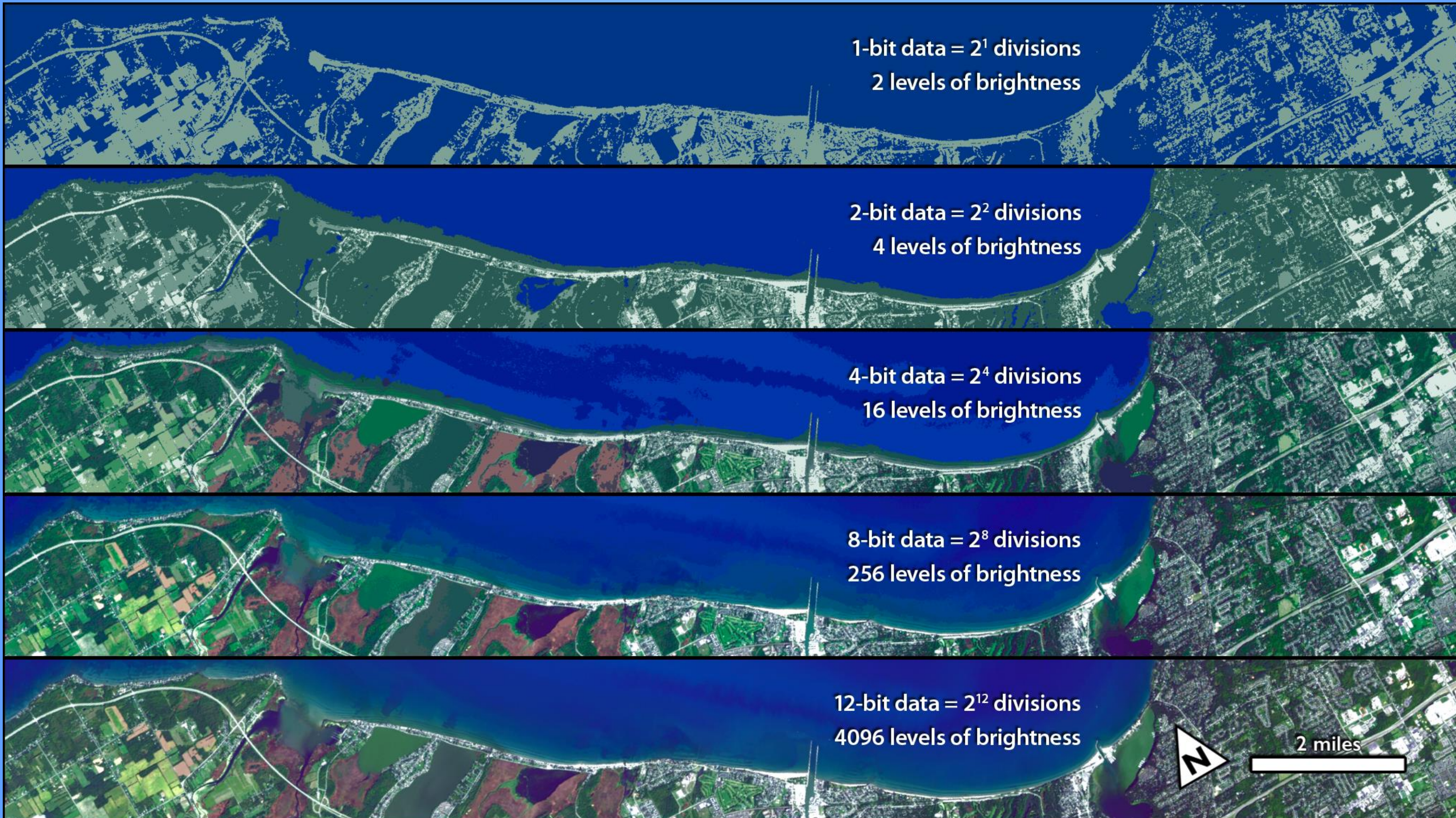
RADIOMETRIC RESOLUTION

8 bits ↓ 11 bits ↓

1	2	3	4	5	6	7	8	9	10	11	Number of bits
2	4	8	16	32	64	128	256	512	1024	2048	Maximum Values



RADIOMETRIC RESOLUTION
Lake Ontatio shoreline



www.nasa.gov

Basic characteristics of some satellite systems

Satellite	*Spatial resolution*	*N° of bands*	*Temporal resolution*	*Swath*	*Sensor*	*Data availability*
Landsat 1-5	79 m	4	16 days	185 km	MSS	1975-1993
Landsat 5, 7	30 (28.5)m	7	16 days	185 km	TM	1984-
Landsat 7	15 m	1	16 days	185 km	Panchromatic	1999-
SPOT	10 m	1	26 days	60 km	Panchromatic	1986-
SPOT	20 m	3	26 days	60 km	HRV	1986-
RADARSAT	8 – 100 m	1	24 days	50 – 500 km	SAR	1995-
IRS-1C	5.8 m	1	22 days	70 km	Panchromatic	1996-
IRS-1C *	23.5 m	4	22 days	142 km	LIS-III	1996-
ERS-1/2	30 m	1	35 days	100 km	SAR	1992-
METEOSAT	2500 -5000 m	3	minutes	4000 km	SAR, VIS, IR	1972-
NOAA AVHRR	1100 – 4000 m	1 – (5)	12 hours (24 hours)	2400 km	AVHRR	1981-

*ERS-1 mission was ended on 10 March 2000 by a failure in the on-board attitude control system

Basic characteristics of some satellite systems

- **IKONOS 2 (lunched in September 1999)**
  - 4 multi-spectral channels with spatial resolution of 4 m and 1 panchromatic channel with spatial resolution of 1 m
  - Revisiting time is 3 days; radiometric resolution is 11 bits/pixel (2048 tones)
- **TERRA (lunched in December 1999) and AQUA (2002) satellites (EOS)**
  - **MODIS** (MODerate resolution Imaging Spectro-radiometer): swath width is 2330 km; revisiting time is 1-2 days; mapping LAI, green cover, biomass, PAR, NDVI, EVI, etc.
  - 36 bands between 0.4 and 14.4 μm (2 – 250m, 5 – 500m, 29 – 1 km)
  - **ASTER** (Advanced Spaceborne Thermal Emission and Reflection Radiometer): mapping land surface temperature, reflectance, elevation.
- **QUICKBIRD (lunched in October 2001)**
  - Spatial resolution: 0.61 m in pan-mode and 2.44 m in multispectral mode
  - Temporal resolution: variable from 1 to 14 days
- **ENVISAT ESA (lunched in March 2002)**
  - Monitor land use, oceans, atmosphere, ice caps
  - ASAR sensor - Alternating Polarization SAR
  - Various resolution/swath combination (from 10 m to 1km and up to 400 km swath)
- **SPOT 5 (lunched in May 2002)**
  - Spatial resolution: 5 m in pan-mode and 10 m in multispectral (visible and NIR)
  - Temporal resolution: 5 days (3 days in European latitudes)

Table 1 – Satellite remote sensing platforms and their spectral or spatial resolution, return frequency, and suitability for precision agriculture (PA). P refers to purple, B to blue, G to green, R to red, IR to infrared, NIR to near infrared, MIR to mid infrared, TIR to thermal infrared. Suitability class L refers to low, M to medium and H to high.

Satellite (year)	Spectral bands (spatial resolution)	Return frequency (*d*)	Suitability for PA
Landsat 1 (1972)	G, R, two IR (56 × 79 m)	18	L
AVHRR (1978)	R, NIR, two TIR (1090 m)	1	L
Landsat 5 TM (1984)	B, G, R, two NIR, MIR, TIR (30 m)	16	M
SPOT 1 (1986)	G, R, NIR (20 m)	2–6	M
IRS 1A (1988)	B, G, R, NIR (72 m)	22	M
ERS-1 (1991)	Ku band altimeter, IR (20 m)	35	L
JERS-1 (1992)	L band radar (18 m)	44	L
LiDAR (1995)	VIS (vertical RMSE 10 cm)	N/A	H
RadarSAT (1995)	C-band radar (30 m)	1–6	M
IKONOS (1999)	Panchromatic, B, G, R, NIR (1–4 m)	3	H
SRTM (2000)	X-band radar (30 m)	N/A	M
Terra EOS ASTER (2000)	G, R, NIR and 6 MIR, 5 TIR bands (15–90 m)	16	M
EO-1 Hyperion (2000)	400–2500 nm, 10 nm bandwidth (30 m)	16	H
QuickBird (2001)	Panchromatic, B, G, R, NIR (0.61–2.4 m)	1–4	H
EOS MODIS (2002)	36 bands in VIS-IR (250–1000 m)	1–2	L
RapidEye (2008)	B, G, R, red edge, NIR (6.5 m)	5.5	H
GeoEye-1 (2008)	Panchromatic, B, G, R, NIR1, NIR2 (1.6 m)	2–8	H
WorldView-2 (2009)	P, B, G, Y, R, red edge, NIR (0.5 m)	1.1	H

Source: Mulla, 2013

QuickBird Satellite Sensor Characteristics

Launch Date	October 18, 2001
Launch Vehicle	Boeing Delta II
Launch Location	Vandenberg Air Force Base, California, USA
Orbit Altitude	450 Km
Orbit Inclination	97.2º, sun-synchronous
Speed	7.1 Km/second - 25,560 Km/hour
Equator Crossing Time	10:30 a.m. (descending node)
Orbit Time	93.5 minutes
Revisit Time	1-3.5 days depending on Latitude (30º off-nadir)
Swath Width	16.5 Km x 16.5 Km at nadir
Metric Accuracy	23-meter horizontal (CE90%)
Digitization	11 bits
Resolution	Pan: 61 cm (nadir) to 72 cm (25º off-nadir) MS: 2.44 m (nadir) to 2.88 m (25º off-nadir)
Image Bands	Pan: 450 - 900 nm Blue: 450 - 520 nm Green: 520 - 600 nm Red: 630 - 690 nm Near IR 760 - 900 nm

Landsat 7: Main characteristics of the Thematic Mapper bands and fields of application

Band	*Wavelength [μm]*	*Characteristics and Fields of Application*
1	0.45-0.52 (blue)	Senses blue-green visible light. Maximum penetration of water which is useful for mapping in shallow water. Also useful for distinguishing soil from vegetation and deciduous from coniferous plants.
2	0.52-0.60 (green)	Senses green visible light. Matches green reflectance peak of vegetation. Useful in assessing plant vigor.
3	0.63-0.69 (red)	Senses red visible light. Matches chlorophyll absorption band. Useful in discriminating vegetation types.
4	0.76-0.90	Sensed reflected near infrared (NIR). Useful for determining biomass content and for mapping of bodies of water which appear opaque.
5	1.55-1.75	Senses reflected mid-infrared. Indicates moisture content of soil and vegetation. Penetrates thin clouds. Good contrast between vegetation types. Useful for differentiation between snow and clouds.
6	10.40-12.50	Senses thermal infrared. Can be used at night. Useful for thermal mapping (heat distribution from industrial activities), fire monitoring, estimating of soil moisture and animal distribution.
7	2.08-2.35	Senses reflected infrared. Wavelength coincides with the absorption bands of hydroxyl ions in minerals. Combination of bands 5 and 7 used for mapping hydro-thermally altered rocks associated with mineral deposits.

NASA & USGS – Landsat 8

- Guarantee the continuity/compatibility of Landsat data and comparison with the historical data
- Mainly for land cover and land use change over time
- Lunched on February 2013
- Data available from 30 May 2013 free of charge
- Revisiting time 16 days with 8 days offset in respect to Landsat7
- Pixel size: 15 meters/30 meters/100 meters (panchromatic/multispectral/thermal)
- 400 scenes a day in respect to 250 of Landsat 7
- 6 spectral bands corresponding to Landsat 7, 2 thermal bands (instead of 1 in Landsat 7) + 3 new (a deep blue coastal / aerosol band to measure water quality, a shortwave-infrared cirrus band to improve detection of high thin clouds, and a Quality Assessment band to evaluate the quality of data for each pixel – e.g. presence of clouds, snow)
- Improved data quality (12-bit radiometric resolution)
- Plan to operate 5.25 years although the technical operation time could reach 10 years

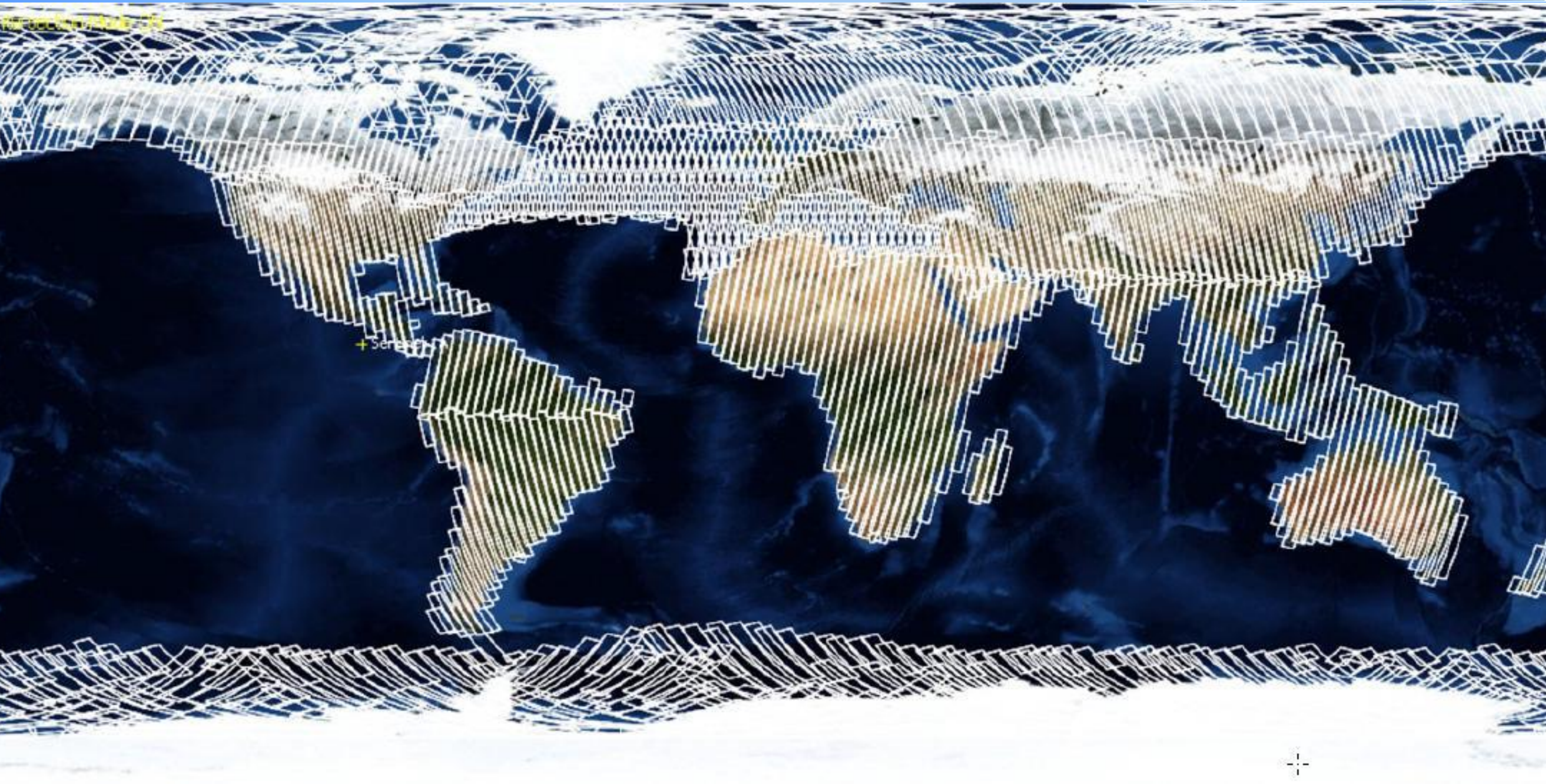
Landsat 8 bands

Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) Launched February 11, 2013	Bands	Wavelength (micrometers)	Resolution (meters)
	Band 1 - Coastal aerosol	0.43 - 0.45	30
	Band 2 - Blue	0.45 - 0.51	30
	Band 3 - Green	0.53 - 0.59	30
	Band 4 - Red	0.64 - 0.67	30
	Band 5 - Near Infrared (NIR)	0.85 - 0.88	30
	Band 6 - SWIR 1	1.57 - 1.65	30
	Band 7 - SWIR 2	2.11 - 2.29	30
	Band 8 - Panchromatic	0.50 - 0.68	15
	Band 9 - Cirrus	1.36 - 1.38	30
	Band 10 - Thermal Infrared (TIRS) 1	10.60 - 11.19	100 * (30)
	Band 11 - Thermal Infrared (TIRS) 2	11.50 - 12.51	100 * (30)

ESA – Sentinel (1 & 2)

- 6 missions planned – 2 already in orbit; each mission is based on a constellation of two identical satellites to fulfil revisit and coverage requirements, providing robust datasets for Copernicus Services.
- **Sentinel-1** is a polar-orbiting, **all-weather, day-and-night radar imaging mission (SAR) for land and ocean services**. The first Sentinel-1 satellite was launched on a Soyuz rocket from Europe's Spaceport in French Guiana on 3 April 2014, spatial resolution down to 5 m, temporal resolution 6 days, swath width 250 km.
- **SAR advantage** of operating at wavelengths not impeded by cloud cover or a lack of illumination
- **Sentinel-2** is a polar-orbiting, multispectral high-resolution imaging mission (13 spectral bands) for land monitoring to provide: **imagery of vegetation – LAI map (plant growth), soil and water cover, inland waterways and coastal areas.**
- Sentinel-2 data available **free of charge** for public and private sector - deliver information for emergency services (land use change and associated risks).
- **Sentinel 2A** lunched on 23 June 2015, temporal resolution 5 days, radiometric resolution 12 bit, Swath width 290 km (Landsat7 - 185 km, SPOT5 - 120 km).
- **Sentinel-3** is a multi-instrument mission to measure sea-surface topography, sea- and land-surface temperature, ocean colour and land colour with high-end accuracy and reliability. The mission will support ocean forecasting systems, as well as environmental and climate monitoring.

