## Chapter 2 – Electromagnetic Radiation

An understanding of proximal remote sensing begins with a consideration of the nature of electromagnetic (EM) radiation and the nature of energy transfer. Energy transfer occurs several ways, as conduction (direct contact), convection (e.g. moved by air or water currents), and radiative transfer (the transfer of electromagnetic energy). It is this last form of transfer that we are primarily concerned with here.

EM radiation has a dual nature, and can be represented both as particles (photons) and as waves. When describing the *intensity* of radiation, we often use the concept of *flux*, the number of photons traversing a unit area in a unit time (Figure 1).
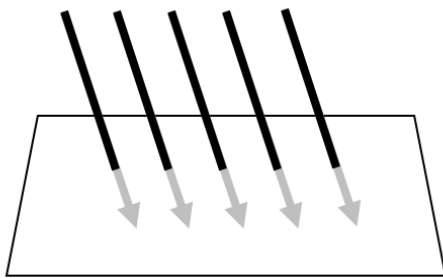
Figure 1.

Flux (of electromagnetic radiation in this case) is a measure of the number of photons traversing a given area in a given amount of time (e.g. µmole photons per square meter per second)

EM radiation can also be represented as a wave (Figure 2), and can be described both by wavelength (λ) and amplitude. The wavelength concept is another way to express the amount of energy, with short wavelengths having high energy (high frequency), long wavelengths having low energy (low frequency). Wavenumber (the reciprocal of wavelength), although less commonly used in spectroscopy, is another way to represent this energy.
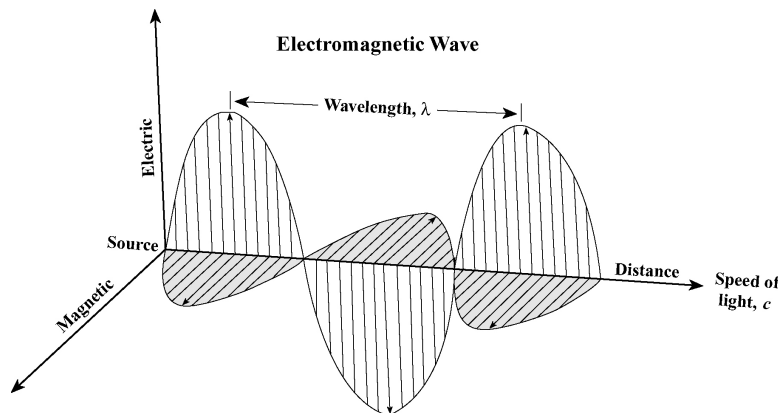
Figure 2.

Depiction of an electromagnetic wave, having both electric (vertical) and magnetic (horizontal) components. The wavelength is given by the peak-to-peak distance (or trough-to-trough distance). Jensen 2007

Wavelength (λ) and frequency (ν) are inversely related by the speed of light (*c*).

$$\lambda = c / \nu \qquad \text{eq. 1}$$

and energy (Q) is related to frequency (ν) by Planck's constant (h = 6.626 x $10^{-34}$ J s), where J indicates Joules and s indicates seconds. Thus, high frequency (high energy) is

associated with smaller wavelengths, and low frequency (low energy) is associated with longer wavelengths.

