Chapter 6
Sensing of Crop Properties

Hermann J. Heege and Eiko Thiessen

Abstract Sensing of crops by visible and infrared reflectance allows estimating the chlorophyll concentration within leaves as well as the leaf-area-index. The product of the chlorophyll concentration within leaves and the leaf-area-index supplies the chlorophyll content per unit field area. Recording this criterion repeatedly during the season provides reliable estimates of the site-specific yield potential as based on past growing conditions.

Fluorescent light too can sense the chlorophyll concentration within leaves or the functioning of the photosynthetic apparatus of crops. Infrared reflectance as well as thermal radiation can be used to get information about the site-specific water supply of crops. From the backscatter of radar waves, information about the biomass, the leaf-area-index and especially about the crop species for vegetation classification within large agricultural areas can be obtained.

Proximal sensing from farm machines allows direct site-specific control of farm operations in real-time. On the other hand, remote sensing from satellites lends itself for repeated recording of fields or larger areas during the growing season. Yet remote sensing needs radiation that can penetrate the atmosphere.

Keywords Chlorophyll sensing • Fluorescence sensing • Infrared reflectance • Sensing by microwaves • Visible reflectance • Water sensing • Yield sensing

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6.1 Basics of Sensing by Visible and Infrared Reflectance

Crop properties often vary even more than soil properties do. This is, because they depend not only on the respective soils but on many additional factors as well such as microclimate, species, variety, growth stage, farming operations, nutrient supply, weed competitions and pest infestations. It certainly is useful to know, which factors are responsible for differences in crop development. Yet before such questions can be pursued, temporal and spatial differences in crop growth must be identified. And for doing this on a site-specific basis with a sufficiently high resolution – similar to the situation with soil properties – sensing via electromagnetic radiation offers challenging opportunities.

There exist fundamental differences in the **temporal variation** or stability of crop properties compared to most soil properties. The most important soil properties such as texture, organic matter content and cation-exchange-capacity often vary spatially, yet remain rather constant during a growing period. The sole exception to this is the water content of soils. But the main crop characteristics – such as biomass, structure of plants and ingredients – change steadily while a crop develops. Consequently for crop properties, the respective time of sensing is very important as it is for soil water.

Sensing of crop properties by means of electromagnetic radiation predominantly relies on **reflectance**. Theoretically, it could be based on transmittance or even absorbance as well. However, both the transmitted- and the absorbed radiation cannot easily or not at all be recorded on-the-go via proximal sensing by farm vehicles or via remote sensing from aerial platforms or satellites.

But it should be realized that the reflectance itself depends heavily on the absorbance as well as on the transmittance. This is because irradiance (= incident radiation) that is absorbed or transmitted is not available any more for reflection.

From visible radiation that hits healthy and growing plants, the dominant part is absorbed for **photosynthesis** (Fig. 6.1, left). Consequently, both the reflectance and the transmittance are rather small in this part of the spectrum. However, there are differences within the visible region. The reflectance is smaller in the blue and in the red part than in the green range. Because the blue and especially the red light are better suited for photosynthesis. The higher reflectance in the green range causes the color of growing crops.

When dealing with crops, the **near-infrared range** from 700 to 2,500 nm is subdivided. Because the lower part of this range – 700 to 1,300 nm – has an extremely low absorbance and consequently a very high reflectance and transmittance. And contrary to this, the upper part of this range has regions of very high absorbance by water and thus low reflectance and low transmittance (Figs. 6.1 and 6.2). Therefore with crops only the lower part from 700 to 1,300 nm is denoted as near-infrared, whereas the upper part from 1,300 to 2,500 nm is named **shortwave-infrared**. The inconsistency in definition when dealing with soils (Table 5.4) or crops might be confusing. The respective wavelength range must be noted.