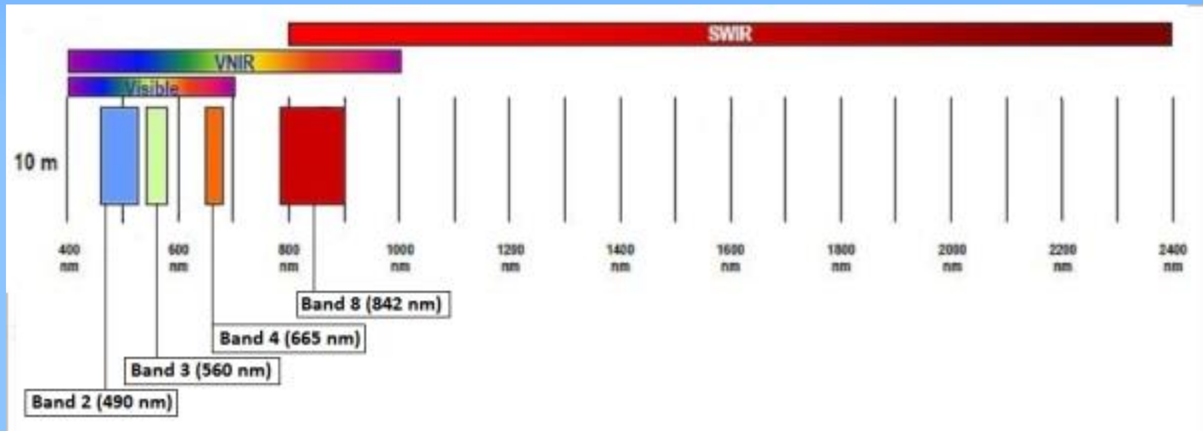
ESA – Sentinel coverage



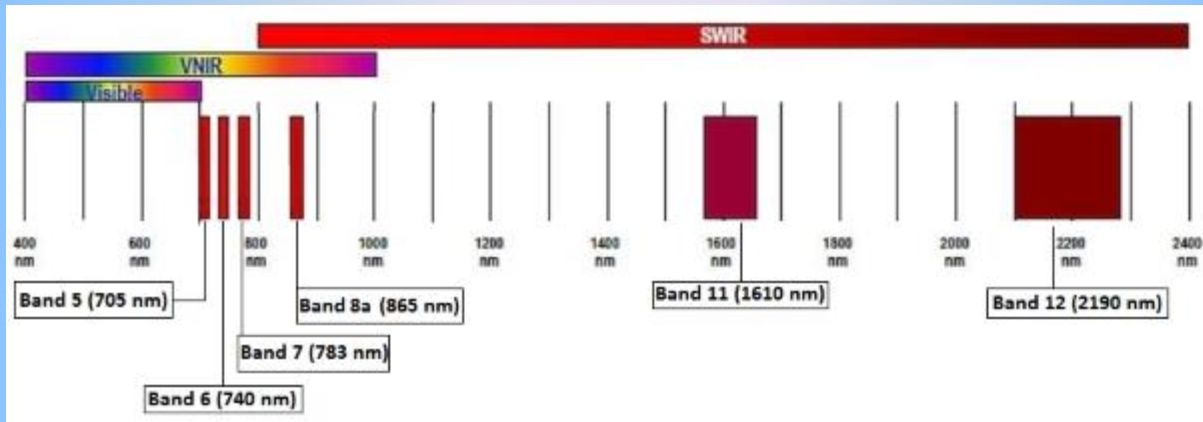
Sentinel 2, spatial resolution and bands

Spatial resolution

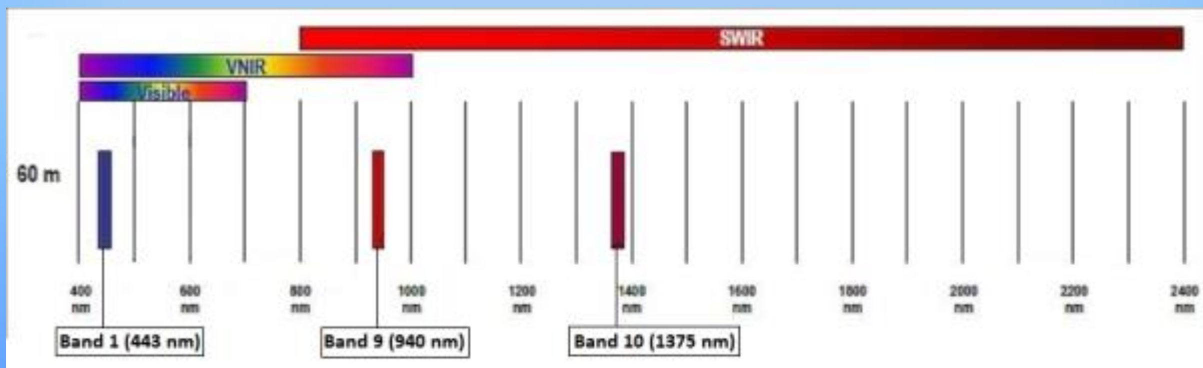
10 m



20 m



60 m



ESA – Sentinel 2 data use in agricultural sector

- Open source toolbox Sen2Agri was developed to generate crop masks, crop type maps and crop status indicators.
- The Sen2Agri toolbox enables users to produce agricultural information on a national scale, based on Sentinel-2 and Landsat-8 observations.

Czech Republic, www.esa.int

Yield estimation for winter wheat using satellite data in comparison to the yield map as measured with a combine harvester

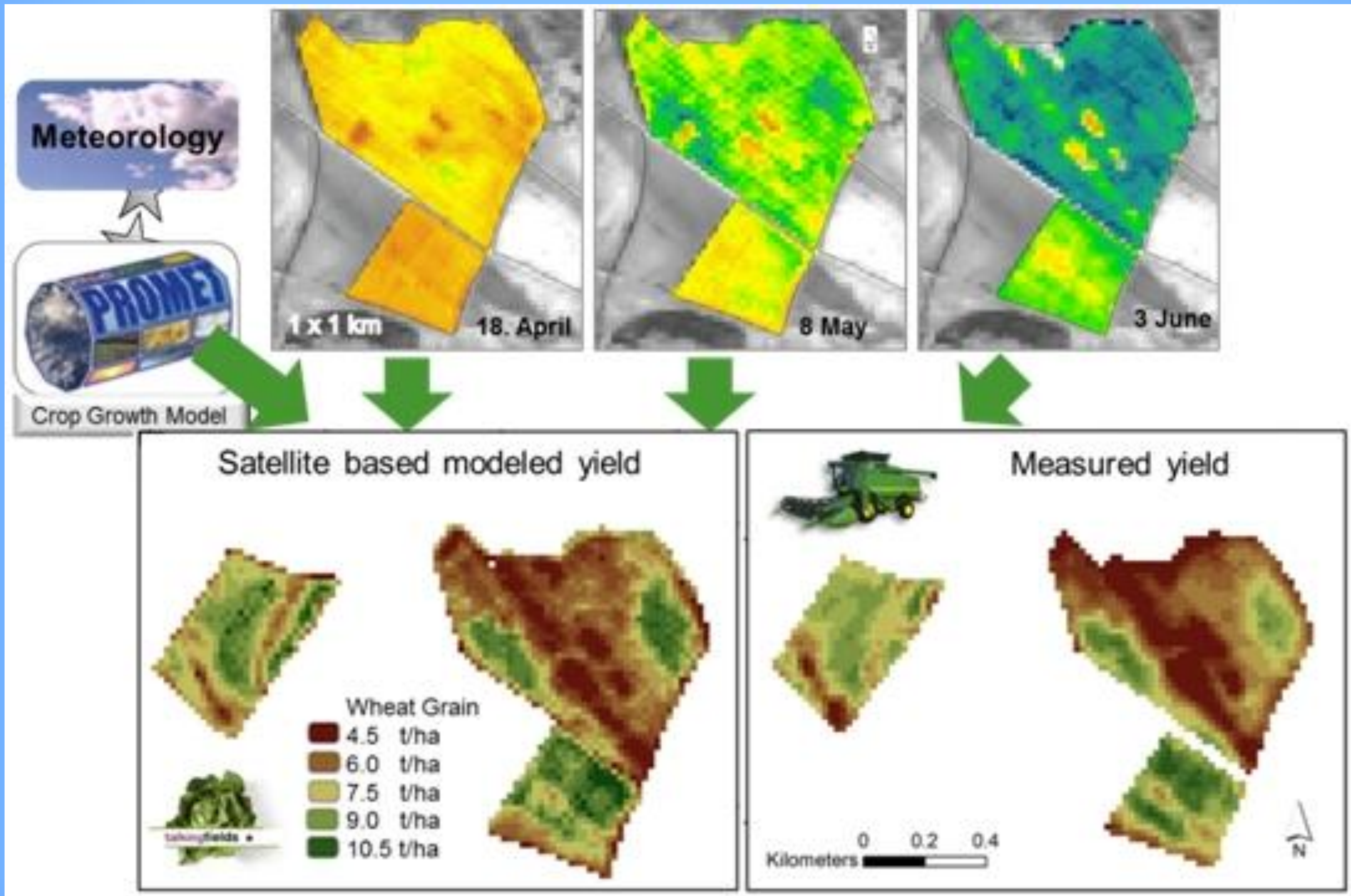


Image display

- **Pixels:**
  - the size depends on the spatial resolution - the basic units of an image, organized in rows and columns as a raster data model.
  - represent a rectangular location and its reflectance value (response within different bands)
- **Images:**
  - Monochrome - with pixel values of 0 (off) or 1 (on), scanned data
  - Grayscale - with pixel values from 0 (black) to 255 (white) and various levels of gray, black-and-white aerial photos or the view of a single band of a multi-spectral image, and
  - Multi-spectral - with pixel values from 0 to 255 for each band on the spectrum (Digital Numbers per pixel per band), satellite data (Landsat, SPOT)
  - responses of different bands can be represented by bars in a histrogram-like plot
- **Display**
  - any three bands can be displayed simultaneously - the color display is created as the combination of red, green and blue (RGB) values.

Landsat Thematic Mapper image data set

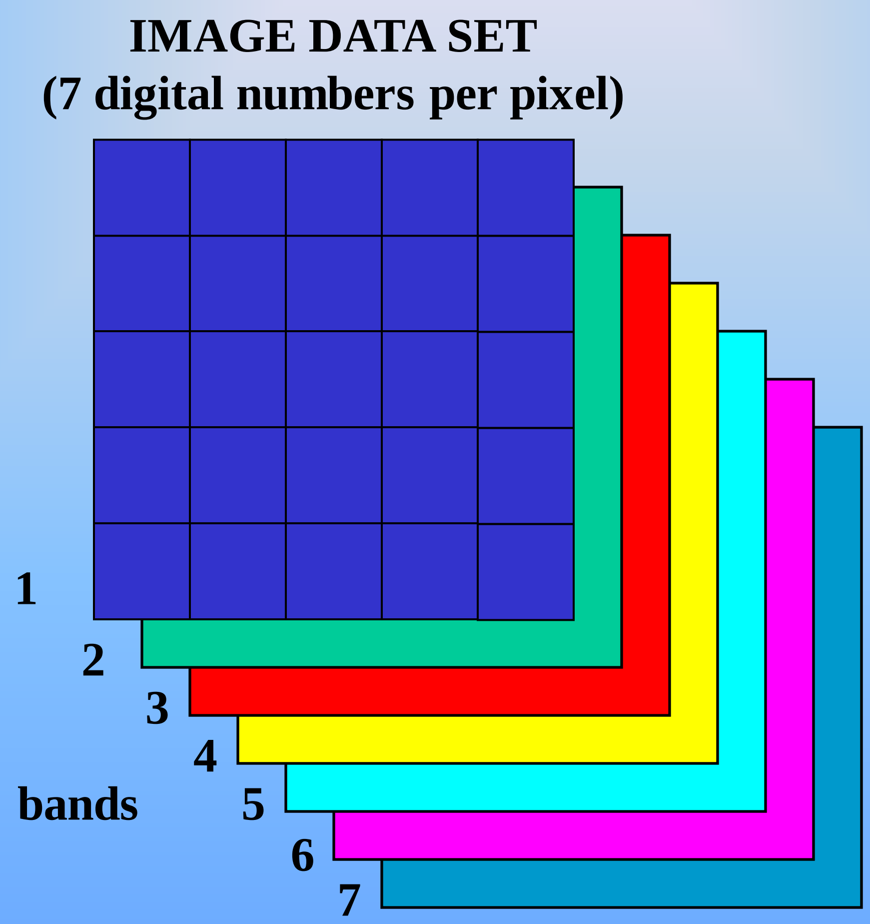


Image processing

- **Contrast stretching:**
  - enlarge the range of pixel values when original range is narrow
- **Filtering:**
  - improve the quality of an image by reducing the “noise” (low pass) or increasing the contrast (high pass)
- **Geometric correction:**
  - process of rotating and scaling - the points on an image coincide with the ground control points (GCP), GPS application for an accurate estimation of coordinates
- **Re-sampling:**
  - assignment of pixel values for geometrically corrected image
- **Reclassification:**
  - relate the pixel values to phenomena

Linear stretching

15	14	15	14
13	12	13	14
12	11	12	13
12	10	11	12

Image to be stretched

255	204	255	204
153	102	153	204
102	51	102	153
102	0	51	102

Stretched image

$$new\_value = \frac{(old\_value - old\_\min)}{(old\_\max - old\_\min)} 255$$

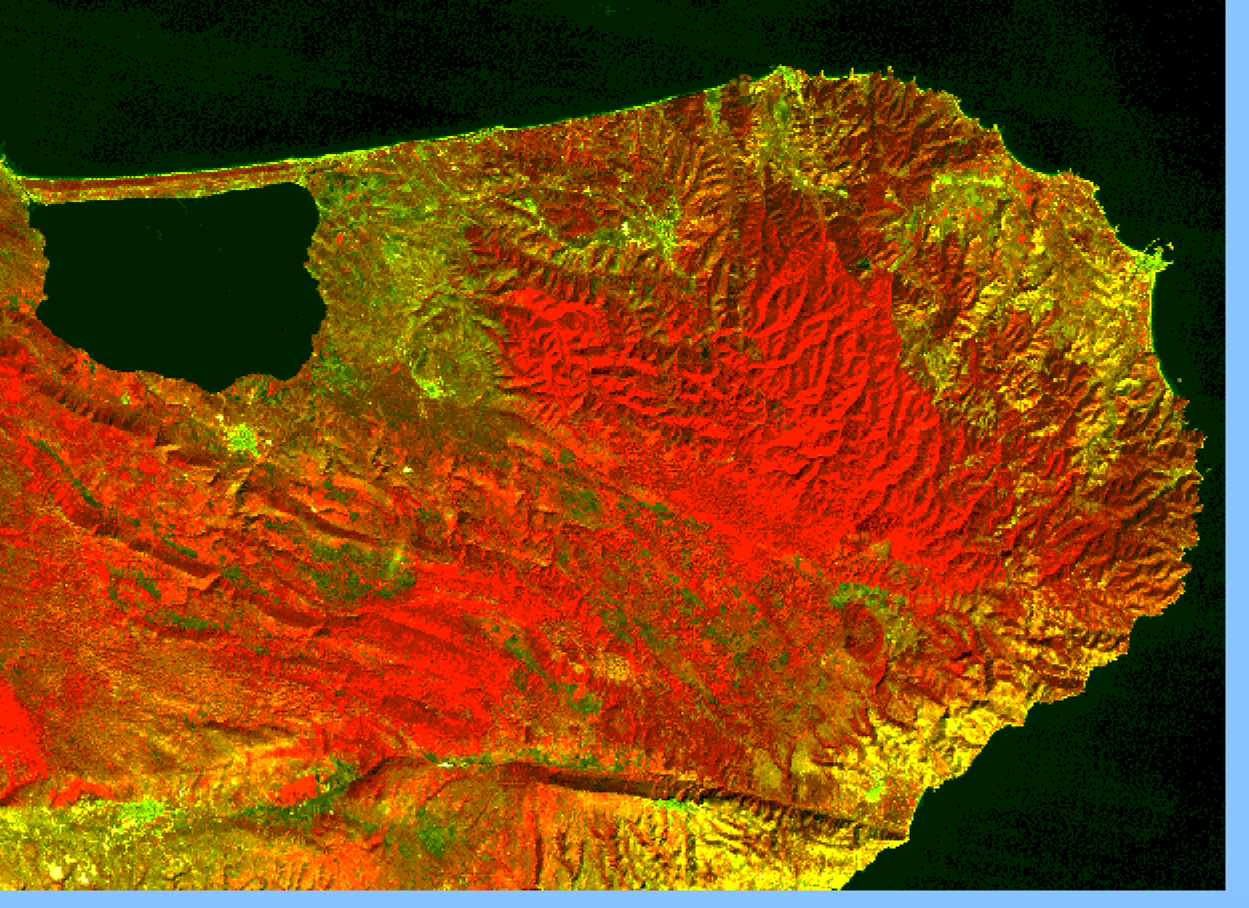
Image re-sampling

- **Nearest neighbor technique:**
  - calculates the value for an output pixel by assigning it the value of the nearest pixel in the input image
- **Bilinear interpolation technique:**
  - calculates the value of an output pixel from the values of the four nearest pixels in the input image based of the weighted distance to these pixels
- **Cubic convolution:**
  - calculates the values of an output pixel by fitting a smooth surface through the sixteen nearest pixels in the input image.
- **How to determine which of the three methods to use?**
  - The use of nearest neighbor method has more sense for categorical data (land use classes) while the bilinear interpolation and cubic convolution could be used for continuous data (rainfall, temperature)
  - Cubic convolution is smoother (and slower) than bilinear interpolation

