# 3.3 Remote sensing for crop monitoring

## 3.3.1 Remote sensing of crops: the main principles

**Remote sensing** is the technique of acquiring spectral information on an object, typically a piece of earth surface, with a sensor distant from the object, typically on board on a satellite, an airplane, and more recently an UAV.

Remote sensing has been widely used since the seventies to characterize and monitor earth surface and atmosphere and in particular the natural and agricultural vegetation.

**Applied to agriculture, remote sensing techniques** can be **useful for** a variety of **purposes**, among which the main ones are, parcel boundary detection, crop recognition, crop area estimation, and, in the context of precision agriculture, crop growth monitoring, the computation of various soil and crop biochemical and biophysical properties that may induce or be indicative of plant stress that may be used for site-specific management recommendations concerning crop fertilization, irrigation, protection (insect and fungal infestation), weed management, or incorporated into crop yield and production forecasting models.

**Spectral remote sensing** technique is based on the **principle** that the solar electromagnetic radiation (EMR) is either absorbed, transmitted, or reflected by the studied surface, and that the pattern of the reflected part, as recorded by an optical sensor, is directly dependent on the surface properties, i.e. the particular material (vegetation, soil, rock,…), its physical (e.g. plant and canopy structure) and chemical (e.g. plant nitrogen, chlorophyll and water content) state, and can consequently be used for its characterization.

The most relevant **spectral range** for the study of the vegetation consider wavelengths in the [350-2500 nm] range, including the visible (VIS, 380-750 nm), near-infrared (NIR, 750-1400 nm) and a part of the short-wavelength infrared (SWIR, 1400-3000 nm). However, given **atmospheric water vapor** highly disrupt the solar EMR around 1400 nm, 1900 nm and 2500 nm spectral regions, the later are not usable for sensors operating in outdoor conditions (i.e. by satellite or airborne sensors) (Figure 3-a-b-c-e). The thermal infrared spectral range (TIR, 3000-15000 nm) is also used in order to characterize the vegetation surface temperature.

Aside from spectral remote sensing, **RADAR remote sensing**, considering wavelengths in the approximate range of 1 cm to 1 m and self-emitting the energy it uses, can also be useful to characterize vegetation surface, but won't however be considered in this study.

**Spectral remote sensors** can be of 2 types, multispectral, or hyperspectral, though the latter is currently scarcely represented on satellite. While multispectral sensors delivers a few (3 to ~10) broad (~20 to 250 nm wavelength width) spectral bands, hyperspectral delivers a high number (~ 60 to 500) of contiguous narrow (~10 - 20 nm wavelength width) spectral bands.

The variation of reflectance (the reflected EMR/incoming EMR ratio), from a particular land cover with respect to wavelengths constitutes its **spectral signature** (Figure 2) and may enable its differentiation from another land cover type and/or state (Figure 2 and Figure 3).

Healthy **green vegetation** provides a characteristic **spectral signature** (green spectrum in Figure 2) that presents a low reflectance in the **visible** part of the spectrum, also known as the Photosynthetically Active Radiation (PAR), due to a strong EMR absorption used for photosynthesis. In particular, while leaf pigments are responsible for a part of this absorption, with chlorophyll a and b absorbing EMR in the blue (~400-500 nm) and red (~600-700 nm) regions, and carotenoids absorbing EMR in the blue region principally, the green light (500 to 600 nm) is relatively less absorbed, which results in a reflectance peak in the green surrounded by reflectance depressions in the blue and red regions, reason why the green vegetation appears "green". The important reflectance rise in the transition zone between the VIS and the NIR correspond to the so called "**red-edge**" (~680-750 nm). The **NIR** region is characterized by a relatively high reflectance, also known as the "NIR plateau", due to a small EMR absorption and high EMR scattering, which is mainly controlled by structural parameters of the vegetation cells, leaves and canopies (Asner, 1998; Knipling, 1970; Mohammed et al., 2000). The **SWIR** region presents an intermediate reflectance featuring 3 spectral regions (around 1450 nm, 1950 nm and 2500 nm) importantly impacted by water absorption related to leaf water content.

Crop **spectral signature is influenced by a complex interaction of numerous factors,** sometimes interdependent, that relate to crop type and development, management, environmental and measuring conditions (Figure 3).

Evidently, different **crops** may present different spectral signatures (Figure 3-a). This also holds true, but to a lesser extent, for different crop varieties that may differ in phenology timing (early senescing vs stay green), height, or even ability to extract nutrients, to compete with weeds, resist to disease,…

**Crop growth stages** (Figure 3-b) directly condition the canopy closure (ground cover), the proportion of non-photosynthetic background such as soil and litter visible on a remote sensed image, the crop physiological evolution (green till senescent), all of these strongly impacting the crop reflectance. Crop emergence mark the apparition of the green reflectance peak, biomass development contributes to a general reflectance increase in the NIR and SWIR regions, and crop maturity, accompanied by senescence process, result in a general reflectance increase throughout the 350-2500 spectral range, with in particular, in the visible, a relatively more important increase in the red region.