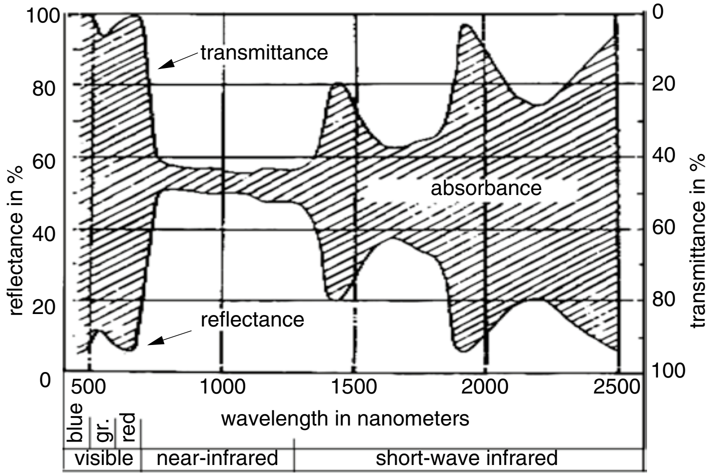


Fig. 6.1 Reflectance and transmittance spectra of wheat leaves (variety: Talent) in the visible and infrared range. The *shaded part* is the absorbance. The latter plus the reflectance and transmittance add up to respectively 100 % (From Guyot 1998, altered)

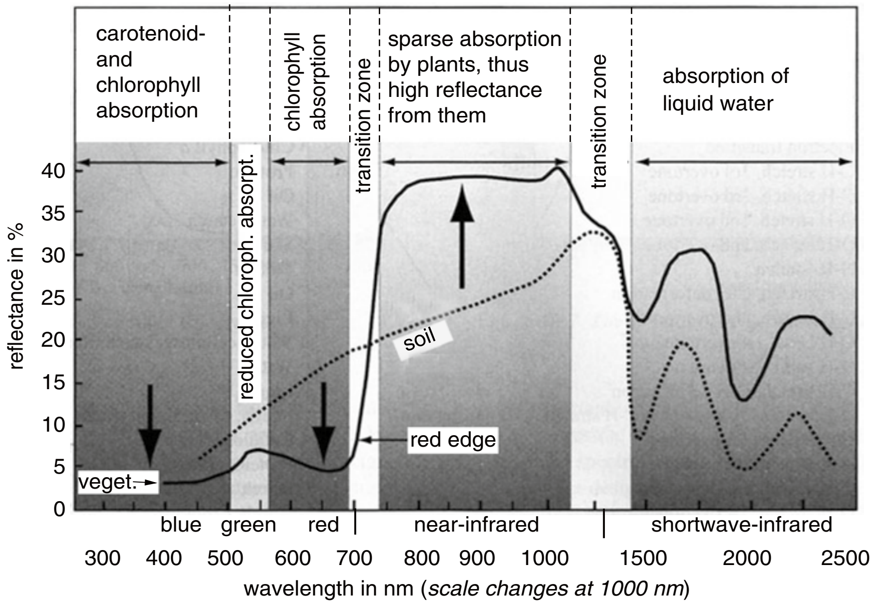


Fig. 6.2 Reflectance spectra of vegetation and soil in the visible-, near-infrared and shortwave-infrared range (From Jensen 2007, altered)

When regarding the general course of the spectra that are reflected from soil or from vegetation, some distinct differences show up (Fig. 6.2). The reflectance from soils increases rather steadily and uniformly with the wavelength in the visible and near-infrared range. Contrary to this, the reflectance of plants in the visible regions is defined by the absorbance for photosynthesis and hence is below that of soil. Yet within the near-infrared range, the absence of absorbance for photosynthesis allows a multiplication of the reflectance from crops. The result of this is a steep rise of the reflectance in the transition zone from the visible to the near-infrared radiation. This steep rise in the reflectance is generally known as the "**red edge**" because it is located between the visible red- and the near-infrared radiation.