True-color composite image

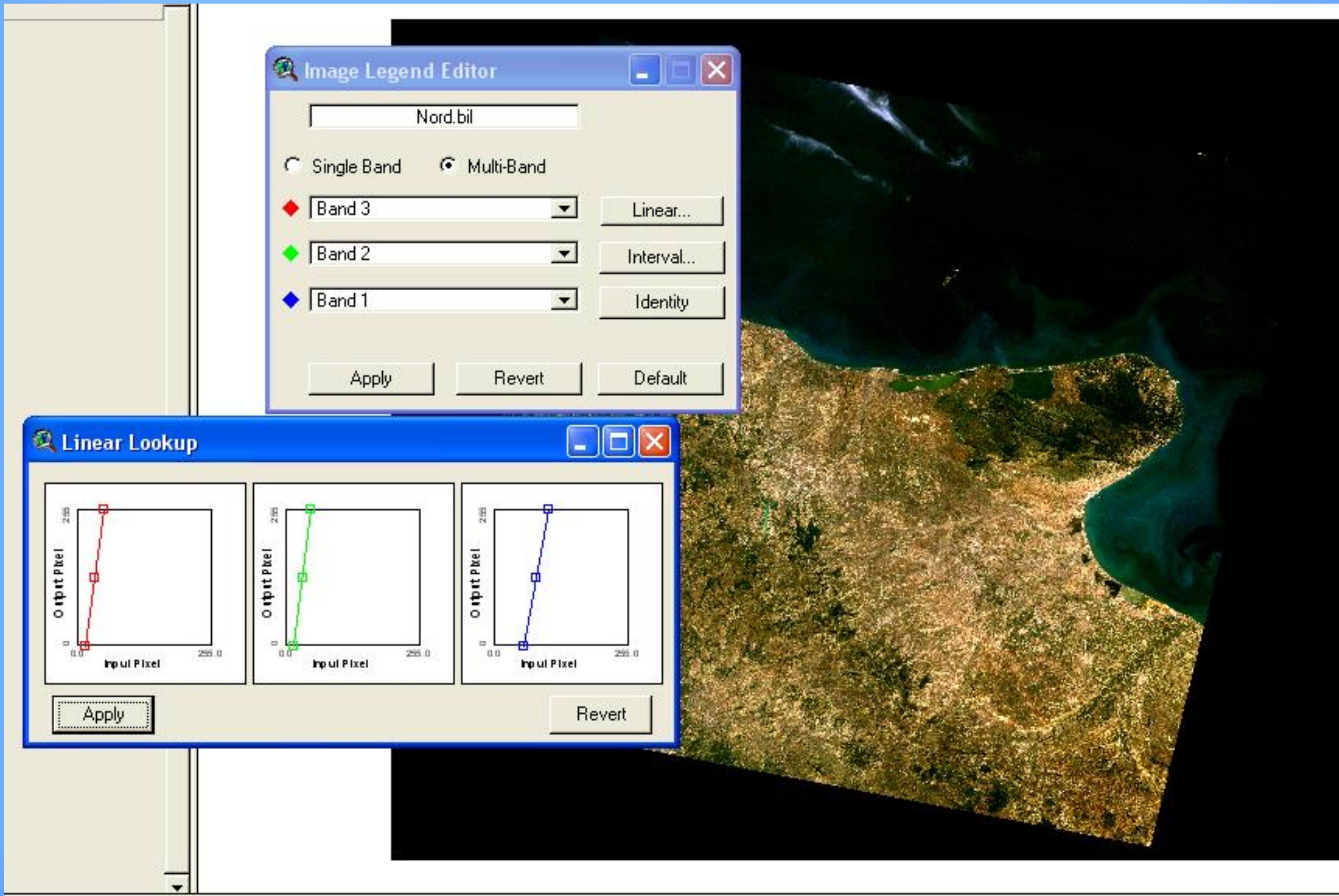
TM3 - red color
TM2 - green color
TM1 - blue color

False-color composite image

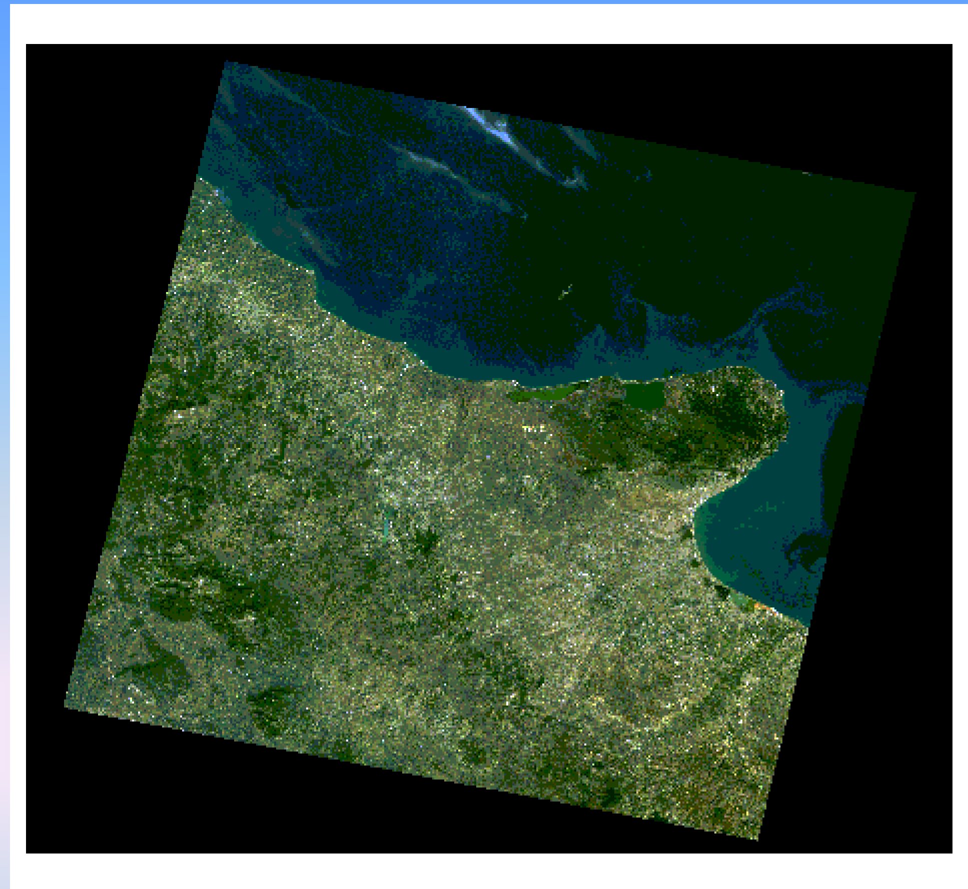


TM4 - red color
TM3 - green color
TM2 - blue color

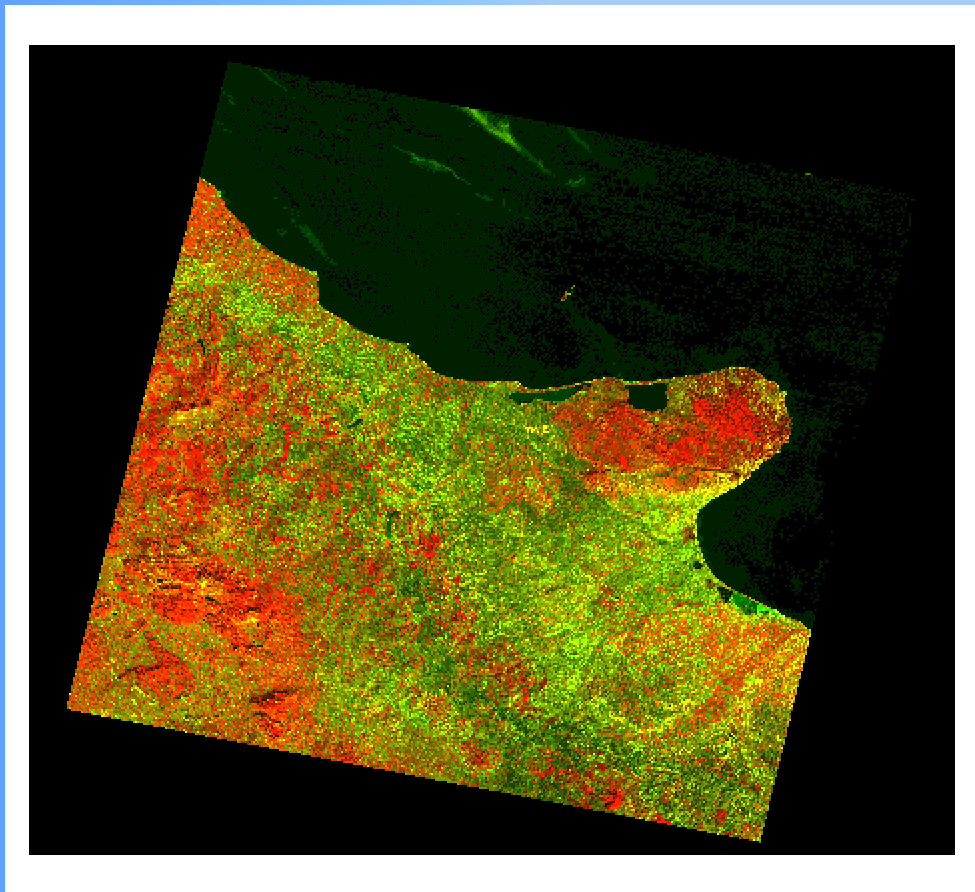
How it is working in ArcView



Landsat Image of the Northern part of the Apulia Region



True-color composite image



False-color composite image

Image classification 1

- **Supervised classification:**
  - Examples of classes of interest (training sites) are identified a priori and they are used for the classification of remaining pixels to one of the classes
  - Training site locations should be those with as pure a sample of the information class as possible - they are used to "train" computer to recognize spectrally similar areas for each class.
  - Computer programmes (algorithms) are used to determine the numerical "signatures" for each training class.
  - Then, each pixel is compared to these "signatures" and labeled as the class it most closely resembles digitally.

Image classification 2

- **Unsupervised classification:**
  - classes are derived from the data without prior knowledge of what they might be, and then the user has to determine what each class means
  - clustering algorithms - groupings of pixels with similar reflectance characteristics in a multi-band image
  - the user specifies the number of clusters to be looked for in the data
- **Hybrid classification:**
  - combination of unsupervised and supervised classification
  - first, an unsupervised classification, class formation by means of clustering algorithms, is applied to the mean spectral values of an image subset including the pixels of ground-truth plots (i.e. of crop Kc values)
  - then, the resulting spectral classes are used as training signatures for the supervised classification of the whole image.

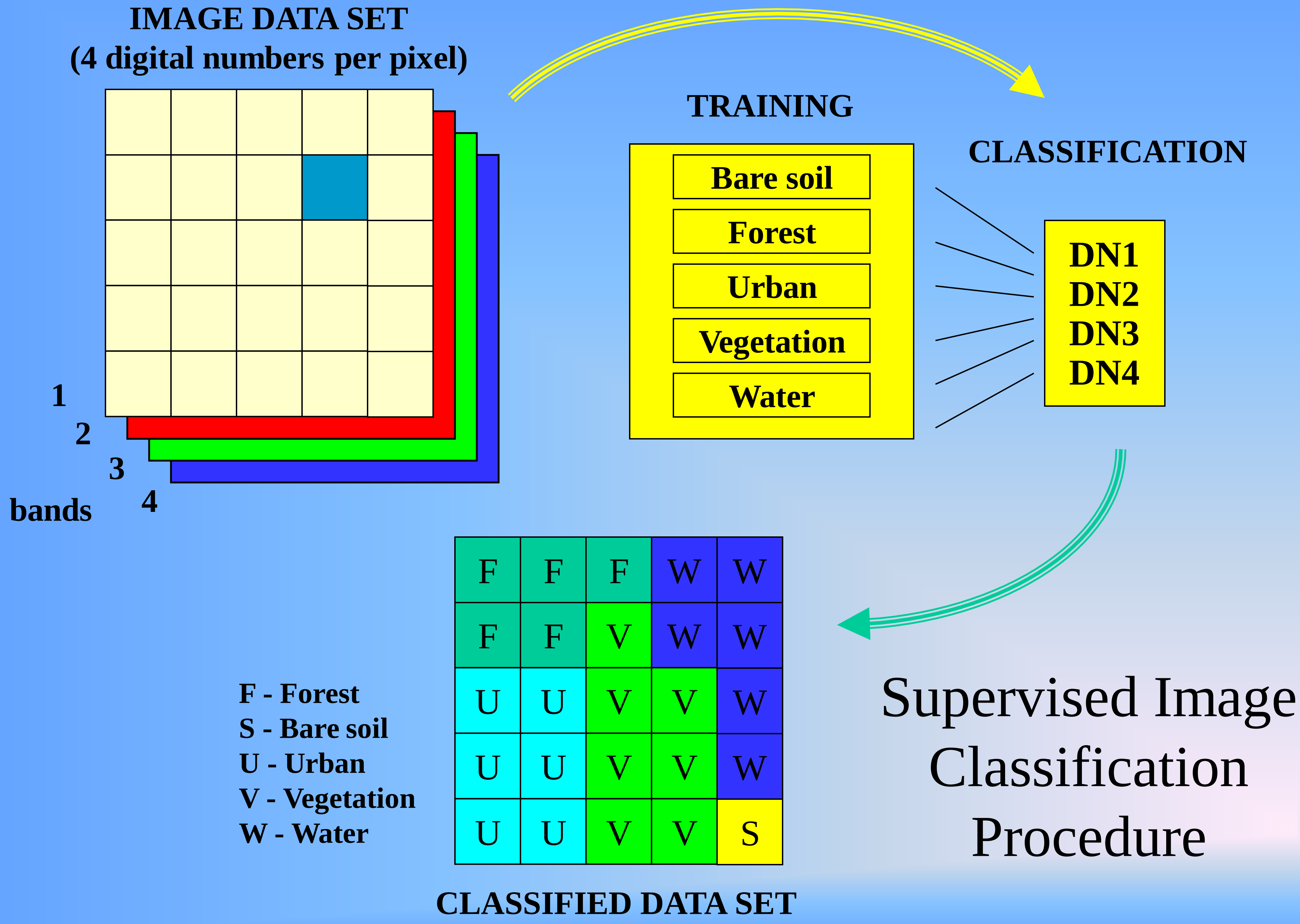
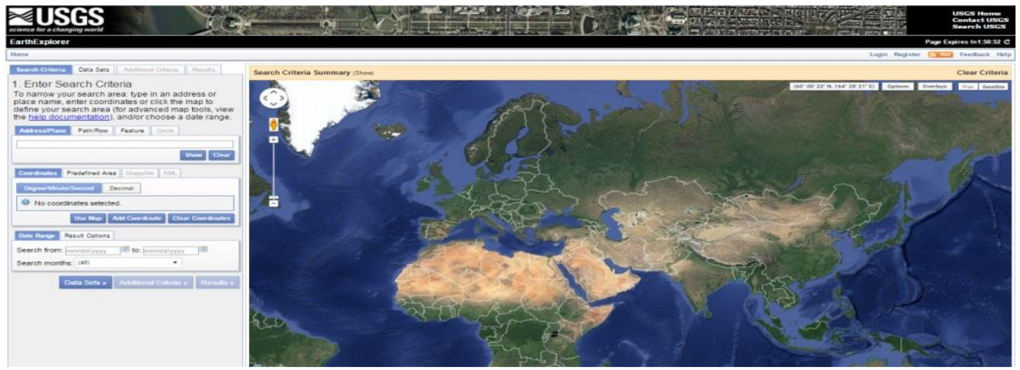


IMAGE DATA SET
(4 digital numbers per pixel)
1
2
3
4
bands
TRAINING
Bare soil
Forest
Urban
Vegetation
Water
CLASSIFICATION
DN1
DN2
DN3
DN4
F F F W W
F F V W W
U U V V W
U U V V W
U U V V S
F - Forest
S - Bare soil
U - Urban
V - Vegetation
W - Water
CLASSIFIED DATA SET
Supervised Image Classification Procedure