The crop canopy density is often characterized by the **LAI,** the one-sided canopy green leaf area per unit ground surface area (Watson, 1947 in Xavier and Vettorazzi, 2004) (Figure 3-c). Higher LAI contributes to a very clear reflectance increase in the NIR, and to a lesser extent in the SWIR1 (1400-1900 nm), while presenting a very limited and often inconsistent variation in SWIR2 (1900-2500 nm) region. In the visible, while LAI from 0 to ~2 makes the green peak to emerge with a reflectance decrease in the red, LAI > ~2 is often reported as not impacting anymore the visible range (saturation), despite various patterns are found in the literature (Asner, 1998; Darvishzadeh et al., 2008; Daughtry et al., 2000; Jacquemoud et al., 2009).

The **leaf inclination** is another canopy structure parameter highly impacting its spectral response, with planophile leaves presenting higher reflectance in the whole 350-2500 nm spectral range compared to erectophile ones (Punalekar et al., 2016) (Figure 3-d).

Various **crop stresses, nutrients, water or diseases related**, may also considerably impact the crop reflectance. A stressed crop will very typically present a generalized higher reflectance in the VIS induced by a reduction of leaf photosynthetic pigment concentration, particularly chlorophyll, resulting in a reduction of the photosynthetic activity (Ashraf and Harris, 2013). While healthy vegetation presents a lower green reflectance peak corresponding to a darker green, a moderately stressed vegetation often presents an increased green reflectance peak corresponding to lighter green vegetation, and a more severe stress results in a relatively more important reflectance increase in the yellow and red regions, which is responsible for the typical yellowing of stressed crops.

A **nitrogen stressed crop** (Figure 3-e) has the particularity to present a marked lower reflectance in the NIR, mainly due to a lower biomass development, and, in the SWIR, a higher reflectance is observed only in case of important nitrogen deficiency with the SWIR2 showing a more important increase than SWIR1 in some references (Feng et al., 2008; Guo et al., n.d.; Ranjan et al., 2012).

A **phosphorous stress** is reported to result, for some crops, in a purple tint of the leaves, leaf sheathes or stems  (Chen et al., 2014; Osborne et al., 2002a; YARA crop Nutrition, n.d.) which is mainly due to an increase of the production of anthocyanin (Marschner, 1995 in S. L. Osborne *et al.*, 2002) that is responsible for a strong absorption of the green light, while causing very slight or no absorption of the blue and red light respectively.

While a relatively **moderate hydric stress** typically results in a global reflectance increase throughout the 350-2500 nm spectral range compared to well-watered vegetation, along with the attenuation of the water absorption features in the SWIR, a particularly **severe hydric stress** (senescent vegetation) may finally result in a reflectance decrease in the first part of the NIR and reveal, in the SWIR, absorption features related to other leaf biochemical such as protein, lignin and cellulose (Figure 2 and Figure 3-f) (Bayat et al., 2016; Hoffer and Johannsen, 1969; Kokaly et al., 2017; Yu, 2000; Zygielbaum, 2009).

**Diseases** (Figure 3-g) may impact the VIS-NIR-SWIR-TIR spectral range, with, for example, the following behavior observed: a green reflectance decrease and blue and red reflectance stability (Apan et al., 2004), a red increase and blue-green increase or decrease (Mahlein, 2016), a NIR increase (Mahlein, 2016), decrease or stability (Kuska et al., 2015) and decrease (Apan et al., 2004; Muhammed, 2005), a SWIR increase (Apan et al., 2004; Mahlein, 2016), and a TIR increase in (Falkenberg et al., 2007; Nicolas, 2004).

**Measuring conditions** and in particular the **solar and sensor viewing zenith angle** and their **relative azimuth angle**, as well as the **topographic configuration** of the area and related field slope orientation, also strongly impact crop reflectance given its highly anisotropic behavior (Figure 3-h). The relative orientation of **crop rows** is another geometrical parameter that may also impact crop reflectance, depending on the type and development of the crop canopy (space between consecutive rows, canopy closure level and crop height).

**Atmospheric conditions** are another source of reflectance variation, though "atmospheric correction methods" are abundantly used to attenuate their impact.