EM radiation of many wavelengths together constitute a spectrum (Figure 3). A spectrum (plural: spectra) can also be an expression of EM radiation as a function of wavelength. Examples include reflectance spectra (reflectance as a function of wavelength), absorptance spectra (absorptance as a function of wavelength), and absorbance spectra (absorbance as a function of wavelength). Further examples include radiance (in energy units) as a function of wavelength (see Chapter 4 for further discussions of spectra). While spectra can be used to represent other things besides EM radiation, (e.g., sound spectra), here we will primarily be concerned with EM radiation spectra.
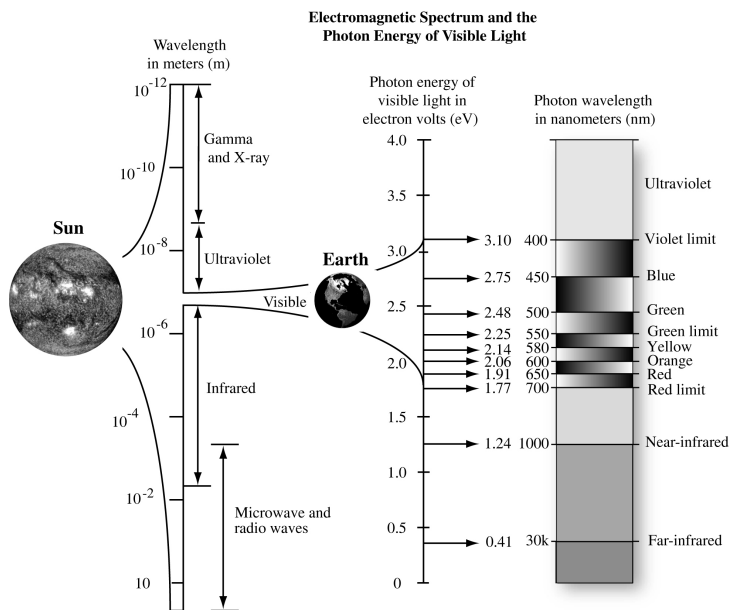


Figure 3.

The electromagnetic spectrum depicted as a scale from high energy (top) to low energy (bottom). The visible spectrum (blue to red, or 400-700 nm), shown on the right, is nested within shorter and longer wavelengths. Visible light (the part the human eye can see and the parts plant use for photosynthesis) is simply a small portion of the total electromagnetic spectrum, and instruments (e.g. spectrometers) can effectively extend our vision beyond the visible range.

### *Solar radiation*

All objects emit EM radiation as a function of temperature. Very hot objects, like our sun, emit large amounts of energy, and cool objects emit relatively little energy. When describing this relationship between temperature and emission, physicists have developed the theoretical concept of a "black body," a perfect absorber with characteristic emission properties. While real objects are never perfect black bodies they often approximate black bodies in their radiative properties. The relationship between a black body temperature and the radiation emitted can be expressed by the Stefan-Boltzmann Law:

$$P/A = \sigma\, T^4 \qquad\qquad \text{eq. 2}$$

Where $P$ indicates the power (total radiant energy) emitted over a given area ($A$), and $T^4$ indicates temperature (expressed in Kelvin, K) to the 4th power, and $\sigma$ is the Stefan-Boltzmann constant ($5.6697 \times 10^{-8}$ W/($m^2K^4$)).

Wien's Displacement Law states that the wavelength of the emission peak ($\lambda_{max}$) is a function of temperature (T, in Kelvin, where K = °C + 273.15):

$$\lambda_{max} = k/T \qquad \text{eq. 3}$$

where k is a constant (2898 μm K). The sun, which has a temperature of approximately 5800K, has a peak wavelength in the visible (400-700 nm) region.

The relationship between an object's temperature, the peak wavelength of energy emitted ($\lambda_{max}$), and the power (P) of that energy is illustrated in Figure 4.
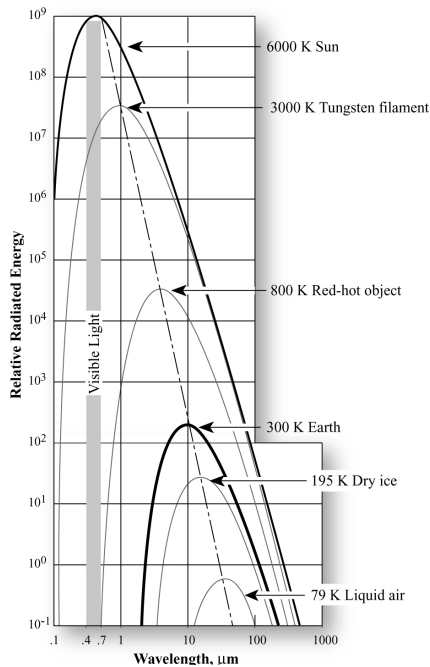


Figure 4.