However, the curves of the spectra in Fig. 6.2 represent **average situations** just in order to show the principal differences in reflectance between soil and vegetation. In detail, the reflectance spectra of soils differ according to texture, organic matter and chemical constituents (Fig. 5.23). And those of vegetation too depend on type, ingredients and chemical composition. The sensing possibilities by means of reflectance rely on these differences.

The most important differences for vegetation result from biomass and chlorophyll. The **biomass** always has been a very significant criterion for defining the development of a crop. For forage crops, the total aboveground plant mass is utilized, hence the biomass in t per ha as well as its ingredients are of interest. With grain crops, the main objective is not the total aboveground biomass but mainly the reproductive part of it. Yet for all crops, the leaf area is important since photosynthesis takes place in the leaves. Consequently the **leaf-area-index** of crops is a significant criterion in order to assess the development. It is defined as the relation between the photo-chemically active, one-sided leaf area and the ground surface. In a simplified way, the leaf-area-index shows how much "factory space" for photosynthesis a crop supplies. Depending on the development stage, species, variety and growing conditions, the leaf-area-index can vary widely. Starting with 0 (zero) before emergence, it can go up to 8 (eight) for well developed, lush grain crops before the ripening process begins.

Within the leaves, **chlorophyll** is the essential driver of photosynthesis and hence of plant production. Hence information about the leaf-area-index must be supplemented by data about the chlorophyll concentration within the leaves, which can be defined by the mass of chlorophyll per unit of leaf area.

So knowledge about the separate effects of chlorophyll on the one hand and the leaf-area-index on the other hand on reflectance spectra is helpful. These effects can be shown separately by using simulation models that have been developed by Verhoef (1984) and Jacquemoud and Baret (1990). Looking at the results from these simulation models (Fig. 6.3), it is obvious that the effect of the chlorophyll per unit leaf area is restricted to wavelengths below the red edge. Above this edge, the chlorophyll per unit leaf area does not affect the reflectance. But in the visible region, the reflectance is the lower, the higher the chlorophyll concentration per unit leaf area is.

Contrary to this, the effect of the leaf-area-index mainly is above the red edge inflection point in the near-infrared range. The reflectance here increases very

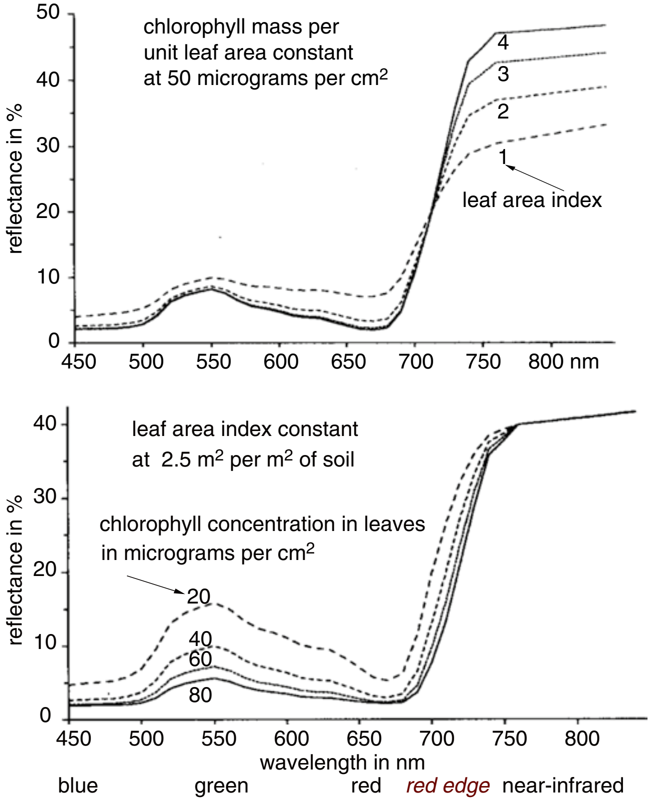


Fig. 6.3 Reflectance of plants depending on either the leaf-area-index (*top*) or on the chlorophyll concentration in the leaves (*bottom*). The curves are based on simulation models. For the *top graph*, the chlorophyll mass per unit leaf area is constant. Vice versa, for the *bottom graph*, the leaf-area-index is constant (From Reusch 1997, altered)