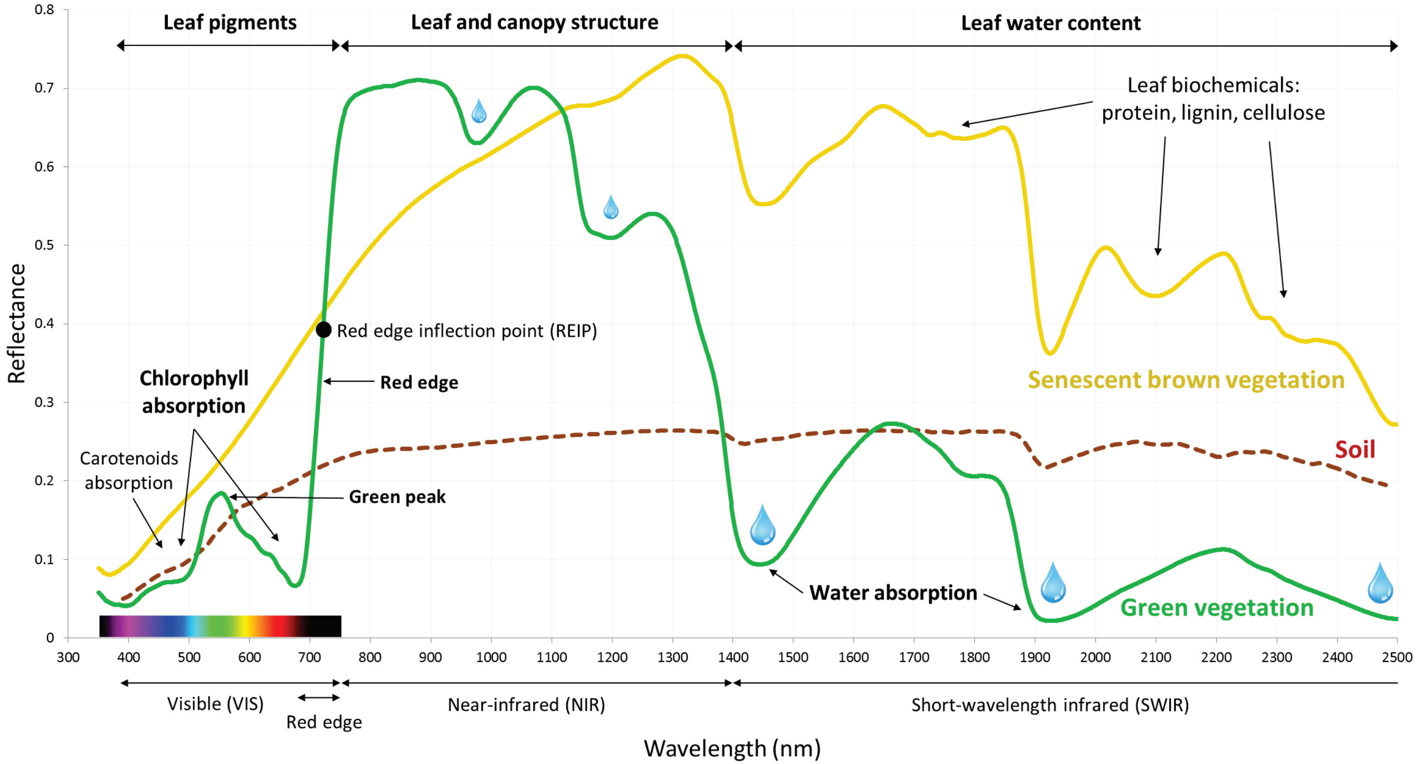


**Figure 2 : Dominant factor controlling leaf reflectance.** Vegetation spectra correspond to bundles of leaves and stems of Spartina alterniflora, a wetland perennial grass, from Kokaly *et al.* (2017). Soil spectrum from Clark (1999). Figure adapted from Kokaly *et al.* (1998), Bowker *et al.* (1985), Curran (1989) and Thenkabail *et al.* (2013).

**Figure 3 : Variation of vegetation reflectance for some parameters.**

(i) Reflectance measured 3 cm above plants of fields of **various crops** (maize, rice, clover and wheat) at maximum vegetative growth stage, adapted from Arafat *et al.* (2013).

(ii) Reflectance measured for a paddy rice field at **several growth stages** (from transplanting to maturity), adapted from Qi *et al.* (2011).

(iii) Canopy reflectance simulated with SAIL model (Verhoef, 1984) for **various LAI**, adapted from Asner (1998).

(iv) Canopy reflectance simulated with PROSAIL model (Jacquemoud et al., 2009) for **various leaf angle distribution** ($LIDF_a$ parameter - Leaf Inclination Distribution Function, values ranging from-1.0 for completely erectophile leaves to 1.0 for completely planophile leaves), adapted from Punalekar *et al.* (2016).

(v) Reflectance measured 1 meter above wheat field canopy at booting growth stage for **various mineral nitrogen (urea) fertilization rates**, adapted from Feng *et al.* (2008).

(vi) Reflectance measured for **maize leaves at various moisture levels** in laboratory, adapted from Hoffer and Johannsen (1969).

(vii) Reflectance measured on barley leaves affected by **various diseases** (net blotch, rust, powdery mildew), adapted from Mahlein (2016).

(viii) Reflectance measured 40 cm above lawn grass canopy for **various viewing zenith angles** in the forward scattering direction of the illumination source principal plane (azimuth angle = 0°), with a 30° illumination zenith angle, in laboratory, adapted from Roosjen *et al.* (2012).