Illustration of the peak wavelength ($\lambda_{max}$) and the total energy (area under the curve) for objects of different temperatures, according to the Stefan-Boltzmann Law (eq. 2) and Wien's Displacement Law (eq. 3). The tallest curve is for a black body of approximately the same temperature of the sun, so represents an idealized solar spectrum.

Jensen 2007

The actual solar spectrum is not quite the same as that depicted in Figure 4 for several reasons. For one, the temperature is not exactly 6000K, and has varied over the life of the sun. Also, the sun contains a number of gases in its atmosphere that absorb energy in specific narrow spectral bands, causing absorption features in the solar spectrum (Figure 5). The Earth's atmosphere contains further absorption features, primarily due to molecular oxygen ($O_2$), ozone ($O_3$) carbon dioxide ($CO_2$) and water vapor ($H_2O$), causing further deviations from the idealized black-body spectrum. These *greenhouse gases* warm the atmosphere, and cause the solar spectrum to differ from an idealized black-body spectrum. The very narrow absorption features in the solar spectrum due to absorption in the Sun's atmosphere are often referred to as *Fraunhofer Lines* after the physicist Joseph von Fraunhofer, and the absorption features added by the Earth's atmosphere are often called *telluric lines*. Fraunhofer and telluric lines can be useful in proximal sensing both for spectral calibration, and for detecting the tiny signals emanating from chlorophyll fluorescence (Damm et al. 2011).
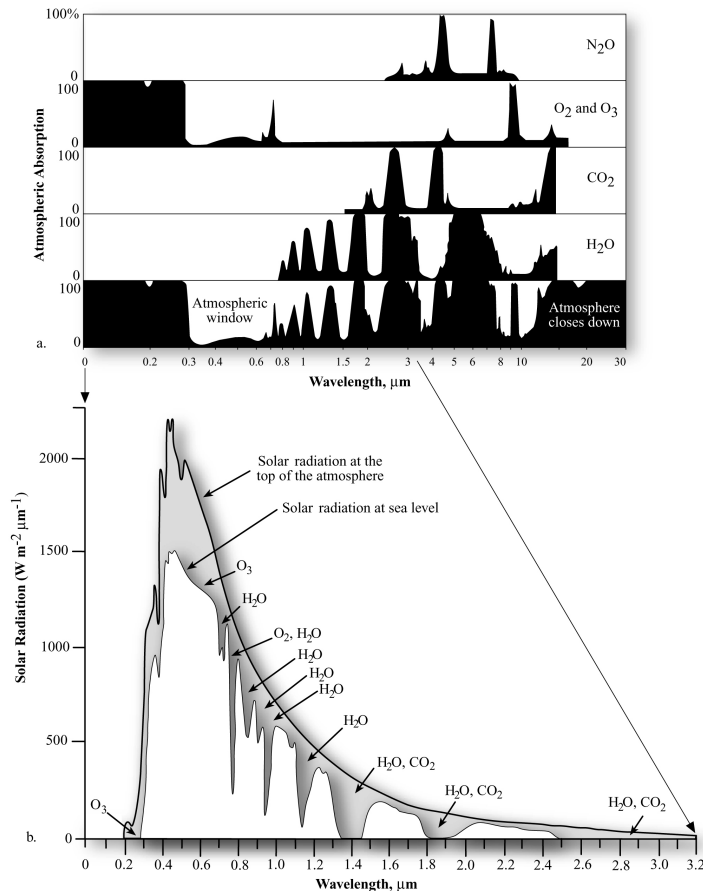
Top: Absorption spectra of various greenhouse gases in the Earth's atmosphere ($N_2O$, $O_2$, $O_3$, $CO_2$, and $H_2O$).

Bottom: Solar spectrum outside the Earth's atmosphere (grey) and at the Earth's surface (white) after absorption by atmospheric gases.