clearly with the leaf-area-index. In the visible region, more leaves generally result in some decrease of reflectance because – even if the chlorophyll content within single leaves is constant – this improves the absorbance. However, the effects of either more leaves or of more chlorophyll within the leaves in the visible range are not the same: more leaves mainly reduce the reflectance in the red part, whereas more chlorophyll lowers it in the green region (Fig. 6.3).

The visible and near-infrared reflectance from both sides of the red edge lends itself for differentiating between soil and plants. Because within this range, the reflectance for soil increases slowly and steadily, however, for vegetation or crops it rises drastically (Fig. 6.2).

Hence the relation between red and infrared reflectance can be used as an **indicator of a vegetation cover** within a field (Fig. 6.4). This holds despite the fact that in a strict sense the reflectance of a bare soil within a field might not be constant as a

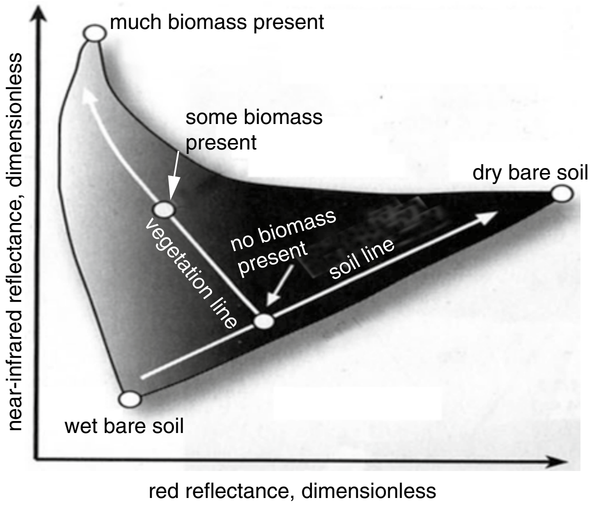


Fig. 6.4 The site-specific significance of red and infra-red reflection within a heterogeneous field. The *black* and *gray shaded* field is bare along the *lower side* but covered with plants in the *upper region*. The soil line extends within bare soil from a wet area into a dry region. The vegetation line goes from bare soil into areas that are progressively vegetated (From Jensen 2007, altered)

result of varying water content, texture, organic matter content and iron content (Fig. 5.23) and that the reflectance of vegetation too can vary (Fig. 6.3). Because in most cases, the general effect of vegetation on the reflectance is much more pronounced than the differences that result from varying soil- or plant properties. The **soil line** and **vegetation line** concept as defined by the red- and near-infrared reflectance in Fig. 6.4 result from this. However, the soil line and vegetation line concept can only supply for a very rough survey in order to differentiate between bare ground and plants.

A more detailed explanation about crop properties requires an analysis of the canopy reflectance curve either while relying on a **full spectrum** approach or on the basis of **discrete wavebands**. A full spectrum analysis might be reasonable if sensing of several crop properties simultaneously is aimed at, *e.g.* biomass, water and nutrients. The techniques that are needed for such multiple crop property sensing are still in a developmental stage. This holds especially for the data processing. On the other hand, discrete waveband sensing lends itself mainly for single or dual crop property recording. Applications for this are in a feasible stage and dealt with in the next section.

6.2 Defining the Reflectance by Indices

The easiest method to get information about vegetation is to create a **simple ratio** of the near infrared to red reflectance, *e.g.* with centres of the respective wavebands at 800 and 670 nm (Figs. 6.2, 6.3 and 6.4). Such **near infrared to red indices** with the formula $R\,800/R\,670$ can be used for differentiating between soil and vegetation within a field by "**green seeking**" in order to obtain **spot spraying** instead of treating the whole area including bare soil. Thus for chemical weed control in a fallow field, a site-specific application of herbicides only in areas – where really weeds stand – is possible. Regions that are free of weeds are not treated.