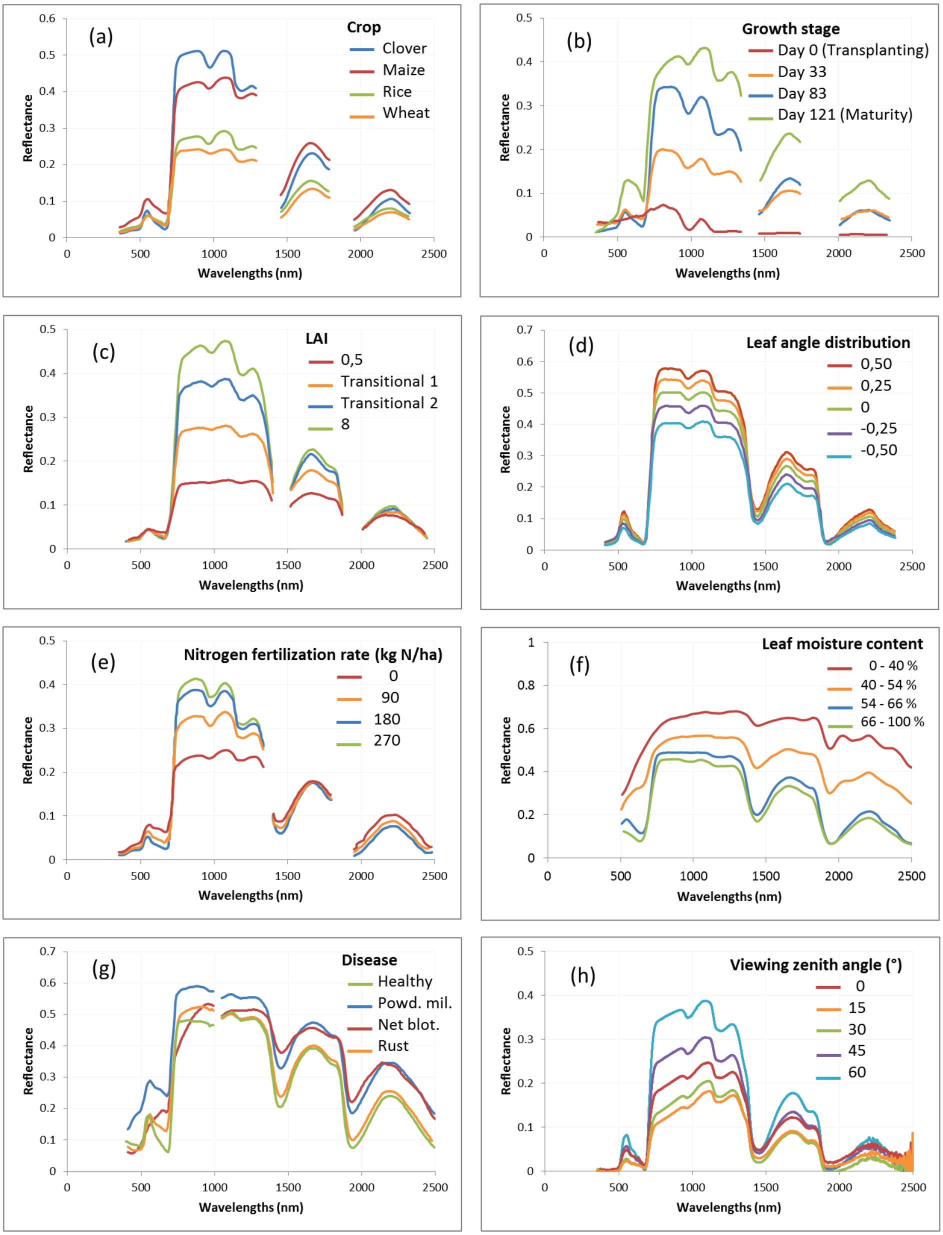


**Figure 3 : Variation of vegetation reflectance for some parameters.**

## 3.3.2 Remote sensing of crop properties

Remote sensing has been used to assess numerous **crop properties** that can be subdivided in 2 main categories, i.e. the **biochemical** crop properties, related to crop chemical elements content, and the **biophysical** crop properties, related to crop biomass and canopy structure as detailed in Alchanatis and Cohen (2012), Gitelson (2012), Roberts *et al.* (2012) and Thenkabail *et al.* (2012).

**Biochemical crop properties** include principally pigments content, i.e. chlorophyll (total, -a, -b), carotenoid, ratio carotenoid/chlorophyll and anthocyanin content, whose relative concentrations will directly impact crop color, nitrogen and crude protein content, content in plant structural materials, i.e. lignin and cellulose, water content and starch content.

**Biophysical crop properties** include ground cover (also called canopy cover, green cover, vegetation fraction, fraction cover (FCOVER)), total or green Leaf Area Index (LAI), specific leaf area (the one-sided area of the leaf divided by the dry weight of the leaf), above ground biomass (wet or dry, total or leaf), canopy volume, plant height, flowering intensity, grain and biomass yield, Fraction of Absorbed Photosynthetically Active Radiation (fAPAR), crop growth stage and phenology.

The **retrieval of crop properties from reflectance** faces **2 major limitations**, i.e. (i) that reflectance generally tend to **saturate** (to be insensitive) at low or high level of a given crop property (e.g. high chlorophyll content), and (ii) that reflectance is the result of a complex interaction of numerous factors that relate to crop type and development, management, environmental and measuring conditions (confer previous section 3.3.1) that may impact the reflectance the same way and may consequently act as **"confounding effects"** in attempt of a specific crop properties retrieval.

The estimation of these crop properties from spectral remote sensing information can be done via 2 distinct approaches: (i) the widely used **empirical statistical modeling**, based on regression between spectral bands or "Spectral Vegetation Indices" (SVI) and the crop properties of interest, or (ii) the less used **physical modeling** which consists in applying Radiative Transfer Models (RTM) based on physical laws.