The ability to detect these features, and the exact appearance of this spectrum, is strongly dependent upon instrument spectral resolution (see Chapter 4)

Jensen 2007.

## Interaction with matter

EM radiation interacts with matter in several ways. Many substances absorb EM radiation, and this absorption is often selective for specific wavelengths. When released, radiation is again emitted, often at a slightly longer wavelength than the absorbed radiation (e.g. in the case of fluorescence). When not absorbed, radiation can be scattered in different directions. Backwards scattering is typically called reflection, and forward scattering is often called transmission. A good understanding of these interactions between radiation and matter is fundamental to proximal sensing.

The particle nature of EM radiation can be visualized as a photon (or discrete group of photons) released during orbital transitions (Figure 6). Using the concept of electronic transitions, when an atom or molecule is excited by the absorption of radiation, an electron is momentarily bumped to a more peripheral orbital. If and when the electron reverts to its ground state, a photon is released. The energy of the photon relates to the size of the orbital transition and these transitions lead to absorption features in spectra at particular wavelengths or colors.
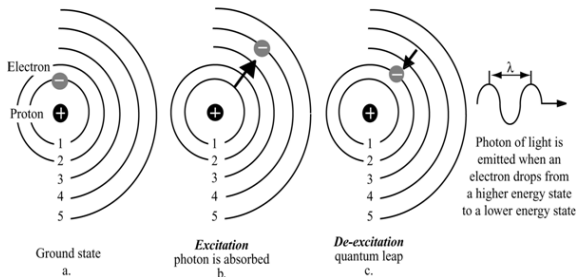
Figure 6. Energy transitions resulting from excitation of an electron to a higher energy state (wider orbital). When the electron returns to the ground state, a photon is released. The energy of a photon (represented as the wavelength, $\lambda$), is directly related to the orbital transitions. Jensen 2007

Sometimes the energy transitions associated with the return of the electron to a lower energy state occurs in such a way that energy is lost to heat (non-radiative transfer) or involves vibrational changes in molecules. In these cases, the energy released is of a longer wavelength (lower energy) than the excitation energy, as happens when pigments fluoresce. Chlorophyll *fluorescence* is an example of such a delayed energy transfer, where visible light is absorbed, and then released a short time later as red- or near-infrared radiation, a so-called "red shift, also known as the Stokes shift (Porcar-Castell et al. 2014).

In addition to characteristic spectral features resulting from these discrete energy state changes, we can also see subtle absorption features in spectra resulting from changes in vibrational state. For example, vibration of -OH groups in water and many organic compounds lead to absorption features in the infrared spectral regions (Ustin and Jacquemoud 2020)
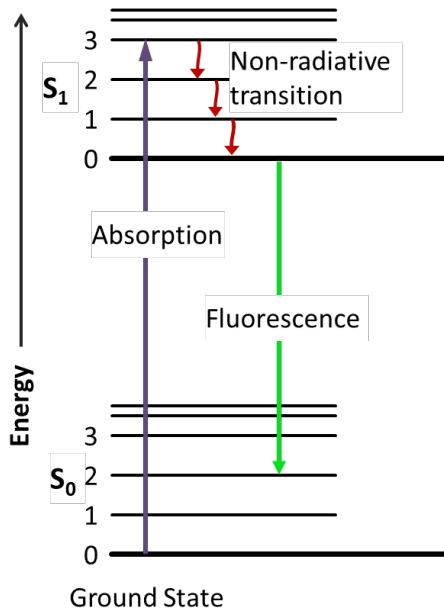


Figure 7.

When electrons return towards the ground state, energy can be released as heat (non-radiative transition) and fluorescence, as shown in this Jablonski diagram. In the case of fluorescence, the amount of energy released is smaller than the initial energy absorbed, and this involves a spectral shift (Stokes shift or red shift). For this reason, fluorescence emission always occurs at a longer wavelength than the original energy absorption (Porcar-Castell et al 2014).

https://en.wikipedia.org/wiki/Jablonski_diagram

The particle nature of EM radiation can also be seen in the photoelectric effect, where a charge-coupled device (CCD) absorbs a photon, and that photon is converted to

electricity by the emission of an electron.  This principle is at the core of many optical detectors, including the CCDs present in many spectrometers.