A similar control system that can detect the weed infestation within a vegetated field relies on sensing the vegetation within the tracks of tramlines. This concept is based on the assumption that the site-specific weed infestation within the tracks of tramlines will extend also into the adjacent area. It can be employed on fields that are bare as well as on those that are fully vegetated by a crop excluding the tracks. But then instead of “spot spraying” – as in fallow fields – the control now results in site-specific **strip spraying**. The respective strip is oriented perpendicular to the direction of travel and its length corresponds to the width of the sprayer. This method inherently cannot be very accurate, since the weed infestation may not correspond to rectangular strips.

A “green seeking” effect can also be realized on the basis of the **Normalized Difference Vegetation Index**, abbreviated **NDVI**. In most cases, this index uses reflectance bands that are centered at 800 and 670 nm too as with the above mentioned simple ratio. But instead of a simple relation, a quotient consisting of the difference and the sum of these bands is calculated. Hence the equation is:

$$\text{Normalized Difference Vegetation Index} = \frac{R\,800 - R\,670}{R\,800 + R\,670}$$

The difference between the wavelengths is “normalized” by relating it to its sum. This is done because the reflectance spectra can be on different levels.

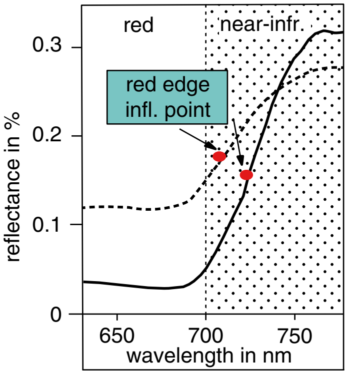
The Normalized Difference Vegetation Index (NDVI) is a widely used standard measure that has been employed since many years for sensing from satellites, from aerial platforms and occasionally also from farm machines. Because of the “normalization”, it might supply more reliable results than the simple ratio of the same wavelengths. Common values of the NDVI are between 0 and 0.8. Very low values (0.1 and below) represent sand, snow or barren areas of rock. Medium measurements (0.2–0.3) correspond to grasslands and shrubs. And higher values (0.5 to nearly 1.0) indicate lush crops as well as temperate and tropical forests. So the NDVI can be used to roughly classify the earth’s surface via satellite data.

In case of sensing from farm machines, the NDVI instead of simple ratios is presently employed in “**green-seeking**” devices for differentiating between soil and vegetation and thus for spot spraying (Fig. 6.5). This technique can be useful for weed control in dryland farming regions where lack of water necessitates rotations with long fallow periods during which weeds must be eliminated. Compared to spraying whole fields, it allows for substantial savings in herbicides and thus reduces their environmental impact. In order to compensate for the additional investment in the green-seeking devices, the technique should be used on adequately large annual areas.

An index that increasingly is used for sensing vegetation is the **Red Edge Inflection Point** (Fig. 6.6). Basically, this index is not defined by a discrete wavelength. Instead, it is located at the precise point where the concave and convex part

Fig. 6.5 Sprayer boom with optical sensors for spot spraying of weeds in a fallow field (Courtesy of Trimble Agric. Div., Westminster, USA, altered)

Fig. 6.6 Red edge inflection points



of the respective reflectance curve along the red edge meet. So the red edge inflection point changes its position along the wavelength scale with the course of the spectrum. If the algebraic formula of the reflectance within the red and adjacent near-infrared range is known, this point can be calculated by differentiating twice and putting the result of this equal to zero.