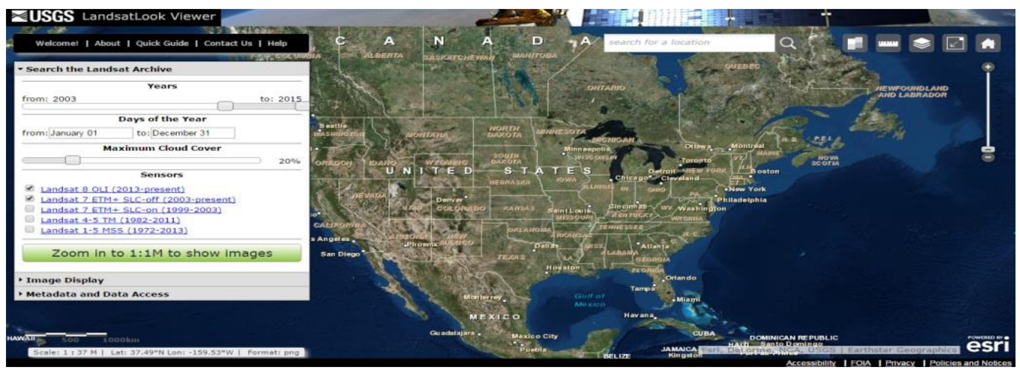
Example: Landsat 8 data free download

Glovis

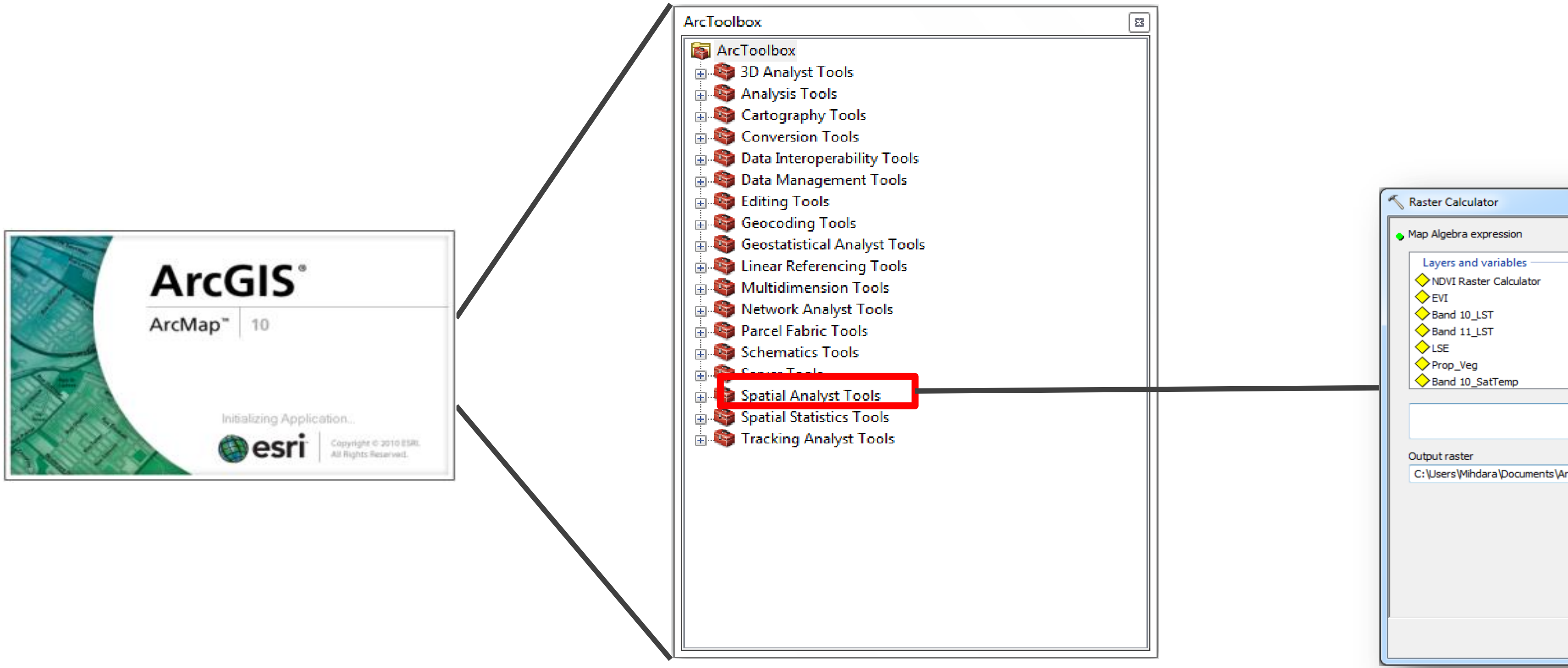
Earth Explorer



LandsatLook Viewer



Landsat 8 images analysis



EXAMPLES

of REMOTE SENSING APPLICATIONS
in
LAND and WATER MANAGEMENT

Remote Sensing application in agriculture

Aerial-based Sensing Methods

- Large areas (district->farm->field->canopy);
- Assessing different combinations of crop/weather/soil/management scenarios;
- Data available continuosly for predefined dates and hours
- Spatial resolution low/moderate/high
- Spectral resolution lower than for G-B and fixed by the provider

Ground-based proximal Sensing Methods

- One Field (field->canopy->plant->leaf);
- Assessing one crop/weather/soil/management scenario
- High temporal resolution: data available for the user-defined dates and hours
- High spatial resolution
- High spectral resolution managable by the user

Spectral reflectance measurements in agriculture

Greenseeker – NDVI measurement

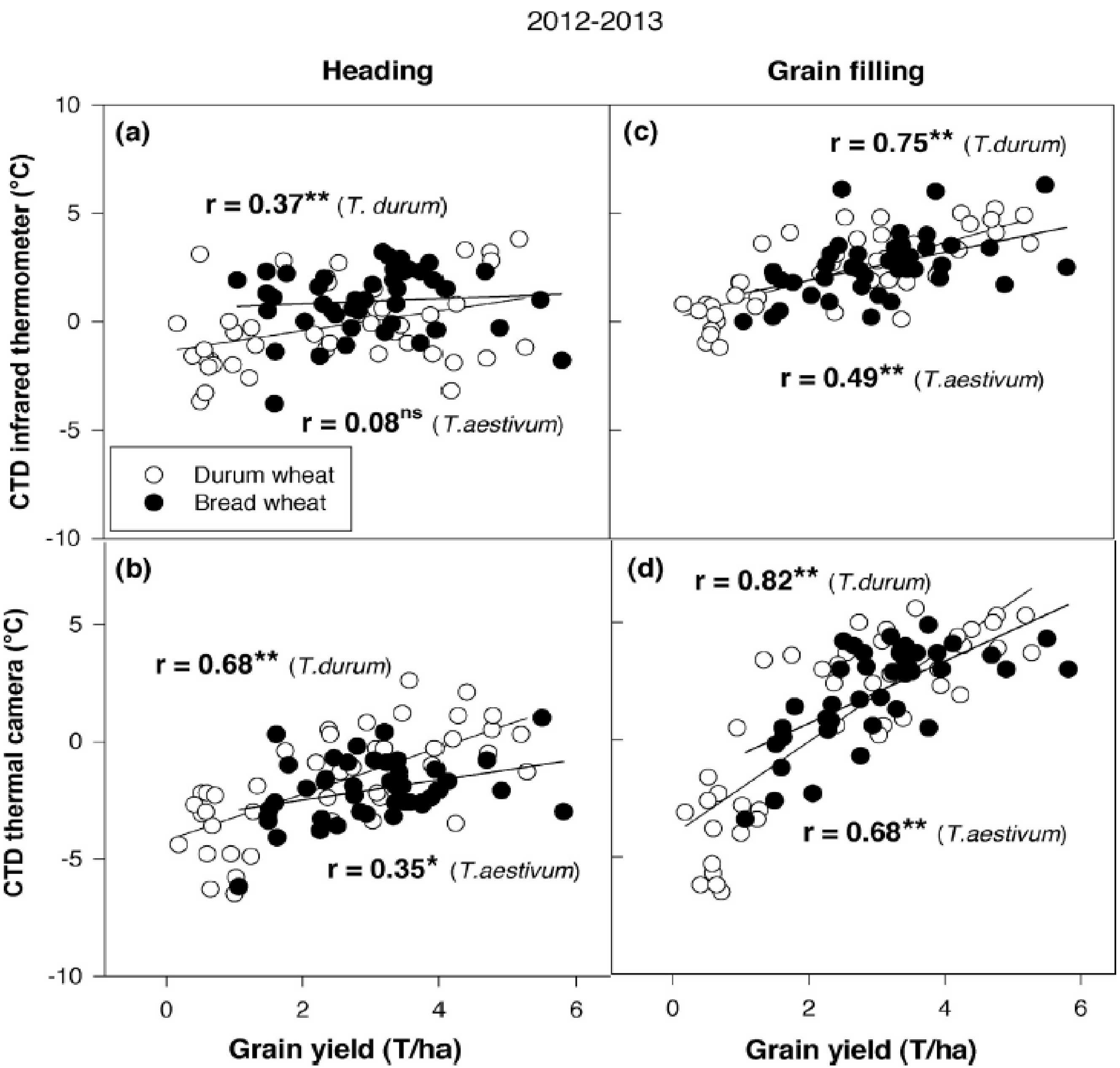
Handheld spectro-radiometer

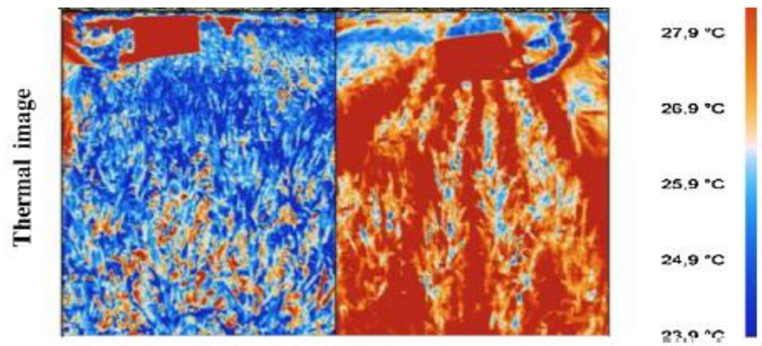
Use of thermal imagery in agriculture

- Measuring of the leaf/canopy/ground temperature
- Thermal wavelength region ranges from 3 to 35 µm but only a part of it is effectively used
- 8 - 14 µm regions is of greatest interest for thermal remote sensing since the atmosphere is fairly transparent and the signal is only lightly attenuated by atmospheric absorption
- Based on the principle that everything above absolute zero (0 K or −273.15˚C or −459˚F) emits radiation in the infrared range of the electromagnetic spectrum
- Accuracy of thermal measurements depend on environmental conditions which influence the thermal properties of the visualized crop.
- Calibration of images according to weather conditions is necessary for comparison between image data obtained during different measuring periods and growth seasons.
- Potential use of thermography in agriculture includes nursery monitoring, **irrigation scheduling**, soil salinity detection, disease and pathogen detection, yield estimation, maturity evaluation and damage detection.

Infrared thermometer *vs* thermal camera

S. Yousfi et al. / Agricultural Water Management 164 (2016) 137–147



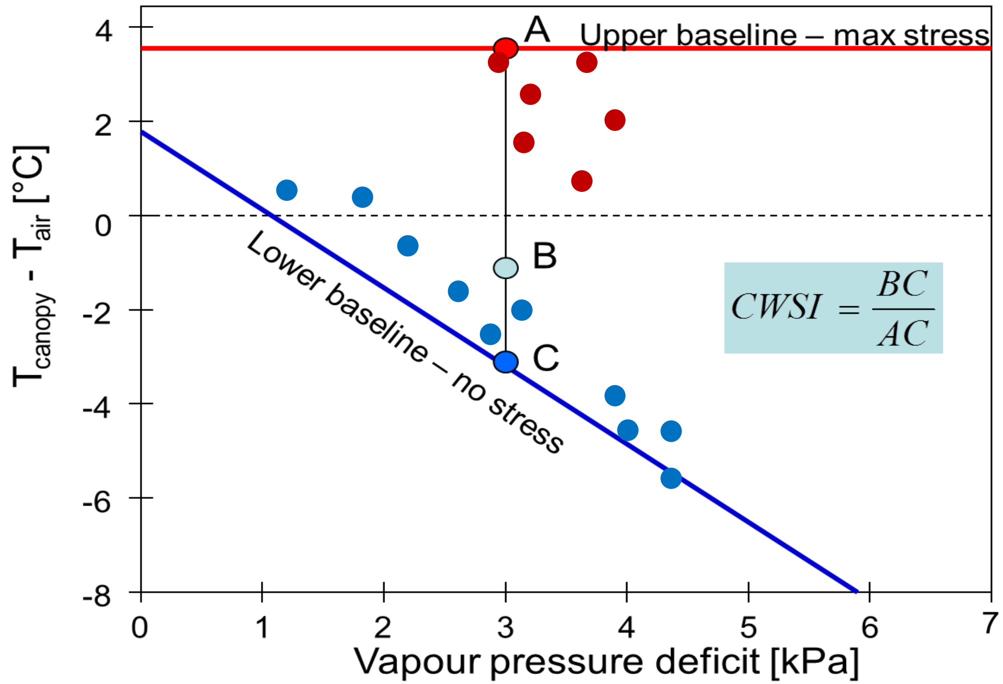


Yousfi et al. 2016. *Agric. Water Manag.*

Assessment and monitoring of water stress:
Crop Water Stress Index (CWSI)

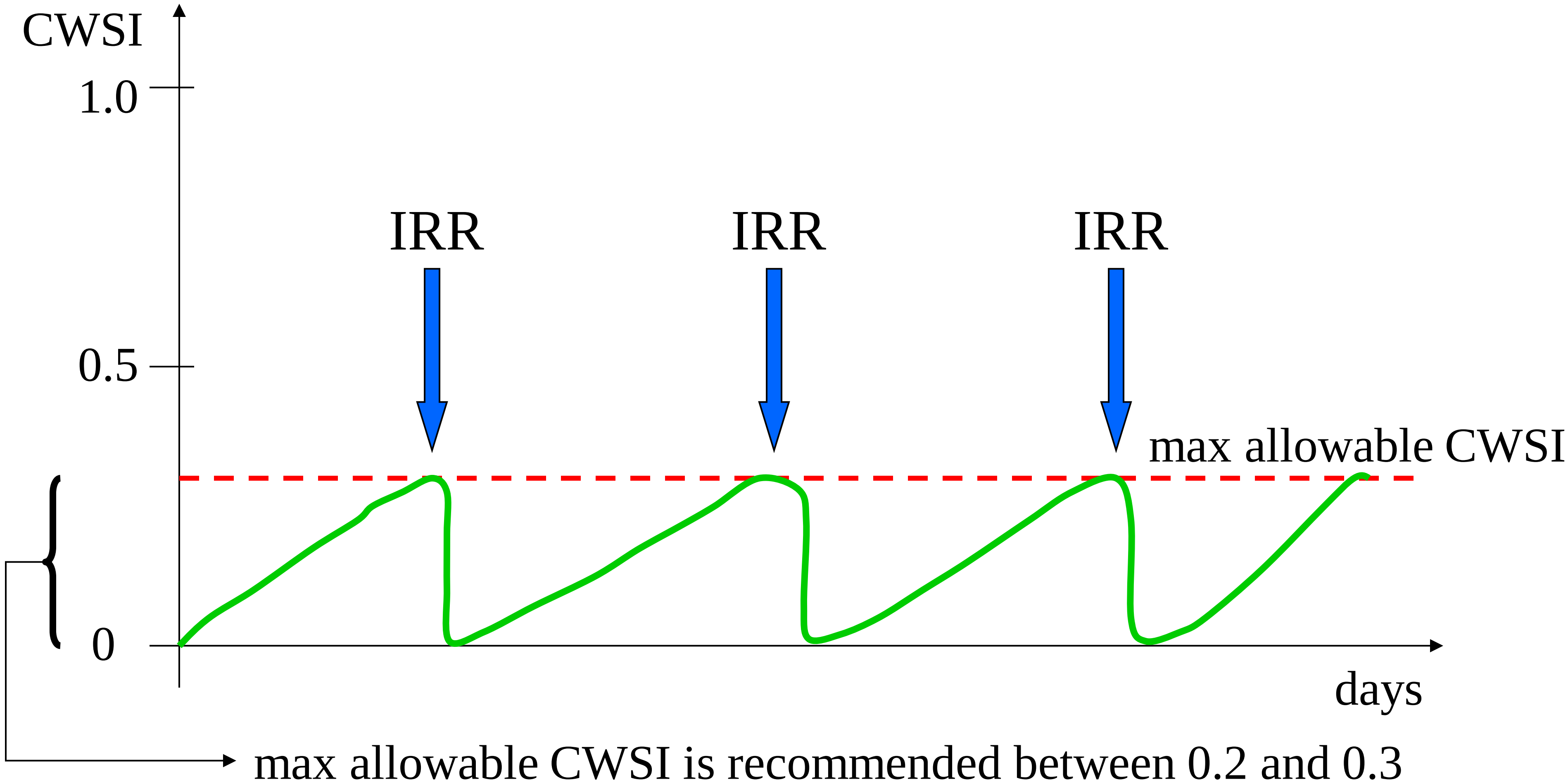
- ⌘ A thermal method for remote detecting of water stress
- Based on the relationship between canopy (leaf) and air temperature difference and VPD

$$CWSI = \frac{\Delta T - \Delta T_{lower}}{\Delta T_{upper} - \Delta T_{lower}}$$



- ΔT – the measured difference between canopy and air temperature
- ΔT_{lower} – the lower limit of canopy minus air temperature (well-watered crop)
- ΔT_{upper} – the upper limit of canopy minus air temperature (non-transpiring crop)

CWSI supports irrigation scheduling ...

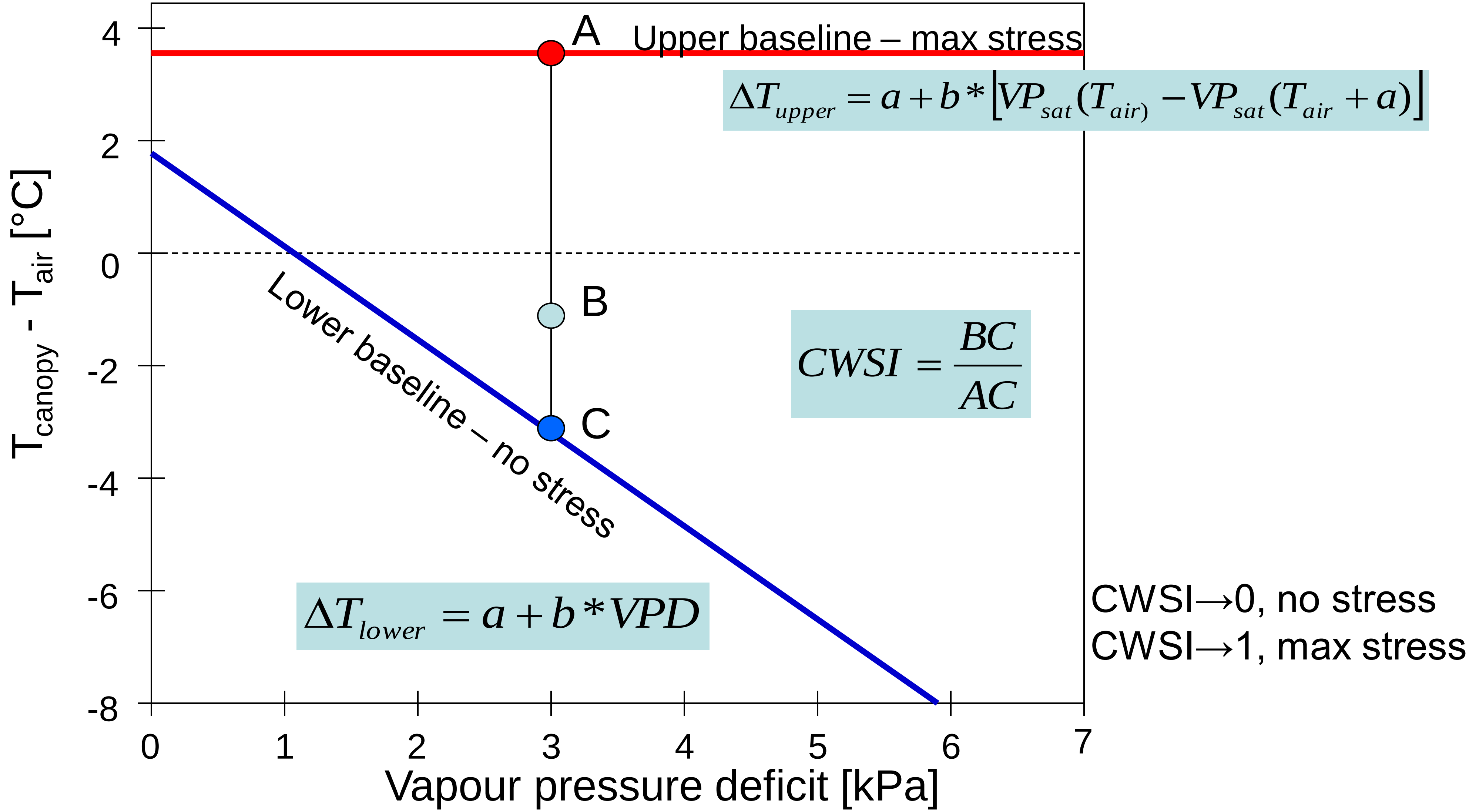


max allowable CWSI is recommended between 0.2 and 0.3

CWSI_irr_threshold is crop specific and should consider yield response to water stress, crop value, etc.