## *Atmospheric Effects*

In addition to the effects of greenhouse gases (Figure 5), the Earth's atmosphere modifies the solar spectrum in various other ways.  A primary means is through scattering by particles of various sizes.  Non-selective scattering occurs by large particles that scatter all wavelengths similarly.  Mie scattering results from particles such as water vapor, smoke, dust or other aerosols that are about the same size as the wavelength of the radiation. Mie scattering is non-selective, meaning all colors of light are scattered equally, as when white clouds scatter sunlight.

Rayleigh scattering is a form of selective scattering that results from particles (e.g., nitrogen and oxygen gas molecules) smaller than the wavelength.  Rayleigh scattering occurs primarily at shorter (blue) wavelengths, which is why the sky often appears blue (Figure 8).  Rayleigh scattering also explains why the midday sun appears yellow and the setting sun often appears red, as blue light is preferentially scattered away from the light path.
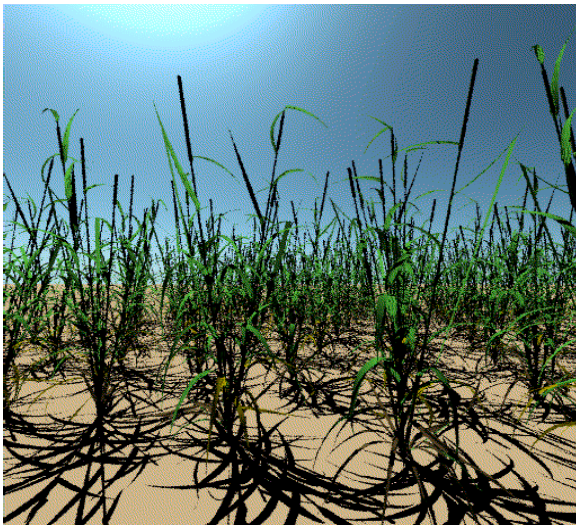


Figure 8.

Blue skies are the result of Rayleigh scattering by small molecules in the Earth's atmosphere. The green color of plant leaves is due to the differential absorption of blue, green and red light by plant pigments (primarily chlorophyll). Since chlorophyll absorbs better in the blue and red than in the green, green light is scattered (reflected and transmitted) more, causing most healthy plants to appear green. At the same time, chlorophyll fluorescence is occurring, but invisible to the naked eye because of the large amount of scattered solar radiation.  Depending upon conditions, we may perceive these effects as different colors.

## *Plant pigments*

Plants contain many pigments, which absorb solar energy, primarily in the visible region (400-700 nm, Figure 9). Our eye pigments are derived from plant carotenoid pigments, which is one reason why humans see wavelengths of light similar to those that plants use for photosynthesis. The several pigment groups together absorb light more effectively than any one pigment alone.  It is the light *not* absorbed (but scattered) that yields the characteristic colors to plant tissues.  For example, healthy leaves look green because green light (550 nm) is not absorbed as well as blue (450 nm) or red (650 nm) by chlorophyll (Figure 9).  Spectral patterns of absorption or scattering (reflection or