This method of calculating the red edge inflection point requires that the reflectance data in the red and the adjacent near-infrared range are available with a high spectral resolution. Therefore, many bands are needed and the method may become expensive. For this reason, several indices that estimate the position of the inflection

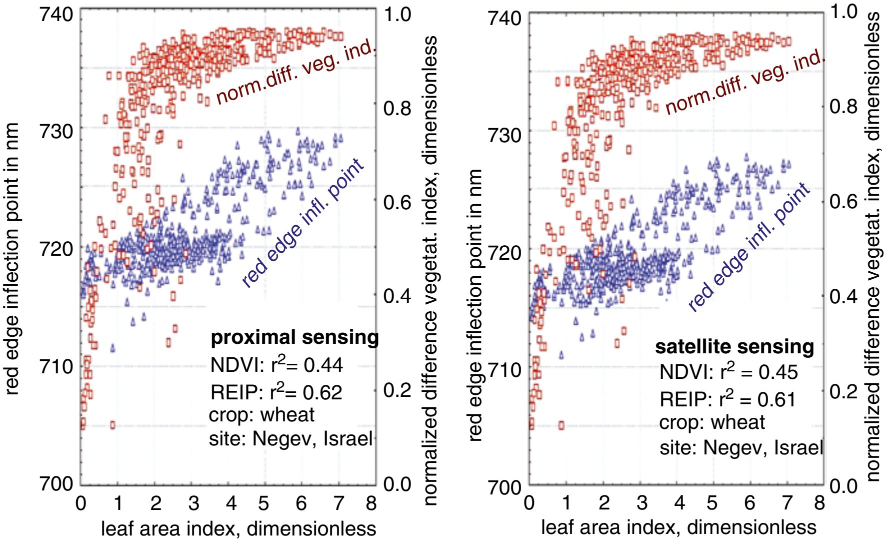


Fig. 6.7 Sensing the leaf-area-index by using the normalized difference vegetation index (NDVI) or the red edge inflection point (From Herrmann et al. 2010, altered)

point from reflectances at just three or four wavelengths in the red edge region have been developed (Dash and Curran 2007; Guyot et al. 1988; Herrmann et al. 2010). Details to these reflectance indices used for approximating the position of red edge inflection point are in the literature cited.

The prime crop property that farmers are interested in is the plant productivity per unit of field area. For this, valuable control signals can be expected from crops itself, since its properties reflect the environment and human activities. Important is the time span between the recording of crop properties and respective control operations. Signals that are derived from real yield monitoring at harvest time imply long time spans and represent conditions that existed within the whole preceding growing season.

In case the signals are from the still growing crop that is to be controlled, the question is, which plant properties deliver suitable data. Prime candidates for such a control system that is oriented at the yield and takes place within the growing season are the **leaf-area-index** and the **chlorophyll concentration**.

The leaf-area-index as well as the chlorophyll concentration within the leaves can be estimated by means of reflectance sensing. When doing this for lush crops, it is important to use a reflectance index that can differentiate between different leaf-area-indices at high levels. The normalized difference vegetation index generally is not able to do this. As can be seen in Fig. 6.7, the estimation by this reflectance index is admittedly very distinct at the start of the growing period, but then flattens out when the leaf-area-index exceeds the value 2. The **saturation** of this present day standard vegetation index at about this crop growth stage has been observed at several places (Serrano et al. 2000; Mistele et al. 2004; Sticksel et al. 2004). This limitation is serious when taking into account that a well developed small grain crop can attain a leaf-area-index of 8. But in areas where the climate does not allow for lush crops, the use of the NDVI may be a satisfactory approach.

When instead of the NDVI the red edge inflection point was used, this saturation effect did not show up (Fig. 6.7). Furthermore, the correlation (r^2) along the whole range of leaf-area-indices was better.

It should be noted that the results of proximal recording with a height of 1.5 m above the ground on the one hand and of sensing from a satellite are very similar (Fig. 6.7, left and right). However, these results were obtained in an arid climate with normally clear skies. In areas with humid climate, such results often cannot be expected because of limitations in the radiation transfer.