CWSI : (T_{canopy}-T_{air}) vs. VPD baseline

("empirical approach", Idso, 1982)



CWSI : Baseline parameters

for various crops – sunlit (no clouds) conditions

Crop	a	b
Alfalfa	0.51	-1.92
Barley (pre-heading)	2.01	-2.25
Barley (post-heading)	1.72	-1.23
Bean	2.91	-2.35
Beet	5.16	-2.30
Corn (no tassels)	3.11	-1.97
Cotton	1.49	-2.09
Cucumber	4.88	-2.52

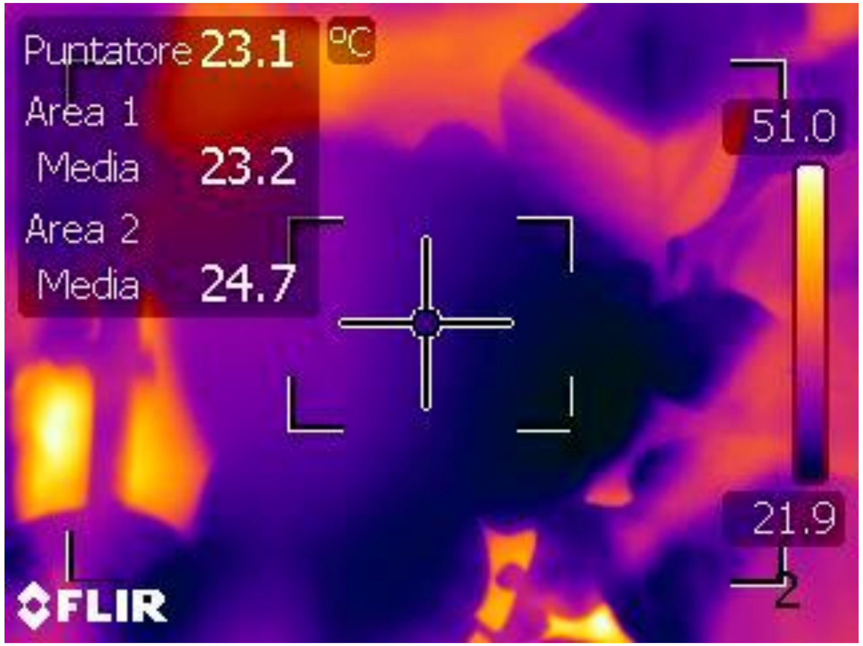
Crop	a	b
Lettuce	4.18	-2.96
Potato	1.17	-1.83
Soybean	1.44	-1.34
Sorghum	2.14	-1.81
Tomato	2.86	-1.96
Wheat (pre-heading)	3.38	-3.25
Wheat (post-heading	2.88	-2.11
Watermelon	3.05	-1.11

Note: CWSI is valid when crop is completely covering the ground

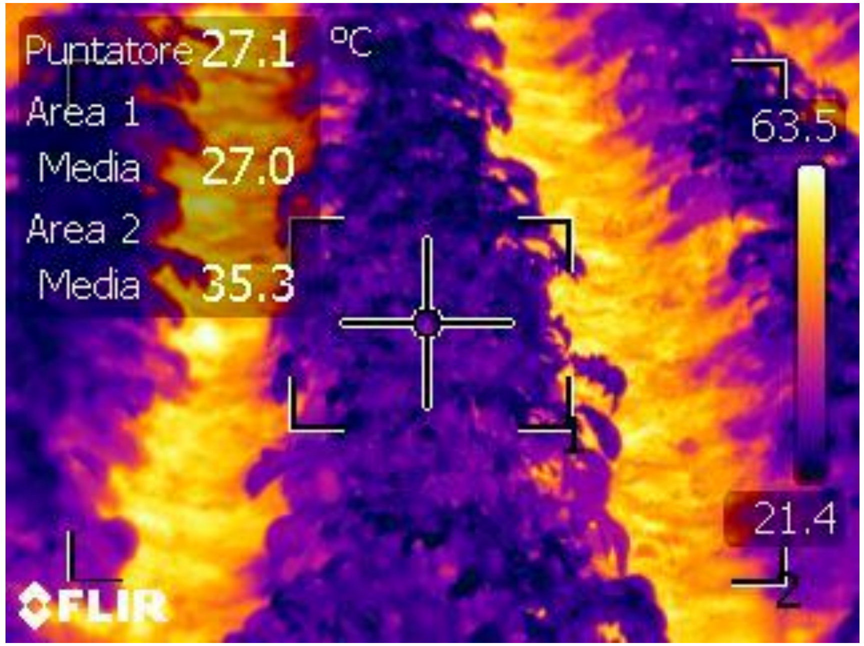
Source: Idso, 1982; Jackson et al., 1988; Clarke, 1997; Orta et al., 2002

<u>Practical example, step 1, data acquisition (thermal images and weather data)</u>

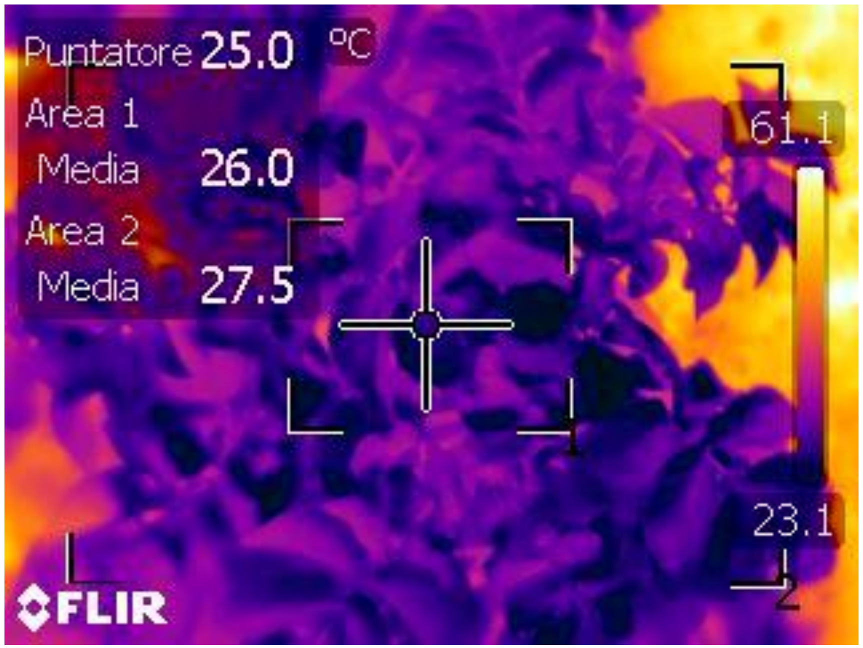
Thermal images, potato crop



Leaf scale



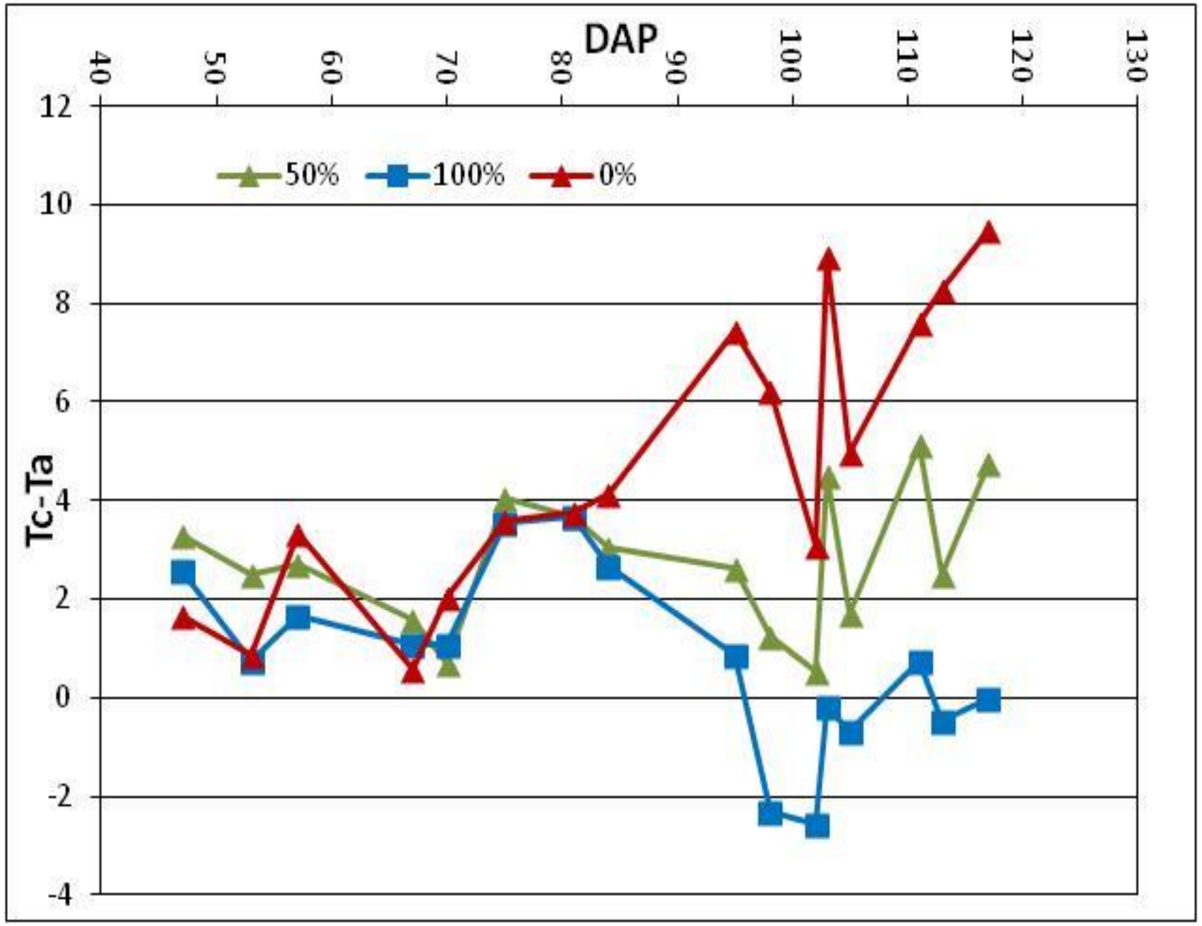
Plot (canopy with inter-rows) scale



Canopy scale

Practical example, step 2, (T_{canopy}-T_{air}) estimation and drawing

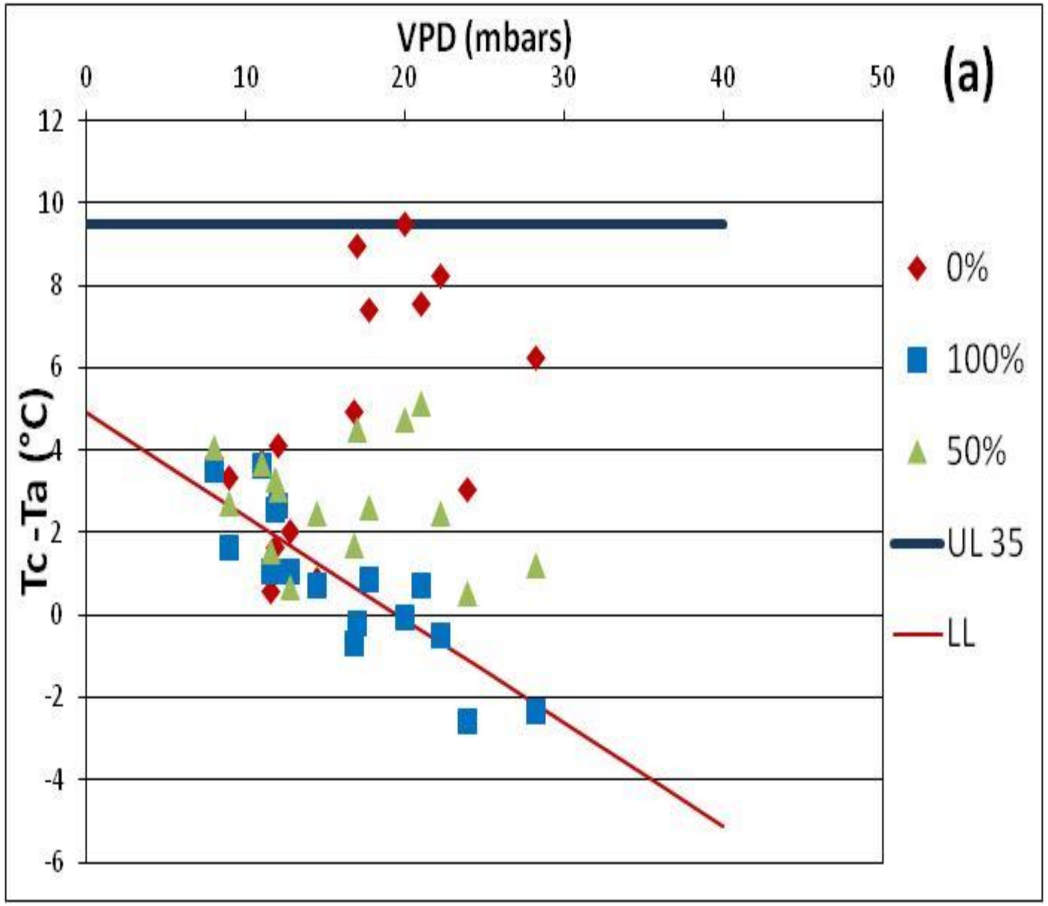
Variation of the difference canopy-air temperature (Tc-Ta) (°C) during the potato growing cycle for the three water regimes



Source: Ben Charfi, 2014

Practical example, step 3, (T_{canopy}-T_{air}) vs VPD drawing and upper and lower T limits determination

Difference canopy-air temperature (Tc-Ta) (°C) versus air vapor pressure deficit (KPa) with the corresponding upper and lower limits