transmission) can be useful in diagnosing the composition, overall health, and physiological performance of vegetation.  Usually, these quantities are normalized to incident irradiance and expressed as absorptance (or absorbance), reflectance and transmittance (see also Chapter 4 – Sampling Considerations, for a discussion of absorptance, reflectance and transmittance).
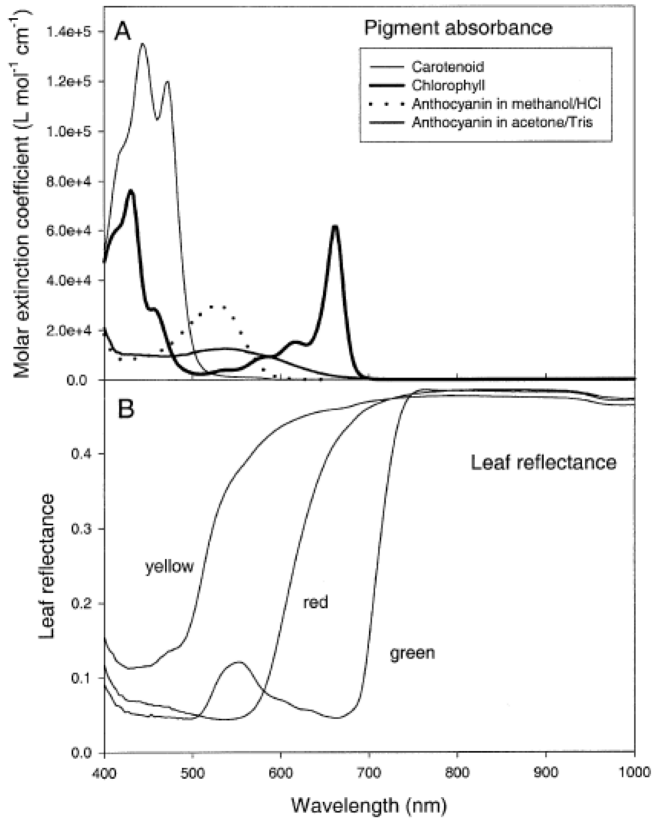


Figure 9.

Absorbance spectra of plant pigments in solution (top) and reflectance spectra of the same pigment groups (by color) in intact leaves. The dips in the reflectance spectra roughly correspond to the peaks in absorbance for different pigment classes.  The multiple scattering of intact leaves has the effect of broadening the pigment absorption and reflectance spectra (b) relative to isolated pigments (a).  The chemical medium (e.g. solvents used) further modify the spectra from the native spectra in the leaf.

Sims & Gamon 2002

### Beer-Lambert Law

The *Beer-Lambert Law* (often called *Beer's Law*) defines *absorbance* (*A*), and relates it to the amount of absorbing material.  Beer's Law is commonly used to quantify a number of substances, including plant pigments.. According to Beer's Law, the absorbance (*A*) is directly proportional to the optical depth ($\tau$) of the medium.

$$A = f(\tau) \qquad\qquad (eq. 1)$$

And the absorbance (*A*) is related to the negative log of the transmittance (*T*):

$$A = -\log T \qquad\qquad (eq. 2)$$

where transmittance ($T$) is the ratio of the exiting light intensity ($I_t$) to the incident light intensity ($I_i$). Absorbance* can be expressed as the negative log of ratio of the exiting light intensity ($I_t$) to the incident light intensity ($I_i$)

$$\text{Absorbance} = -\log( I_t / I_i). \qquad \text{(eq. 3)}$$

Beer's Law helps explain many optical properties of absorbing media, including the atmosphere, liquids, and leaves arranged in a plant canopy, and can be used to quantify the amount of a substance in a non-scattering liquid or gas medium. Beer's Law states that the attenuation of radiation occurs *exponentially* with depth (or optical path length) in the medium. Thus, it takes little chlorophyll, or few leaf layers in a canopy to absorb most of the radiation, which is why leaves and canopies absorb so much radiation, particularly in the blue and red regions.