6.2.1 *Precision in Sensing of Chlorophyll*

The higher the chlorophyll content of the leaves, the smaller their reflectance is (Fig. 6.3, bottom). Therefore, if for a particular wavelength λ instead of the straight reflectance R_λ, its inversion or its reciprocal is used, a more convenient relation is obtained. Because this inversion $(R_\lambda)^{-1}$ just rises and falls as the chlorophyll content does.

Indicating the chlorophyll effect can be further improved if any interfering with the leaf-area-index is taken care of. Because tendentially, a high leaf-area-index affects the reflectance in the visible range in a similar way as a high chlorophyll content within leaves. However, the result of the leaf- area-index on the spectrum mainly shows up in variations of the near-infrared reflectance (Fig. 6.3, top). Consequently, a further logical step is to subtract the inverted reflection of this near-infrared range – abbreviated $(R_{NIR})^{-1}$ – from the inversion of the respective reflection in the visible range. The thus created difference $(R_\lambda)^{-1} - (R_{NIR})^{-1}$ supplies an optical index that is linearly proportional to the chlorophyll content in spectral bands of the green and red edge range (Gitelson et al. 2003).

It is finally suggested to correct for variations in the leaf structure of crops (Gitelson et al. 2003). These variations are taken care of by multiplying the difference $(R_\lambda)^{-1} - (R_{NIR})^{-1}$ with the non inverted reflectance in the near-infrared range R_{NIR}. This product can be simplified:

$$\{(R_\lambda)^{-1} - \left(R_{NIR}\right)^{-1}\} \times R_{NIR} = (R_{NIR} / R_\lambda) - 1$$

So from these logical deductions, there resulted three indices for estimating the chlorophyll effect, namely

- the simple **inverted reflectance**: $\mathbf{(R_\lambda)^{-1}}$
- the **difference of the inversions**: $\mathbf{(R_\lambda)^{-1} - (R_{NIR})^{-1}}$
- the **reflectance ratio minus one**: $\mathbf{(R_{NIR}/R_\lambda) - 1}$.

The ability of these three indices to estimate the chlorophyll in leaves is shown in Fig. 6.8 by means of their coefficients of determination (r^2) from experiments in

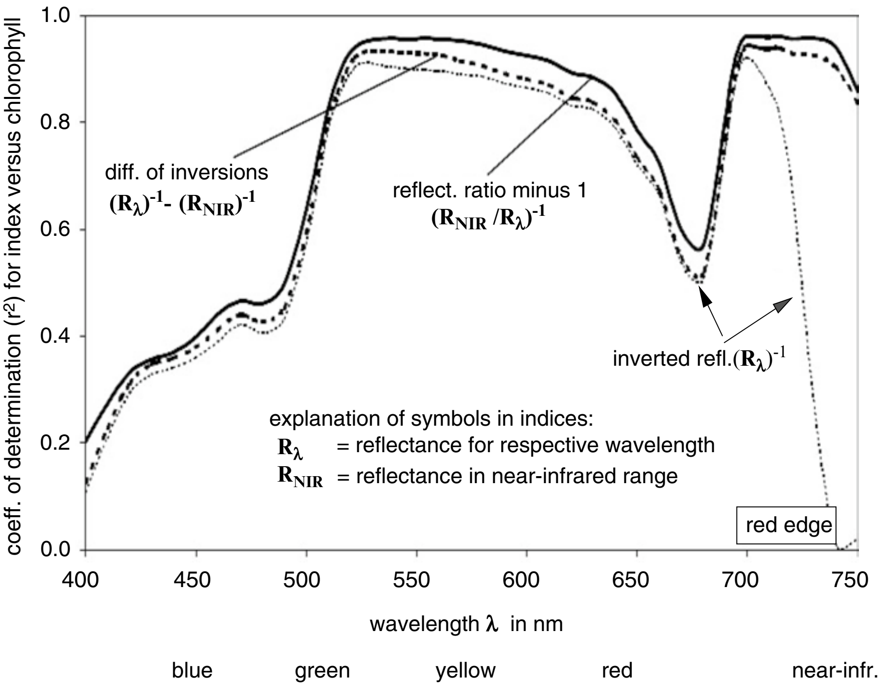


Fig. 6.8 Coefficient of determination (r^2) of three reflectance indices versus chlorophyll content of leaves (From Gitelson et al. 2003, altered)