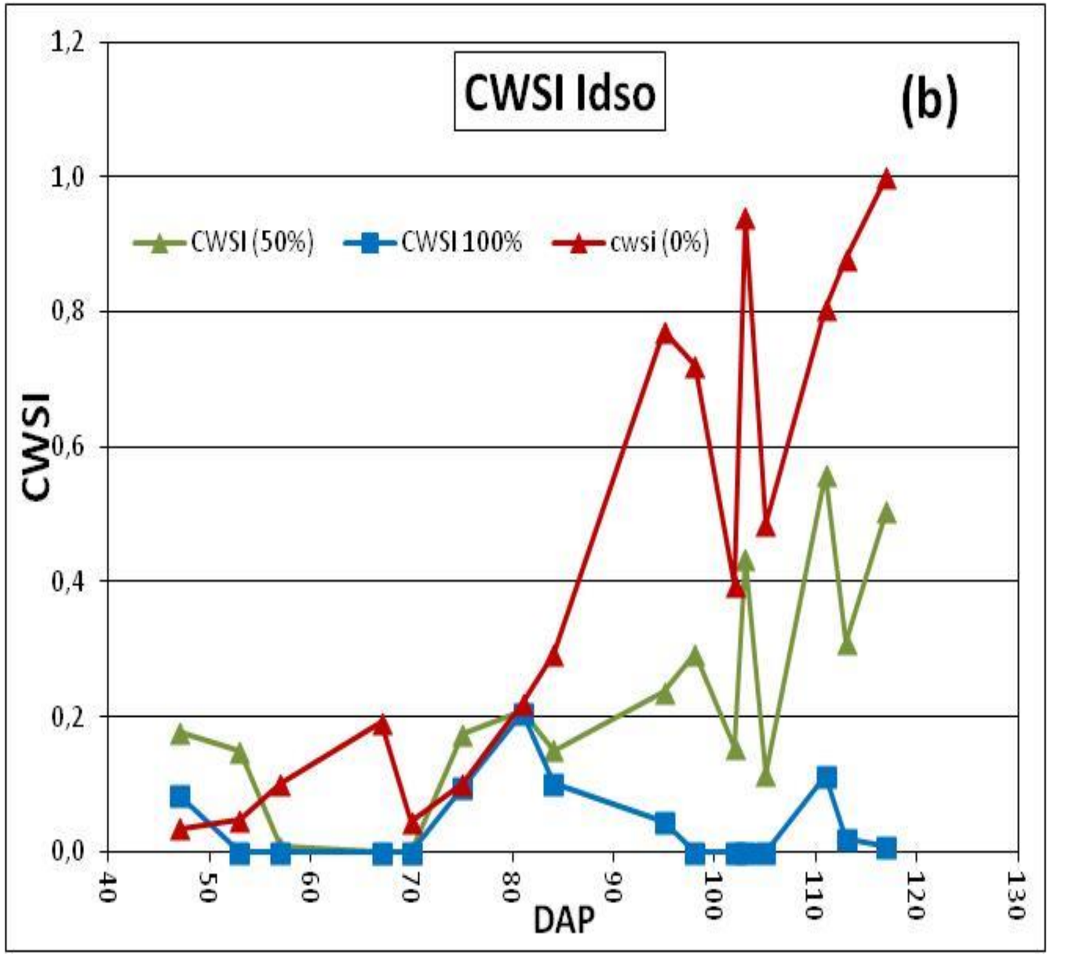


$$\Delta T_{upper} = 9.5\ °C$$

$$\Delta T_{lower} = 4.9 - 0.25 * VPD$$

Source: Ben Charfi, 2014

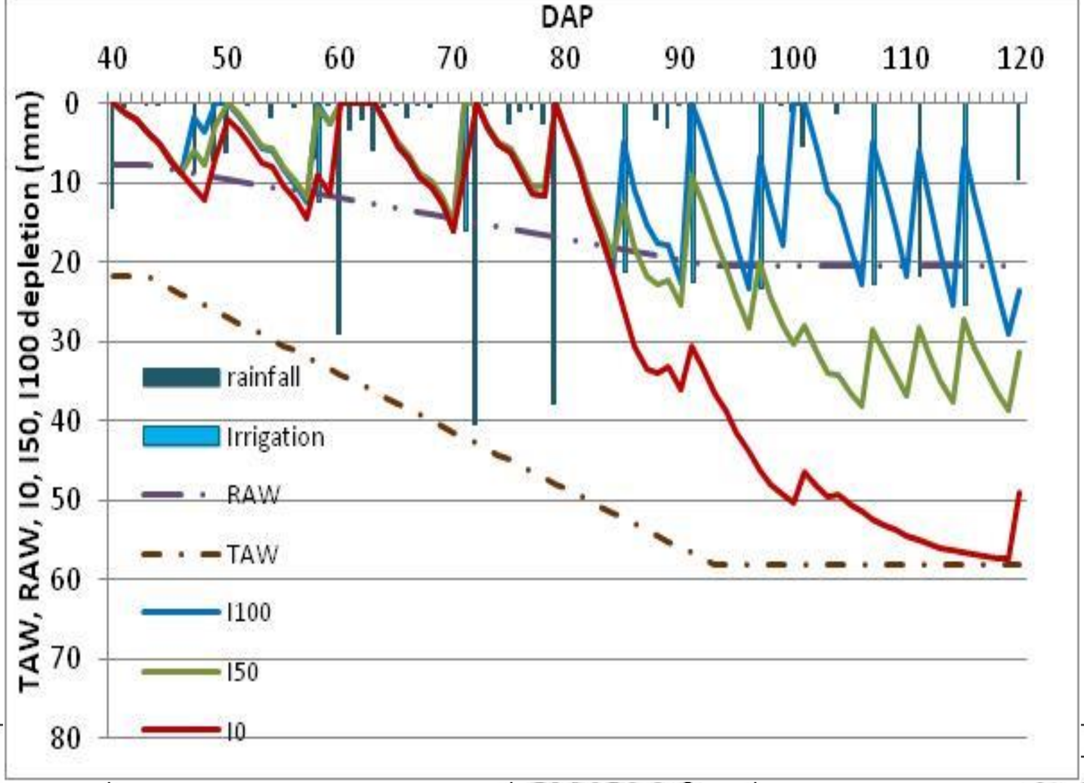
Idso's Crop Water Stress Index variation for the three irrigation regimes during the potato growing cycle



Source: Ben Charfi, 2014

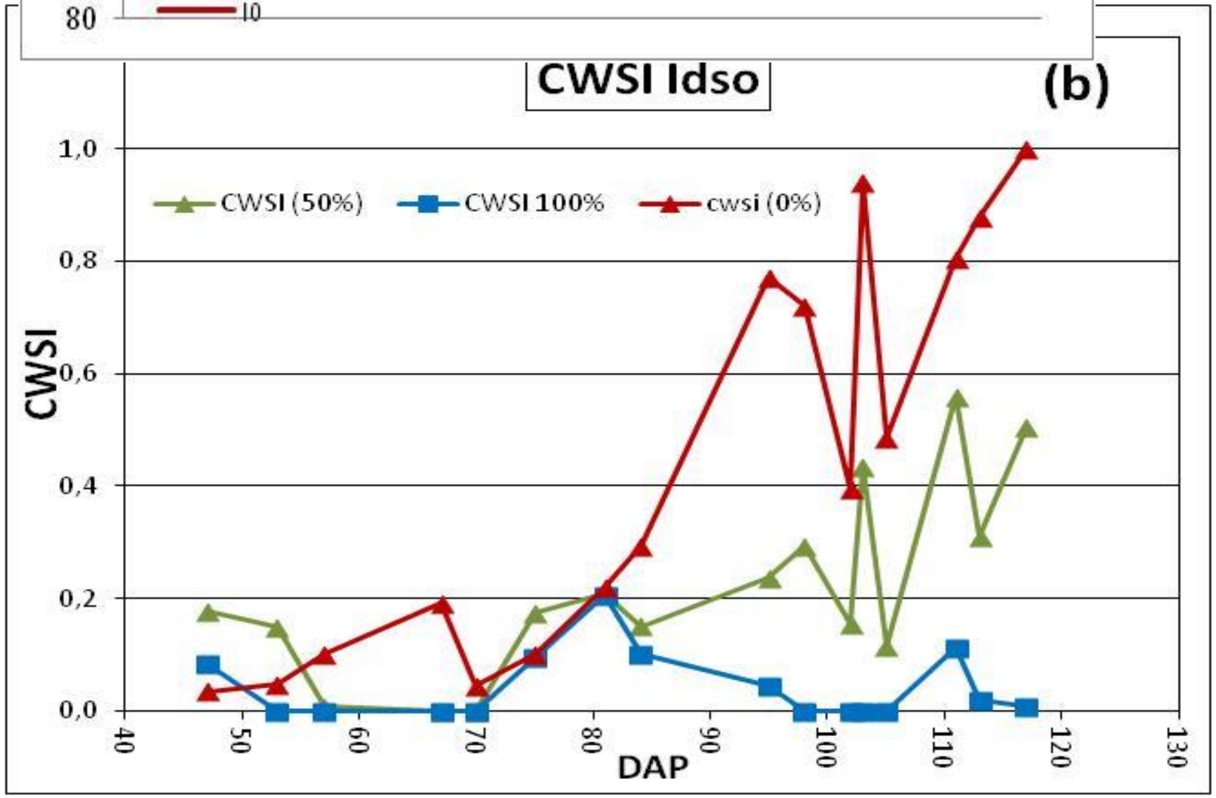
Practical example, step 5, comparison

Soil water content in the root zone



vs

Crop Water Stress Index



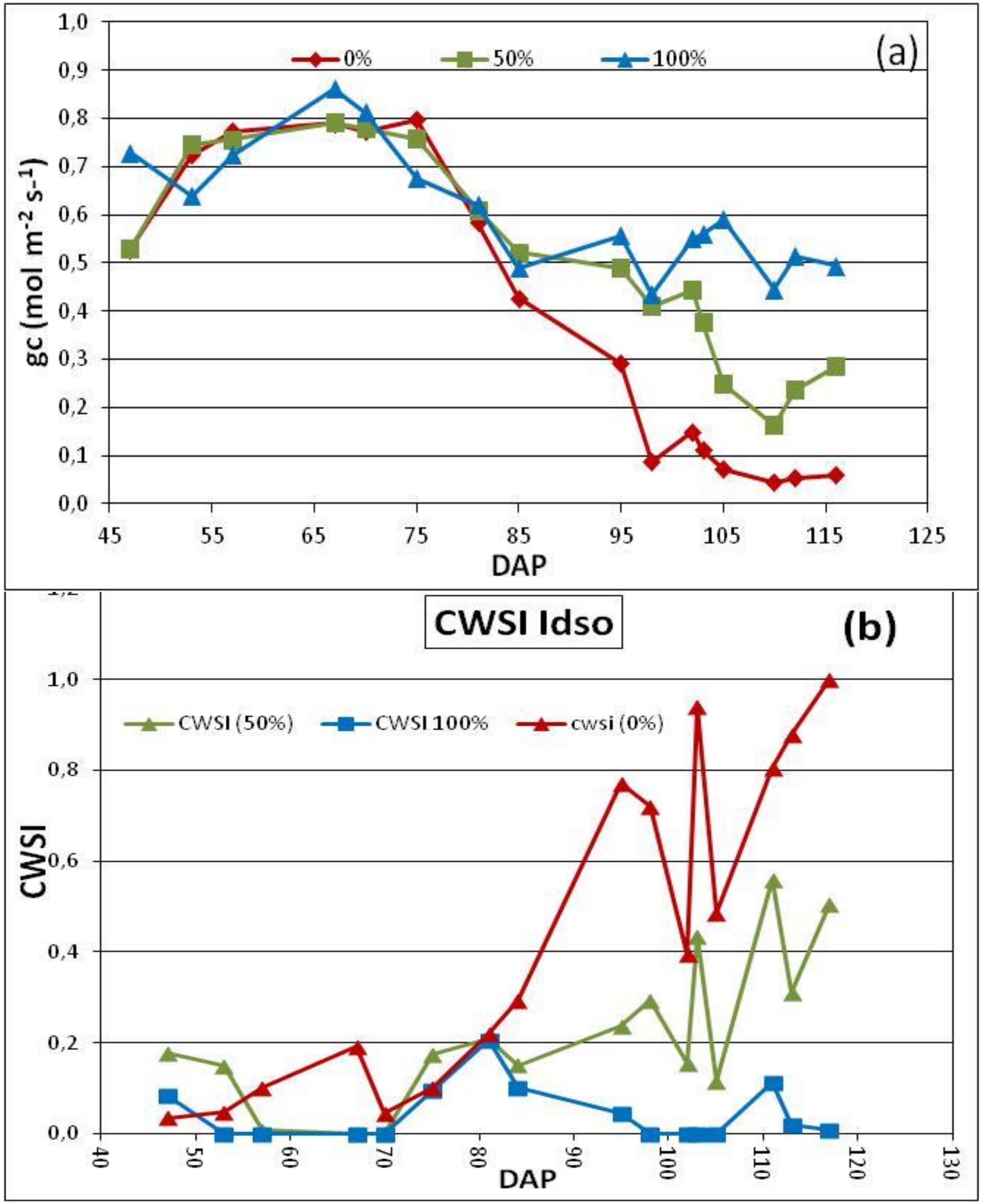
Source: Ben Charfi, 2014

Practical example, step 5, comparison

Stomatal conductance

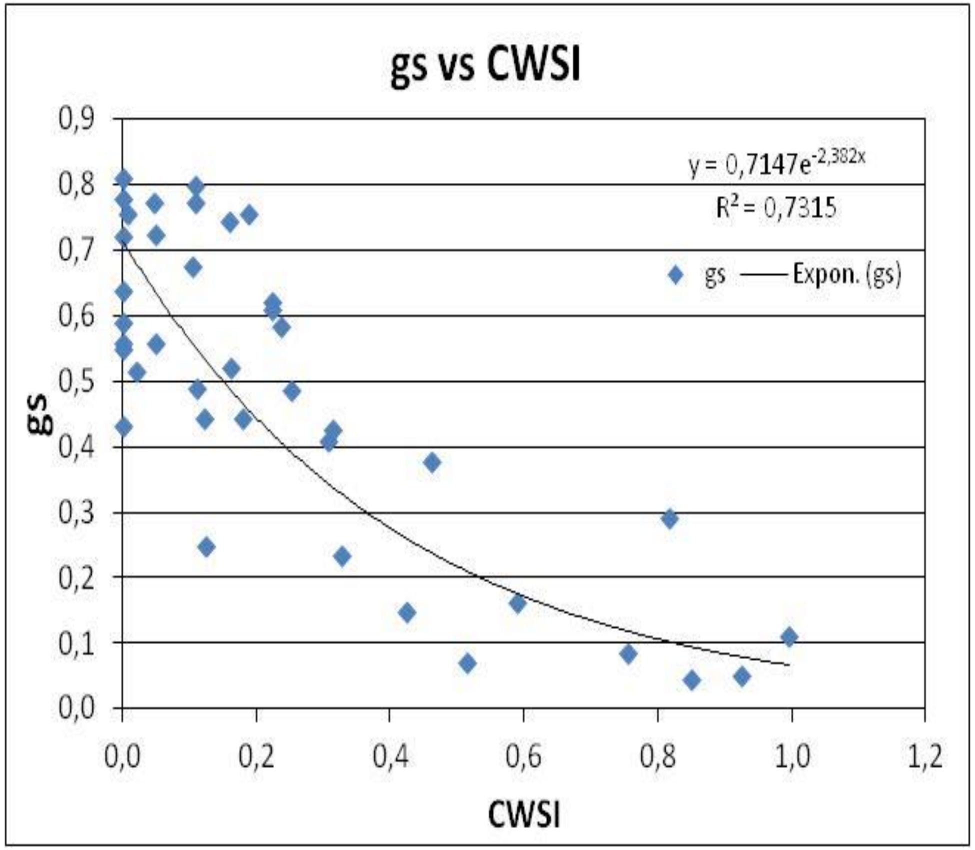
vs

Crop Water Stress Index



Source: Ben Charfi, 2014

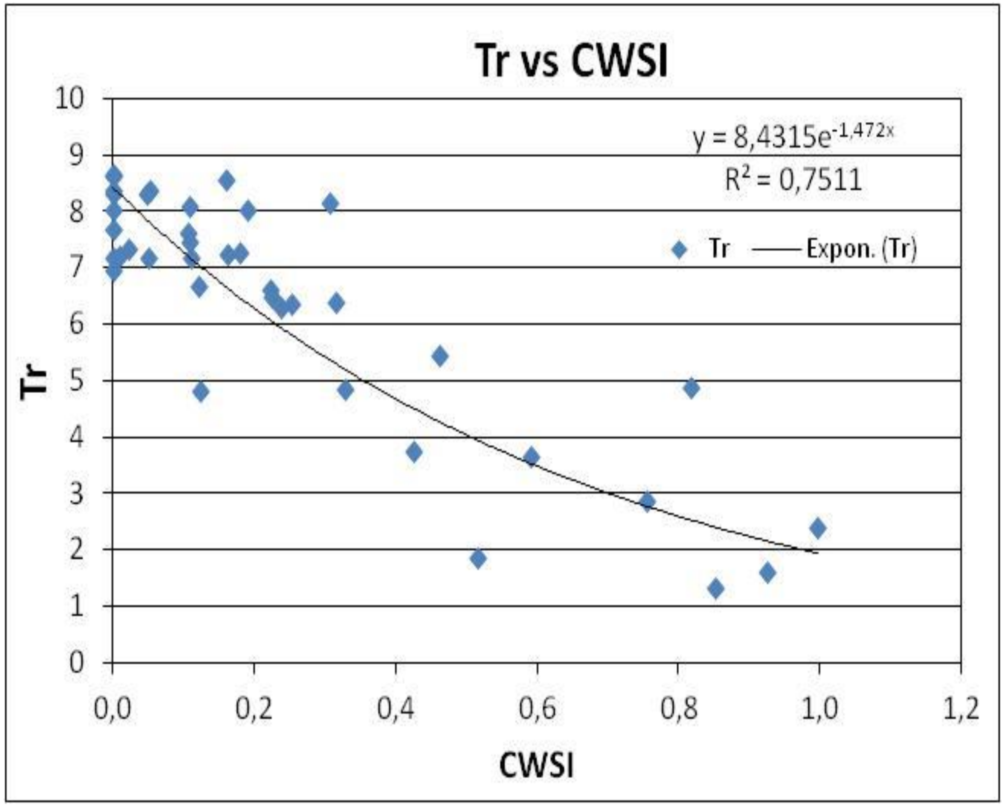
Stomatal conductance vs Crop Water Stress Index



Source: Ben Charfi, 2014

Practical example, step 6, relationship with other variables

Transpiration vs Crop Water Stress Index



Source: Ben Charfi, 2014

CWSI: theoretical approach of Jackson et al., 1988)

UPPER BASELINE ESTIMATE

$$(T_c - T_a)_{ul} = \frac{r_a(R_n - G)}{\rho C_p}$$

- R_n is the net radiation (W m−2), estimated as the difference between incoming net shortwave and outgoing net longwave radiation using Eqs. (38), (39), and (40) in FAO-56 and an albedo = 0.23;
- G = soil heat flux (MJ m−2 d−1), estimated using Eq. (45) from FAO-56, i.e. G=0.1*Rn;
- ρ (kg m−3) is the density of air approximated as a function of air temperature;
- Cp = specific heat capacity of dry air (1013 J kg−1 ◦C−1); and
- ra is aerodynamic resistance (see next slides for the formula of ra).

The assumption is that the bulk canopy resistance, rc, approaches infinity.