**Vegetation Indices** (VI) combine the reflectance of 2 or more wavelengths in order to maximize their sensitivity to the biochemical or biophysical crop property of interest while minimizing external variation factors (Daughtry et al., 2000) and often integer a wavelength sensitive to the crop property of interest and another one insensitive. These indices may take the **form** of difference, simple ratio, normalized difference, linear combination, derivative, combination of several indices,...

Table 2 presents a non-exhaustive list of some of the main vegetation indices among the numerous developed ones, regrouped by the vegetation properties for the assessment of which they were initially developed and other specificities.

Early remote sensed vegetation indices were used to identify the wider "**green vegetation**" and its "**condition**". They usually took advantage of the very specific vegetation spectral signature by combining a red spectral band related to the strong EMR absorption by chlorophyll with a NIR spectral band characterized by high reflectance scattering.

Later existing and newly developed VI were used to assess more specific vegetation biochemical and biophysical properties.

Numerous VI are dedicated to the assessment of the **canopy chlorophyll content** which is considered as an indicator of vegetation health, vigor and photosynthetic activity, and also as a proxy for vegetation nitrogen nutrition status and content since leaf chlorophyll content is mainly determined by nitrogen availability (Filella et al., 1995). While VI using the red and NIR spectral bands, such as NDVI, were observed to saturate from very low chlorophyll content, VI indices replacing the red by the green or red-edge, or adding a red-edge to red and NIR spectral bands, showed a higher sensitivity to high chlorophyll content (Dash and Curran, 2004; Gitelson et al., 1996; Gitelson and Merzlyak, 1994). Another challenge of chlorophyll VI is to minimize their sensitivity to LAI, as, according to Daughtry *et al.* (2000), the relatively subtle differences in canopy reflectance associated with changes in leaf chlorophyll are often confounded with major changes in plant growth and development.

A few VI were elaborated for the assessment of other vegetation pigments, and especially the **carotenoids/chlorophyll ratio** which is indicative of the photosynthetic efficiency and chlorophyll degradation induced by senescence or plant stress. Some of these indices combine a spectral band in the 550 - 740 nm spectral range, where reflectance increase with chlorophyll degradation, with a spectral band in the 400 - 500 nm spectral range where reflectance remains low, due to retention of carotenoids (Merzlyak et al., 1999; Peñuelas et al., 1995a).

Vegetation indices used for **LAI** assessment are based on a combination of the red and NIR spectral bands, the later continuing to be sensitive even at moderate-to-high vegetation density (LAI from 2 to 6) in crops (Gitelson, 2004) (Figure 3-c). However, basic LAI index such as NDVI approaches saturation asymptotically under conditions of moderate-to-high aboveground biomass, typically from LAI of 2 or 3 (Gitelson, 2004; Haboudane et al., 2004). Various advanced LAI VI try to minimize the disrupting sensitivity to chlorophyll content while maximizing the sensitivity to high LAI, and often include an additional green spectral band. Nguy-Robertson *et al.* (2012) observed that the combination of VI highly sensitive to Green LAI at low to moderate or moderate to high GLAI ranges enabled to accurately assess GLAI across its entire range of variability.

A series of vegetation indices, also designed for the assessment of the green vegetation, LAI, APAR or chlorophyll content, present the specificity of **minimizing the soil background or/and atmospheric disruptive effects on vegetation reflectance**. Those minimizing soil background effect (impact on reflectance of the non-photosynthetic materials background such as soil and leaf litter) rely on the addition of a "soil brightness correction factor" and are intended to be used in conditions of low vegetation density when ground cover is not complete. The atmospheric correction is based on the principle of using the blue spectral band for correction of the atmospheric effect on the red spectral band (Huete et al., 1999; Kaufman and Tanre, 1992).

Finally a series of indices were specifically developed to assess the **canopy water content**. These indices typically combine a wavelength of the 800-900 nm spectral region of the NIR, relatively insensitive to canopy water content, with another wavelength in the NIR around 970 nm or 1200 nm, or in the SWIR, corresponding to water absorption and consequently sensitive to canopy water content.

Regarding the **relative efficiency of different types of sensors** for crop properties assessment, **hyperspectral** sensors are often found more efficient than **multispectral** ones (Hansen and Schjoerring, 2003; Liu et al., 2012; Thenkabail et al., 2004) due to their narrow and numerous spectral bands, despite equivalent efficiency is sometimes observed as in Goel *et al.* (2003). **TIR** sensors present the disadvantage of being sensitive to ambient temperature and wind speed (Mahlein, 2016). TIR reflectance is reported to either provide an earlier (Falkenberg et al., 2007) or later (Nicolas, 2004) crop disease detection compared to VIS or VIS-NIR reflectance respectively.