Beer's Law can be modified to quantify the concentration of an absorbing substance according to:

$$A = \varepsilon\, Lc \qquad \text{(eq. 4)}$$

Where, $A$ is absorbance (measured as $-\log( I_t / I_i)$), $\varepsilon$ is the molar absorption (attenuation or extinction) coefficient for the particular substance of interest, $L$ is the pathlength, and $c$ is the concentration of the absorbing substance. This basic relationship is routinely applied in spectrophotometry and is the basis for laboratory quantification of many liquid substances and is illustrated in Figure 10. Note that this application of Beer's Law assumes a non-scattering solution, usually obtained by filtering or centrifuging the solution prior to measurement.
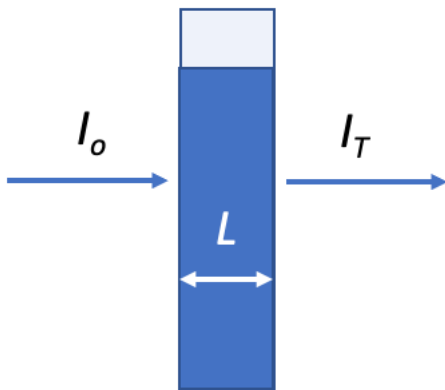


Figure 10 – Schematic illustrating a cuvette containing a solution of unknown concentration ($c$) and molar absorption coefficient $\varepsilon$. If the absorption coefficient ($\varepsilon$) for a particular substance is known, then the absorbance (A) concentration ($c$) of that substance can be calculated from measuring the intensity of the incident ($I_o$) and transmitted ($I_T$) light at a particular wavelength. Note that this relationship is wavelength-dependent (not shown).

Beer's Law can be applied to bodies of water, the atmosphere, or plant canopies to relate the concentration (e.g., algal concentration, gas concentration, or density of vegetation). In nature, scattering is nearly ubiquitous, so modifications to Beer's Law are typically made to account for scattering. In this case, we are adapting a theoretical construct to the

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* Note that absorbance is not the same as absorptance. See Chapter 5.

real world, which often requires a detailed characterization of optical properties of the medium for this adaptation to yield accurate results.

According to the basic physics of Beer's Law this absorption by pigments or leaves is non-linear. Due to this non-linearity, the blue and red spectral regions that align with the peak pigment absorption spectra (Figure 9) are poor *bands* (spectral regions) for assessing pigment content. This is particularly true for the blue region, where strong absorption by chlorophyll is further confounded by the absorption of other pigments (carotenoids and anthocyanins) (Figure 9).  Because chlorophyll absorbs so well in the blue and red that reflectance (or transmittance) in the center of these bands makes a poor chlorophyll index.  By contrast, band *edges* (such as the *red edge* around 700-750 nm, where absorption coefficients are weaker, Figure 9) often make better pigment indices (Sims and Gamon 2002).  Similarly, vegetation indices (such as the Normalized Difference Vegetation Index, NDVI) that utilize reflectance in the red band tend to be non-linear with the amount of absorbing material (green leaf area index or canopy biomass), revealing a fundamental property of how radiation often interacts with matter in a non-linear fashion, approximating Beer's Law (Gamon et al. 1995).  This property is often considered a "failure" or weakness of NDVI when, in fact, it simply reveals that plant canopies tend to obey the laws of physics.  However, because plants are complex biological systems, they often seem to obey physical laws very badly, and we need to adjust our theoretical constructs and model assumptions accordingly.

### *Canopy radiative transfer*

Beer's Law describes the attenuation properties of pigments in solution and can be provide a useful approximation for how radiation is transferred through plant canopies.  If we can assume that plant leaves are randomly oriented (forming a homogenous medium) with simple scattering (a non-turbid medium), then a Beer's Law approximation can be applied, and we can approximate the radiation transfer through a plant canopy with a few very simple equations that are at the core of several of the simple plant radiative transfer models (e.g. SAIL, Verhoef 1985).  However, plant leaves are not ideal absorbers and often exhibit complex scattering behavior.  For example, plants do not orient their leaves randomly, but instead move in very specific ways as plants grow and respond to their environment.  Similarly, many plants exhibit chloroplast movements that further confound the assumptions of simple physically-based radiative transfer models. As a result, plant canopies scatter radiation in complex and dynamic ways that are hard to represent mathematically.  The very peculiar dynamic behavior of living plants that makes them so interesting also makes modeling plant optical behavior challenging.  This is one reason why good empirical measurements, the focus of the next chapter, remain important.

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