LOWER BASELINE ESTIMATE (Jackson et al., 1988)

The lower limit, representing a fully transpiring crop, (Tc − Ta)ll is:

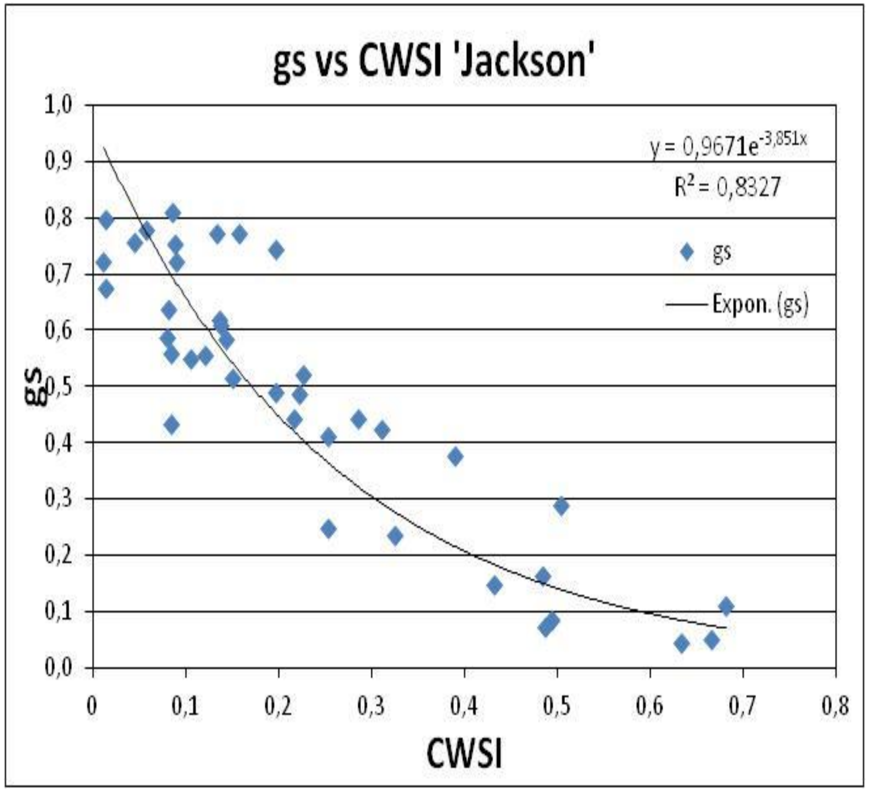
$$(T_c - T_a)_{ll} = \left(\frac{r_a R_n}{\rho C_p}\right)\left(\frac{\gamma}{\Delta + \gamma}\right) - \frac{e_s - e_a}{\Delta + \gamma}$$

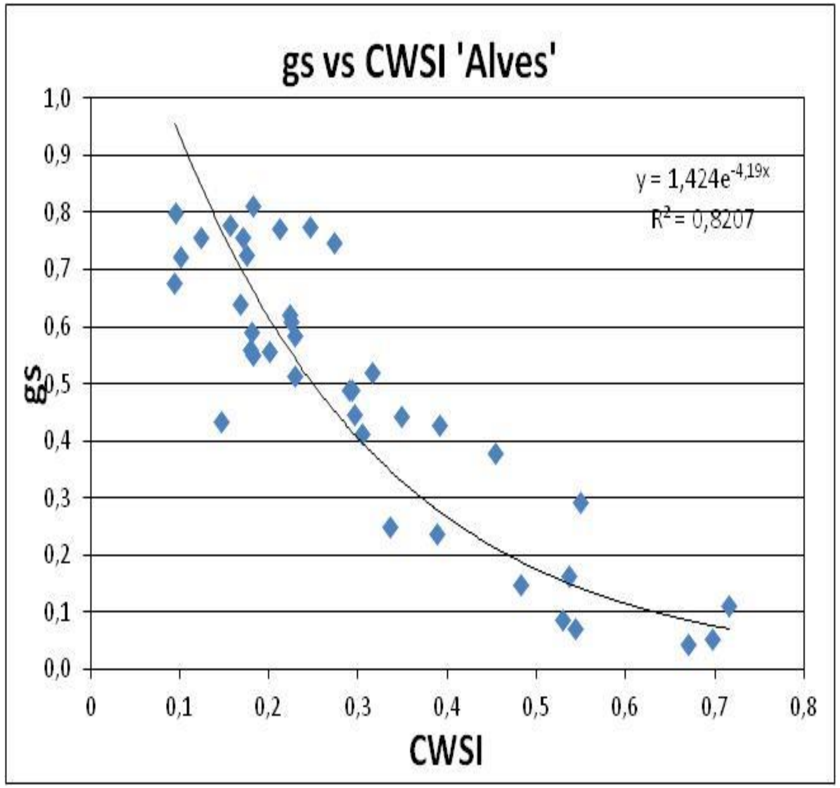
where γ is the psychometric constant (Pa ◦C−1); Δ is the slope of the saturated vapor pressure-temperature relationship calculated at the average of canopy and air temperature expressed in °C; es is saturated vapor pressure, ea is actual vapor pressure, and ra is aerodynamic resistance (s m−1), computed as FAO56

$$r_a = \frac{(\ln(z_m - d)/z_{om})(\ln(zh - d)/z_{oh})}{k^2 u_z}$$

where zm is the height of wind measurements (m); z_{om} the roughness length (m) for momentum transfer, approximated by 0.123 × crop height; z_h the height of humidity measurements (m); d the zero plane displacement height (m), approximated by 2/3 × crop height; z_{oh} the roughness length governing transfer of heat and vapor (m), approximated by 0.1 × z_{om}; k = von Karman’s constant = 0.41; and uz = wind speed (m s−1).

Stomatal conductance vs Crop Water Stress Index
when using other more advanced and complex approaches

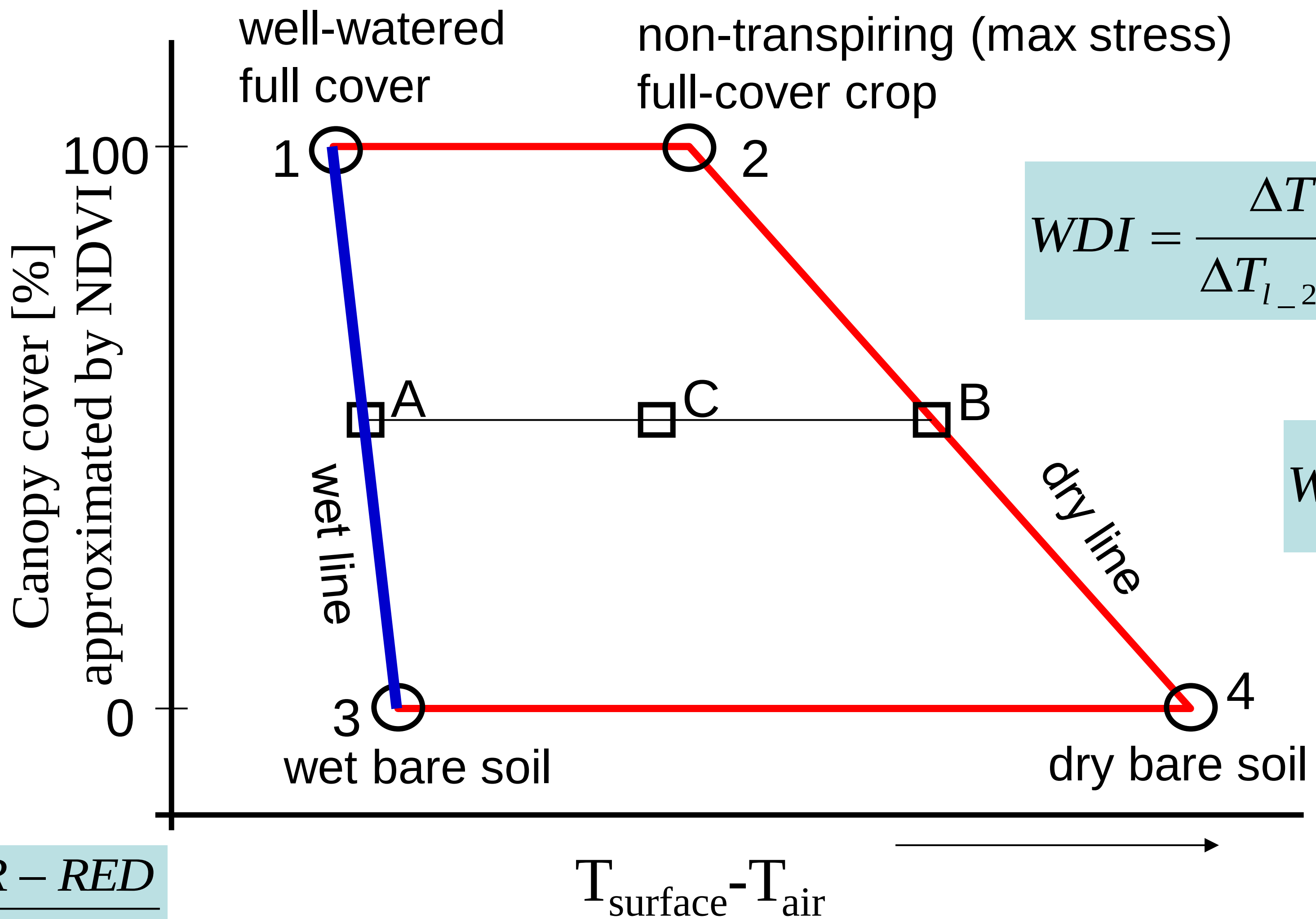




Source: Ben Charfi, 2014

Water Deficit Index (WDI)

when crop does not completely covered the ground



$$WDI = \frac{\Delta T - \Delta T_{l\_1\_3}}{\Delta T_{l\_2\_4} - \Delta T_{l\_1\_3}}$$

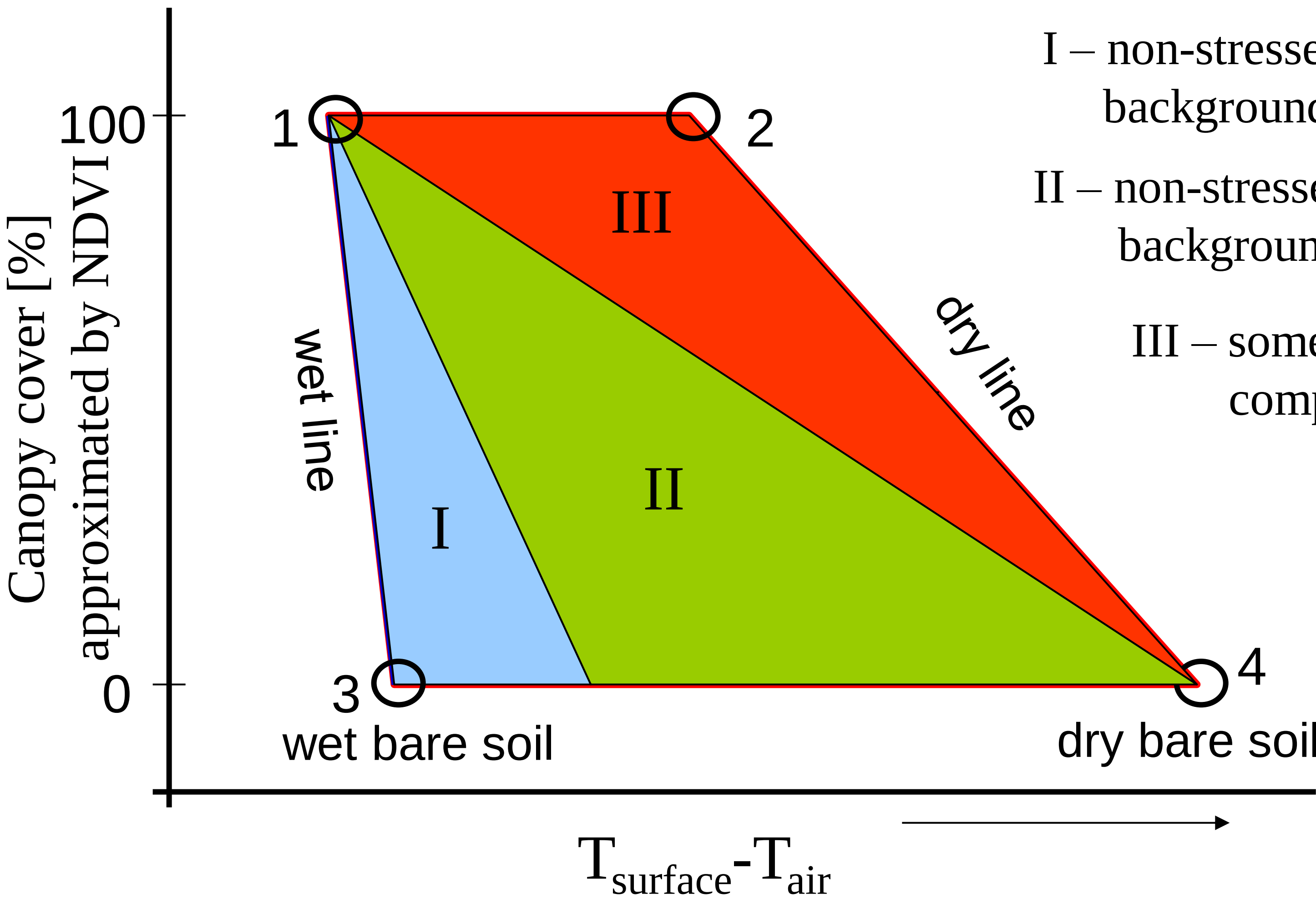
$$WDI = \frac{AC}{AB}$$

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Source: Moran et al., 1994

Example of combination of NDVI & ($T_{surface}$-T_{air})

Water Deficit Index (WDI) ZONES



I – non-stressed plants with a wet soil background

II – non-stressed plants with a drying soil background

III – some degree of water stress and completely dry soil background

$$WDI = 1 - \frac{ET}{ET_{max}}$$

Source: Moran et al., 1994

SATELLITE-BASED IRRIGATION ADVISORY SERVICE

IRRISAT
SATELLITE-BASED IRRIGATION ADVISORY SERVICE

www.eo4water.com

www.irrieye.com

- Types of users:
  - Farmers, small and large scale agri-businesses,
  - Water managers at irrigation scheme or catchment level,
  - Authorities in charge of water management (irrigation consortia, river basin authority, government), National Irrigation Plan Monitoring Office.
- The technological implementation of satellite-based irrigation advisory services needs to find a compromise between the following elements:
  - availability of ancillary input data, with no or minimal contribution from end-users;
  - elaboration and processing time, with minimum possible timelag between E.O. acquisition date and information delivery to final users (less than 24 hours);
  - accuracy of algorithms for deriving crop water requirements, with minimum possible parameterisation.

Source: Vuolo et al., 2015, Agric. Water Manage.

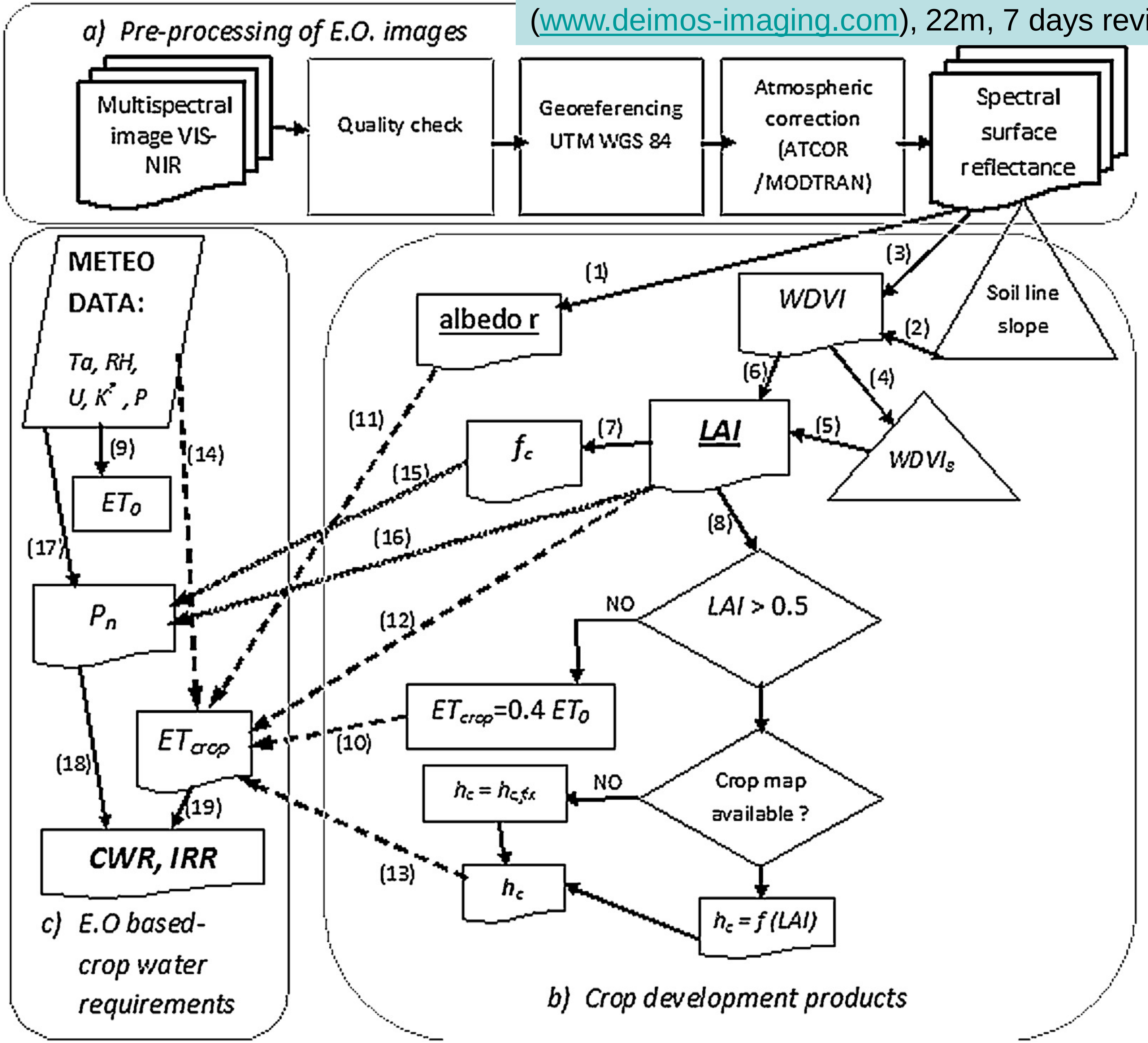
IRRISAT
SATELLITE-BASED IRRIGATION ADVISORY SERVICE

Products delivered to final users

Product characteristics	List of maps or text information	How products support the user needs
Static (updated once per growing season)	• Basic GIS layers (irrigation unit boundaries) (**vector layer**) • Irrigated areas and crop inventory (**maps and/or vector layer, before the end of the season**)	1. Support to visualisation, analysis and data interpretation 2. Control on irrigated areas
Dynamic (Updated with each new satellite acquisition or weekly)	• Colour composites (**maps**) • Leaf area index (LAI) (**maps**) • Crop coefficient (K_c) (**maps and graphical**) • Crop water requirements (**maps and graphical**) • Daily agro-meteorological data (**text and graphical**)	1. Basic agricultural and water planning. 2. Reduction of over-irrigation. 3. Monitoring of crop vigour
Cumulated over time of dynamic data (time interval is flexible)	• Total crop water consumption (e.g. decade or yearly for irrigation scheme) • Statistics and time-series data, graphical information per plot or aggregated to district level based on the irrigation or management unit boundaries (**text and graphical**)	1. Monitoring and control of exploitation plans. 2. Calculate seasonal crop specific crop water use.