## Table 2 : Spectral vegetation indices and their specificity.

| Spectral Vegetation Index (SVI) | Abbreviation | Equation | Reference* | Specificity** | |
|---|---|---|---|---|---|
| Ratio VI<br>Simple Ratio | RVI<br>SR | $\frac{NIR}{red}$ | (Birth and McVey, 1968)<br>(Jordan, 1969) | Vegetation color, LAI | Early green vegetation indices |
| Normalized Difference VI | NDVI | $\frac{NIR - red}{NIR + red}$ | (Rouse, J.W. et al., 1973) | Vegetation greenness | |
| Tasseled Cap green VI<br>Green VI | TCGVI<br>GVI | $-0.2848\, R_{450:520} - 0.2435\, R_{520:600} - 0.5436\, R_{630:690} + 0.7243\, R_{760:900} + 0.0840\, R_{1550:1750} - 0.1800\, R_{2080:2350}$ | (Kauth and Thomas, 1976) | Green vegetation | |
| Difference VI | DVI | $NIR - red$ | (Tucker, 1979) | Green leaf area and biomass, total and green biomass, leaf water content, chlorophyll content | |
| Corrected Transformed VI | CTVI | $\frac{NDVI + 0.5}{\lvert NDVI + 0.5 \rvert}\sqrt{\lvert NDVI + 0.5 \rvert}$ | (Perry and Lautenschlager, 1984) | Green vegetation | |
| Ratio RE3/RE2 | RE3/RE2 | $\frac{R_{740}}{R_{720}}$ | (Vogelmann et al., 1993) | Total chlorophyll content | Chlorophyll content |
| Red Edge Inflection Point | REIP | Red Edge Inflection Point | (Vogelmann et al., 1993) | Total chlorophyll content | |
| Ratio of first derivative D715/D705 | D715/D705 | $\frac{1^{st} derivative\, R_{715}}{1^{st} derivative\, R_{705}}$ | (Vogelmann et al., 1993) | Total chlorophyll content | |
| Greenness I | G | $\frac{R_{554}}{R_{677}}$ | (Zarco-Tejada et al., 2004) | Chlorophyll content | |
| Green NDVI | GNDVI | $\frac{NIR - green}{NIR + green}$ | (Gitelson et al., 1996) | Chlorophyll a content<br>More sensitive to high chlorophyll a content than NDVI | |
| Red Edge NDVI | RENDVI | $\frac{R_{750} - R_{705}}{R_{750} + R_{705}}$ | (Gitelson and Merzlyak, 1994) | Chlorophyll a content<br>Sensitive to high chlorophyll a content | |
| MERIS Terrestrial Chlorophyll I | MTCI | $\frac{R_{753.75} - R_{708.75}}{R_{708.75} - R_{681.25}}$ | (Dash and Curran, 2004) | Chlorophyll content<br>Sensitive to high chlorophyll content | |
| Simple Ratio VI | | $\frac{R_{750}}{R_{710}}$ | (Zarco-Tejada et al., 2001) | Chlorophyll content<br>Minimize effect of shadow and LAI variation | |
| Modified Simple Ratio I | $mSR_{705}$ | $\frac{R_{750} - R_{445}}{R_{705} - R_{445}}$ | (Sims and Gamon, 2002) | Chlorophyll content<br>Compensate for high leaf surface (specular) reflectance | |
| Modified Normalized Difference I | $mND_{705}$ | $\frac{R_{750} - R_{705}}{R_{750} + R_{705} - 2R_{445}}$ | (Sims and Gamon, 2002) | Chlorophyll content<br>Compensate for high leaf surface (specular) reflectance | |
| Chlorophyll Absorption Ratio I | CARI | $CAR_{Canopy}\frac{R_{700}}{R_{670}}$ | (Kim et al., 1994) | APAR, chlorophyll content,<br>Minimize the effect of non-photosynthetic background | |
| Renormalized Difference VI | RDVI | $\frac{NIR - Visible}{\sqrt{NIR + Visible}}$ | (Roujean and Breon, 1995) | fAPAR<br>Minimize soil background effect | |
| Modified CARI | MCARI | $[(R_{700} - R_{670}) - 0.2(R_{700} - R_{550})]\left(\frac{R_{700}}{R_{670}}\right)$ | (Daughtry et al., 2000) | Chlorophyll content | |
| Transformed CARI | TCARI | $3\left[(R_{700} - R_{670}) - 0.2(R_{700} - R_{550})\left(\frac{R_{700}}{R_{670}}\right)\right]$ | (Haboudane et al., 2002) | Chlorophyll content<br>Minimize soil background effect | |
| TCARI/OSAVI | TCARI/OSAVI | TCARI/OSAVI | (Haboudane et al., 2002) | Chlorophyll content<br>Resistant to LAI variation, background and solar zenith angle | |
| Red-edge Chlorophyll I | $CI_{red\text{-}edge}$ | $\frac{R_{800}}{R_{710}} - 1$ | (Clevers and Gitelson, 2013; Gitelson et al., 2003) | Chlorophyll and nitrogen content | |
| Green chlorophyll I | $CI_{green}$ | $\frac{R_{800}}{R_{550}} - 1$ | (Clevers and Gitelson, 2013; Gitelson et al., 2003) | Chlorophyll and nitrogen content | |
| Normalized Difference Nitrogen I | NDNI | $\frac{\log\left(\frac{1}{R_{1510}}\right) - \log\left(\frac{1}{R_{1680}}\right)}{\log\left(\frac{1}{R_{1510}}\right) + \log\left(\frac{1}{R_{1680}}\right)}$ | (Serrano et al., 2002) | Nitrogen content | |
| Simple Ratio VI | | $\frac{NIR}{R_{705}}; \frac{NIR}{R_{555}}$ | (Gitelson and Merzlyak, 1994) | Chlorophyll and other pigments for senescent leaves | |
| Normalized Phaeophytinization Quotient I | NPQI | $\frac{R_{415} - R_{435}}{R_{415} + R_{435}}$ | (Peñuelas et al., 1995b) | Chlorophyll degradation | |
| Simple Ratio VI | | $\frac{R_{695}}{R_{420}}; \frac{R_{695}}{R_{760}}$ | (Carter, 1994) | Plant stress (herbicide induced) | |

**Table 2 (cont.) : Spectral vegetation indices and their specificity.**

| Spectral Vegetation Index (SVI) | Abbreviation | Equation | Reference* | Specificity** | |
|---|---|---|---|---|---|
| Physiological or Photochemical Reflectance I | PRI | $\frac{R_{550\ or\ 570} - R_{531}}{R_{550\ or\ 570} + R_{531}}\ or\ \frac{R_{531} - R_{570}}{R_{531} + R_{570}}$ | (Gamon et al., 1992)<br>(Peñuelas et al., 1995a) | Photosynthetic efficiency, carotenoid | Pigments: carotenoid, chlorophyll, anthocyanin |
| Normalized total Pigment to Chlorophyll a ratio I<br>Normalized Difference Pigment I | NPCI<br>NDPI | $\frac{R_{680} - R_{430}}{R_{680} + R_{430}}$ | (Peñuelas et al., 1993)<br>(Peñuelas et al., 1995a) | Ratio pigment/chlorophyll a<br>Photosynthetic efficiency<br>Affected by leaf structure | |
| Simple Ratio Pigment I | SRPI | $\frac{blue}{red}$ | (Peñuelas et al., 1995a) | Ratio carotenoid/chlorophyll a<br>Affected by leaf structure | |
| Structure Independent Pigment I | SIPI | $\frac{R_{800} - R_{445}}{R_{800} - R_{680}}$ | (Peñuelas et al., 1995a) | Ratio carotenoid/chlorophyll a<br>Minimize leaf structure effect | |
| Plant Senescence Reflectance I | PSRI | $\frac{R_{678} - R_{500}}{R_{750}}$ | (Merzlyak et al., 1999) | Ratio carotenoid/chlorophyll change during leaf senescence | |
| Red Green Ratio I | RGRI | $\frac{red}{green}$ | (Gamon and Surfus, 1999) | Anthocyanin content | |
| Specific Leaf Area VI | SLAVI | $\frac{NIR}{(red + SWIR2)}$ | (Lymburner et al., 2000) | Specific leaf area | LAI |
| Wide-Dynamic Range VI | WDRVI | $\frac{aNIR - red}{aNIR + red}$ | (Gitelson, 2004) | Vegetation fraction, LAI<br>Also sensitive to moderate to high vegetation density | |
| Triangular VI | TVI | $0.5\left(120(R_{750} - R_{550}) - 200(R_{670} - R_{550})\right)$ | (Broge and Leblanc, 2001) | Green LAI and chlorophyll content | |
| Modified TVI 1 | MTVI1 | $1.2[1.2(R_{800} - R_{550}) - 2.5(R_{670} - R_{550})]$ | (Haboudane et al., 2004) | Green LAI<br>Minimize the effect of chlorophyll content | Green LAI - Minimize the effect of chlorophyll content |
| Modified TVI 2 | MTVI2 | $\frac{1.5[1.2(R_{800} - R_{550}) - 2.5(R_{670} - R_{550})]}{\sqrt{(2R_{800} + 1)^2 - \left(6R_{800} - 5\sqrt{R_{670}}\right) - 0.5}}$ | (Haboudane et al., 2004) | Green LAI<br>Minimize the effect of chlorophyll content | |
| Modified CARI 1 | MCARI1 | $1.2[2.5(R_{800} - R_{670}) - 1.3(R_{800} - R_{550})]$ | (Haboudane et al., 2004) | Green LAI<br>Minimize the effect of chlorophyll content | |
| Modified CARI 2 | MCARI2 | $\frac{1.5[2.5(R_{800} - R_{670}) - 1.3(R_{800} - R_{550})]}{\sqrt{(2R_{800} + 1)^2 - \left(6R_{800} - 5\sqrt{R_{670}}\right) - 0.5}}$ | (Haboudane et al., 2004) | Green LAI<br>Minimize the effect of chlorophyll content | |
| Perpendicular VI | PVI | $\frac{1}{\sqrt{a^2 + 1}}(NIR - a\,red - b)$ | (Richardson and Wiegand, 1977) | LAI<br>(Uses the soil background line) | LAI - Minimize soil background effect |
| Soil Adjusted VI | SAVI | $\left[\frac{NIR - red}{NIR + red + L}\right](1 + L)$ | (Huete, 1988) | Green vegetation, LAI<br>Minimize soil background effect | |
| Weighted Difference Vegetation I | WDVI | $NIR - a\,red$ | (Clevers, 1989) | LAI<br>Correcting soil background (particularly soil moisture) | |
| Transformed SAVI | TSAVI | $a\frac{(NIR - a\,red - b)}{(red + a\,NIR - ab)}$ | (Baret et al., 1989) | LAI, APAR<br>Minimize soil background effect | |
| Modified SAVI 2 | MSAVI2 | $\frac{2NIR + 1 - \sqrt{(2NIR + 1)^2 - 8(NIR - red)}}{2}$ | (Qi et al., 1994) | Green vegetation<br>Minimize soil background effect | |
| Optimized SAVI | OSAVI | $\frac{(NIR - red)}{(NIR + red + 0.16)}$ | (Rondeaux et al., 1996) | Chlorophyll content<br>Minimize soil background effect | |
| Soil Adjusted Total VI | SATVI | $\frac{SWIR - red}{SWIR + red + L}(1 + L) - \frac{SWIR2}{2}$ | (Marsett et al., 2006) | Green and senescent vegetation cover<br>Minimize soil background effect | |
| Atmospherically Resistant VI | ARVI | $\frac{NIR - \left(red - \gamma(blue - red)\right)^{***}}{NIR + \left(red - \gamma(blue - red)\right)}$ | (Kaufman and Tanre, 1992) | Green vegetation<br>Resistant to atmospheric effects | Green veg. - Resistant to atmospheric effects |
| Global Environmental Monitoring I | GEMI | $\eta(1 - 0.25\eta) - \frac{red - 0.125}{1 - red}$ | (Pinty and Verstraete, 1992) | Green vegetation cover<br>Reduce atmospheric perturbations | |
| Green Atmospherically Resistant VI | GARI | $\frac{NIR - [green - \lambda(blue - red)]}{NIR + [green - \lambda(blue - red)]}$ | (Gitelson et al., 1996) | Wide range of chlorophyll content, photosynthesis rate, plant stress<br>Resistant to atmospheric effects | |