Source: Vuolo et al., 2015, Agric. Water Manage.

(www.deimos-imaging.com), 22m, 7 days revisiting time



LAI estimation steps

1. identification of the soil-line slope (ratio of average bare soil reflectance in NIR and red bands $\rho_{s,NIR}$, $\rho_{s,red}$, usually between 0.9 and 1.3);
2. calculation of the Weighted Difference Vegetation Index WDVI by means of Eq.

$$\mathrm{WDVI} = \rho_{\mathrm{NIR}} - \rho_{\mathrm{red}} \frac{\rho_{\mathrm{s,NIR}}}{\rho_{\mathrm{s,red}}}$$

3. identification of WDVI_{∞} in correspondence of pixels with maximum vegetation cover (usually between 0.55 and 0.75);
4. calculation of LAI by means of Eq.

$$\mathrm{LAI} = -\frac{1}{\alpha} \ln\left(1 - \frac{\mathrm{WDVI}}{\mathrm{WDVI}_{\infty}}\right)$$

where α is an empirical shape parameter, mainly depending on canopy architecture, which is determined from field measurements (as shown later, 0.34–0.35 for Italy and Austria and 0.22 for Australia, with prevailing tree crops); WDVI is the Weighted Difference Vegetation Index, and WDVI_{∞} is the asymptotic valued for $\mathrm{LAI} \rightarrow \infty$.

Effective precipitation and fractional vegetation cover estimates

Effective (net) precipitation estimate (Braden, 1985)

$$P_n = P - aLAI\left(1 - \frac{1}{a + \frac{f_c P}{aLAI}}\right)$$

P – measured preciptiation above canopy
Pn – effective (net) precipitation
LAI – Leaf Area Index
a – empirical parameter (~2.8 mm/day for most crops)
f_c – fractional vegetation cover

$$f_c = -0.0038LAI^4 + 0.054LAI^3 - 0.30LAI^2 + 0.82LAI \quad \forall \quad LAI \leq 5$$

Albedo (reflection coefficient) estimates

albedo (r) needed for deriving the net radiant flux in ETc Eq. is an approximation of the hemispherical and spectrally integrated surface albedo; considering the limited spectral resolution of EO data normally available, the albedo is calculated as a weighted sum of surface spectral reflectance ρ_λ derived from the atmospheric correction, with broadband coefficients w_λ representing the corresponding fraction of the solar irradiance in each sensor band (D'Urso and Calera Belmonte, 2005):

$$r = \sum_{\lambda=1}^{n} \rho_\lambda w_\lambda$$

Crop evapotranspiration estimate

Penman–Monteith (P–M) equation as implemented in the FAO-56 procedure (*one-step approach*), herein indicated with "P-M FAO":

$$ET_{crop} = \frac{86,400}{\lambda}\left[\frac{\Delta\,(R_n - G) + \rho c_p\,(e_s - e_a)\,C_a}{\Delta + \gamma\left(1 + C_a/C_s\right)}\right]$$

where ET_{crop} is expressed in $mm\,d^{-1}$ and:λ is the latent heat of vaporisation of water ($J\,kg^{-1}$)Δ is the slope of the saturated vapour pressure–temperature curve $e_s\,(T)$ ($kPa\,K^{-1}$)R_n is the net radiation flux density ($W\,m^{-2}$)G is the heat flux density into the soil ($W\,m^{-2}$)ρ is the air density ($kg\,m^{-3}$)c_p is the air specific heat ($J\,kg^{-1}\,K^{-1}$)($e_s - e_a$) is the vapour pressure deficit (kPa) at the given air temperature $T_a$$C_a$ is the *aerodynamic conductance* for heat transport ($m\,s^{-1}$)γ is the thermodynamic psychrometric constant ($kPa\,K^{-1}$), andC_s is the *surface conductance* ($m\,s^{-1}$), depending on canopy transpiration and soil evaporation.

More about P-M equation will be studied in the upcoming courses

Crop evapotranspiration estimate 2

The two conductance terms C_a and C_s are calculated as the inverse of the resistances defined by Allen et al. (1998):

$$C_a = \frac{k^2 U}{\ln\left(\frac{z_U - d}{z_{om}}\right) \ln\left(\frac{z_T - d}{z_{oh}}\right)} \quad (4)$$

$$C_s = 0.005 LAI \quad \forall\, LAI \leq 4$$

$$C_s = 0.02 \quad \forall\, LAI > 4 \quad (5)$$

In Eq. (4), k is the von Karman's constant (0.41), z_U and z_T are respectively the measurement heights for wind-speed and temperature, d is the zero-plane displacement height and the variables z_{0m}, z_{0h} represent the roughness lengths for momentum and heat respectively being estimated from canopy height h_c (Brutsaert, 1982). Consequently, C_a becomes essentially a function of wind speed and canopy height.

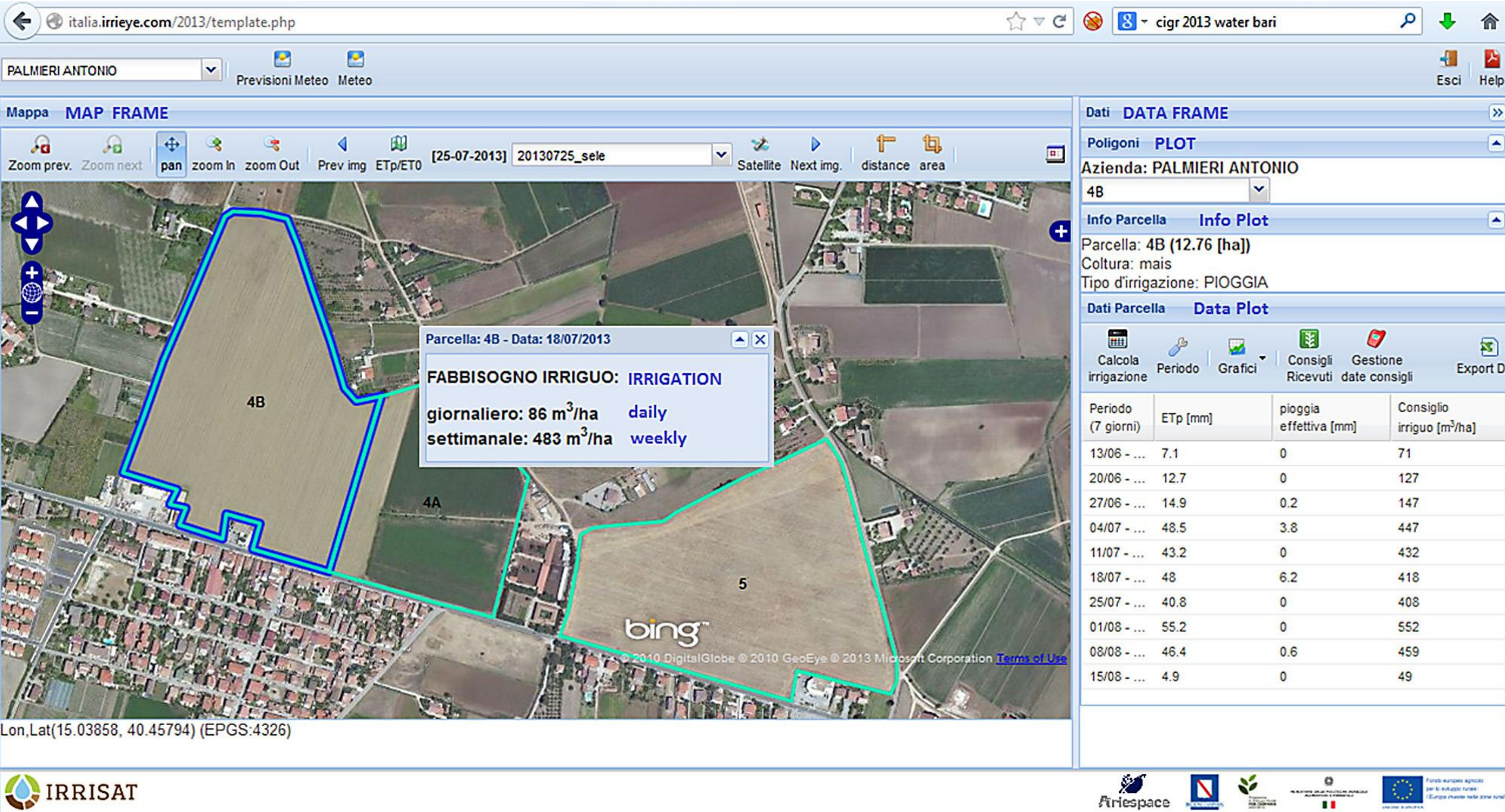
The surface conductance C_s depends on incoming solar radiation, vapour pressure deficit and soil water deficit. Under potential or "standard" conditions, i.e. when soil water availability for transpiration is not limited, C_s can be approximated by Eq. (5); similar expressions can be found in recent studies by Cleugh et al. (2007) and Yan et al. (2012), which can be considered valid for a wide range of irrigated crops.

Minimum data requirements & Reference (grass) evapotranspiration estimate

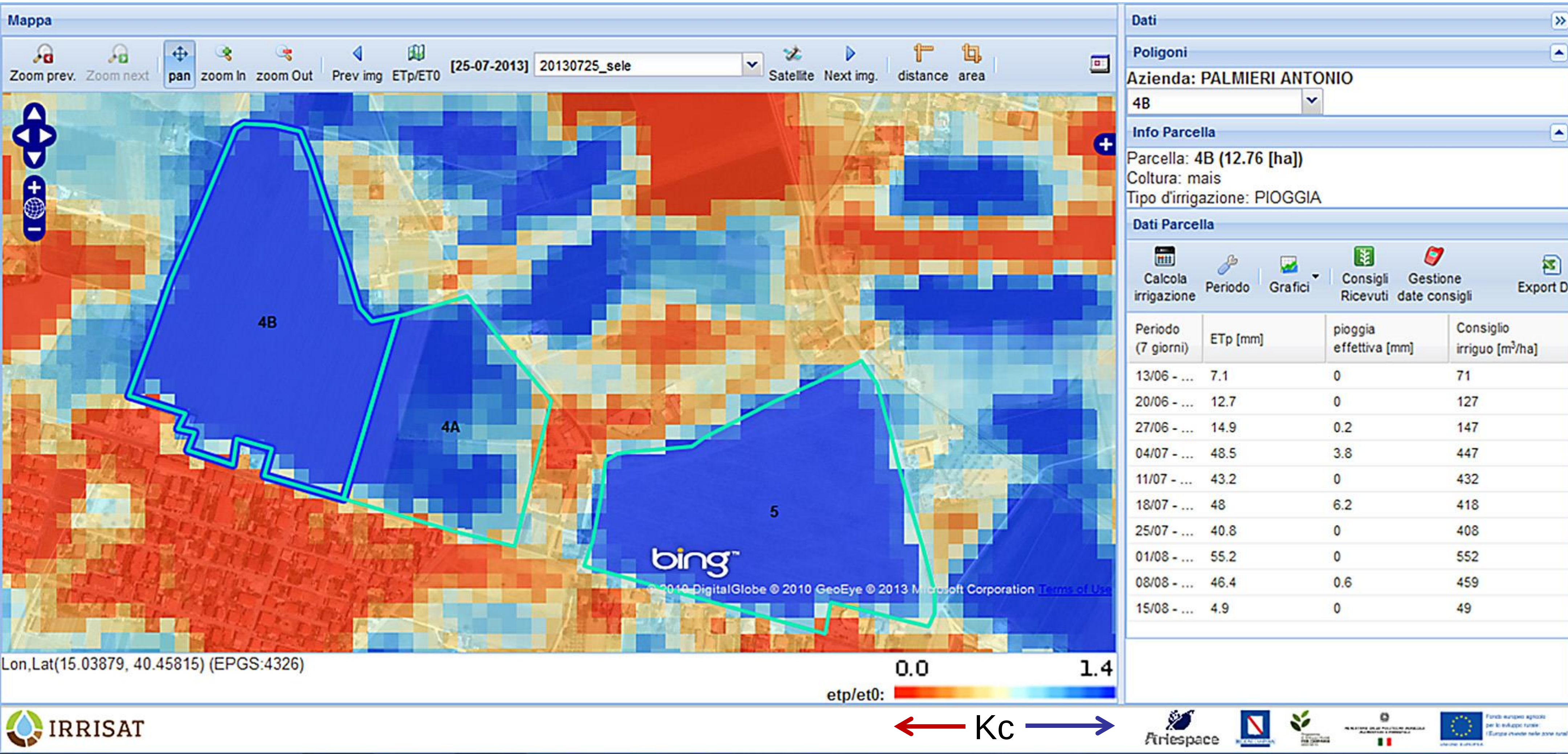
$$\mathrm{ET_{crop}} = \frac{86,400}{\lambda}\left[\frac{\Delta\left(R_n - G\right) + \rho c_p\left(e_s - e_a\right)C_a}{\Delta + \gamma\left(1 + C_a/C_s\right)}\right]$$

The minimum set of climatic data needed for the calculation of Eq. (3) are the air temperature T_a (°C), the relative humidity RH (%), the wind speed U_z ($\mathrm{m\,s^{-1}}$), and the flux density of incoming short wave radiation $K\downarrow$ ($\mathrm{W\,m^{-2}}$). The remaining variables can be either directly measured or estimated from T_a, RH, U and $K\downarrow$ (Jensen et al., 1990). This model considers the canopy as a "*big leaf*", with a surface area expressed by the LAI, a crop height h_c and a hemispherical spectrally integrated albedo r, which is needed to calculate R_n. By using the canopy values for a hypothetical grass reference crop i.e. $h_c = 0.12$ m; $r = 0.23$ and LAI = 2.88, Eq. (3) gives the reference crop evapotranspiration $\mathrm{ET_0}$.

IRRISAT dedicated WebGIS interface for the farmers



ETc/ETo – analytical crop coefficient Kc map overlay (red tones: low values).



Overall cost of the service for the area greater than 3000 ha and 10-11 images is 8-10 €/ha/season

Application of remote sensing I

- **Agriculture:**
  - crop classification
  - estimation of crop yield
  - determination of soil conditions
  - resource management
  - monitoring of the EU Common Agricultural Policy quotas (SPOT)
  - wildlife habitat assessment
- **Land use studies:**
  - land use mapping
  - urban and suburban land use (urban growth)
  - categorization of land capability
  - land degradation and erosion
  - change of land use - map updating
- **Water resources:**
  - determination of water boundaries and surface water areas
  - soil moisture & ET
  - mapping of floods and flooding plains
  - delineation of irrigation fields
  - snow and ice mapping and estimation of snow melt runoff
  - fresh-water reservoirs (lakes) replenishment

Application of remote sensing II

- **Marine environment:**
  - physical, chemical, biological and geological oceanography
  - mapping shoreline changes
  - tracing beach erosion
  - coastal pollution
  - mapping of shallow areas
  - mapping of ice for shipping
  - tracing oil spills and pollutants
  - water quality management
- **Forestry:**
  - forest classification and inventory
  - forest harvest monitoring
  - deforestation and damage (fire) assessment
- **Engineering & Environment:**
  - development of DEM and terrain analysis
  - monitoring effects of man's activities and natural disasters
  - monitoring of water pollution
  - monitoring surface mining and reclamation
  - assessing drought impacts
  - siting for power plants and other industries
- **Geology:**
  - mapping and revision of maps
  - landform mapping
  - mineral exploitation etc.

Applications in water-related issues

- **Remote sensing:**
  - input data for hydrological and crop growth models
  - basis for model parameter estimation
  - application - from field scale ($1km^2$) to the regional scale ($100,000\ km^2$)
  - operational widespread use - land cover & identification of crop species
  - application - precipitation estimates, soil moisture measurements, snow cover assessment, radiation and temperature measurements
  - specially suggested in arid and semi-arid regions (little vegetation to obscure the surface), in flat areas and in areas with no data.
- **Microwave and SAR sensors for hydrology (mounted on aircrafts)**
  - microwave (wavelength of about 21cm) penetrates the surface - soil moisture can be estimated to a depth 5-10 (17) cm

Some priority fields and topics for research

Spatial data input (measurements)	***Multi-scale mapping and inventory***	***Decision Support Models***	***Monitoring and change detection***
• Detecting leaf water content • Temperature measurements (soil, air, crop) • Topography definition • Solar insolation • Soil Moisture • Precipitation estimates • Water resources assessment • Soil characteristics and quality surveys • Biomass and productivity	• Land cover • Crop type identification • Forest location, extent and density • Forest species identification • Post disaster damage detection • Fire risk assessment • Visualisation techniques for multi-source data	• Hydrological management • Irrigation management • Crop management • Regional yield estimate • Crop growth/ yield modeling • Precision agriculture • Fire risk assessment and modeling • Validation and accuracy assessment • Application of Cost /Benefits analysis	• Detecting vegetation stress and damage • Crop area monitoring • Environmental impact assessment

Conclusions

- In the last decade, many GIS have introduced the capabilities for processing remotely sensed data because:
  - remote sensing data have become one of the most important source of information for most GIS based projects
  - raster data structure of remotely sensed images is identical to that used by raster GIS data model which provides an easy integration of data
- The successful use of remote sensing in based on three factors:
  - the presence of distinctive signatures of the land cover classes of interest in the image being classified
  - the ability to reliable recognized these classes in the image, and
  - on-site control and assessment of the accuracy of the results of classification
- The recent studies on the applicability of remote sensing in water-related issues have produced promising results, but much effort is still needed to provide widespread operational use.
- The application of remote sensing and GPS needs highly specialized personnel and use of specific software and hardware facilities