## Table 2 (cont.) : Spectral vegetation indices and their specificity.

| Spectral Vegetation Index (SVI) | Abbreviation | Equation | Reference* | Specificity** | |
|---|---|---|---|---|---|
| Soil Adjusted and Atmospherically Resistant VI | SARVI | $\frac{NIR-(red-\gamma(blue-red))}{NIR+(red-\gamma(blue-red))+L}$ *** | (Huete et al., 1994) | Green vegetation<br>Minimize soil and atmospheric noise | Green veg. - Minimize soil and atmospheric noise |
| Enhance VI | EVI | $2\frac{(NIR-red)}{(L+NIR+C_1 red+C_2 blue)}$ | (Huete et al., 1999) | Green vegetation<br>Improved sensitivity into high biomass<br>Minimize soil and atmospheric noise | |
| 2-band Enhanced VI | EVI2 | $G\frac{NIR-red}{NIR+\left(\frac{6-7.5}{c}\right)red+1}$ | (Jiang et al., 2008) | Green vegetation<br>Minimize soil and atmospheric noise without blue band<br>EVI without blue band | |
| Infrared I<br>Normalized Difference II | II<br>NDII | $\frac{R_{830}-R_{1650}}{R_{830}+R_{1650}}$ | (Hardisky et al., 1983) | Canopy water content | Canopy water content |
| Moisture Stress I | MSI | $\frac{R_{1599}}{R_{819}}$ | (Hunt Jr and Rock, 1989) | Canopy water content | |
| Normalized Difference Water I | NDWI | $\frac{R_{860}-R_{1240}}{R_{860}+R_{1240}}$ | (Gao, 1996) | Canopy water content<br>For closed green canopy | |
| Water I<br>Water Band I | WI<br>WBI | $\frac{R_{970}}{R_{900}}$ | (Peñelas et al., 1993; Peñuelas et al., 1997; Strachan et al., 2002) | Canopy water content<br>For closed canopy and constant LAI | |
| Floating-position WBI | fWBI | $\frac{R_{900}}{min(R_{930-980})}$ | (Strachan et al., 2002) | Canopy water content | |
| Normalized Multi-band Drought I | NMDI | $\frac{R_{860}-(R_{1640}-R_{2130})}{R_{860}+(R_{1640}-R_{2130})}$ | (Wang and Qu, 2007) | Canopy water content<br>For LAI ≥ 2 | |

**Color code** identifies group of indices with similar specificity (last header column).

**VI** = Vegetation Index; **I**= Index; $\mathbf{R_{xxx}}$ = reflectance in a given wavelength expressed in nanometers; **NIR** = near infrared; **SWIR**= shortwave infrared; **CAR**= Chlorophyll Absorption in Reflectance (~depth of the chlorophyll absorption at 670 nm); **a**, **b**, **L**, **η**, **λ**, **γ**, **G**, $\mathbf{C_1}$, $\mathbf{C_2}$ : confer original papers.

* **Reference**: generally, reference of the first paper mentioning the index.

** **Specificity**: specificity of the index as mentioned in the reference paper (Confer *): the vegetation biochemical or/and biophysical property(-ies) for the assessment of which they were initially developed for and other specificities.

*** Reflectances with prior correction for molecular scattering and ozone absorption.

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