laboratories. Along the whole range of visible wavelengths plus the red edge, the prediction is slightly improved in the order of firstly the simple inverted reflectance $(\mathbf{R}_\lambda)^{-1}$, secondly the difference of inverted reflectances $(\mathbf{R}_\lambda)^{-1} - (\mathbf{R}_{NIR})^{-1}$ and thirdly the reflectance ratio minus one $(\mathbf{R}_{NIR}/\mathbf{R}_\lambda) - \mathbf{1}$. So the logical expectations regarding the corrections or enhancing the predictions have been confirmed.

Yet within the visible radiation, the differences between these three indices on the reliability of the estimates are very small compared to the effect of the wavelengths λ. For the best index – the **reflectance ratio minus one** – the r^2 for the wavelengths λ involved goes from 0.20 to about 0.95 (Fig. 6.8). Hence getting reliable predictions about the chlorophyll in the leaves is primarily a matter of selecting the most suitable wavelength bands. The bands should be located either in the green range or in the red edge range and perhaps also in both of them.

Based on the reflectance ratio minus one, the recommended indices and wavelengths for sensing of chlorophyll in leaves are either (Gitelson et al. 2003)

- the green chlorophyll index with the formula $(\mathbf{R}_{NIR}/\mathbf{R}_{520-585}) - \mathbf{1}$, or
- the red edge chlorophyll index with the formula $(\mathbf{R}_{NIR}/\mathbf{R}_{695-740}) - \mathbf{1}$.

The rather wide wavelength ranges in the green region (520–585 nm) and in the red edge region (695–740 nm) leave some tolerances for narrower bands within and hence for adapting radiometers.

The question may arise why in the main absorption regions – the blue and especially in the red range – the chlorophyll prediction is so poor (Fig. 6.8). The explanation for this just is the high absorption of the incoming light in these ranges. As a result of the very high absorption in these ranges, the **depth of light penetration** into the leaf or leaves is rather low. Because even low amounts of chlorophyll suffice to saturate the absorption. And when saturation is attained, a further increase in pigment content influences neither absorbance nor reflectance. In the green and especially in the red edge region, the absorption of the light by chlorophyll is much lower. Therefore the light penetrates deeper (Ciganda et al. 2012) and the sensitivity of absorbance as well as reflectance to the chlorophyll content of the canopy volume is much higher.

This context also explains to a large extent, why the normalized difference vegetation index (NDVI) saturates when it is used for sensing the leaf-area-index (Fig. 6.7). Because the NDVI too relies on red reflectance. Logically the same disadvantage applies for simple ratios of near-infrared to red radiation.

6.3 Sensing Yield Potential of Crops by Reflectance

A key criterion is the crop productivity potential per unit of field area. If this potential can be sensed during the growing season on a site-specific basis, it can supply information for an adequate control of fertilizing, plant protection and irrigation operations.

The chlorophyll content per unit area of the leaves alone cannot serve as an indicator of crop productivity potential because it ignores the leaf area that is available. Likewise, the leaf-area-index alone is not sufficient since it does not provide information about the chlorophyll that is involved. However, it seems reasonable to create the product of the leaf-area-index and the chlorophyll mass per unit leaf area. This product is the chlorophyll mass per unit of field area. It is commonly named chlorophyll index or **canopy chlorophyll** and can be regarded as a key criterion for estimating the productivity of crops.

This key position of the canopy chlorophyll for estimating the productivity of crops results from the fact that it controls the photosynthetic process. And following the original logic of Monteith (1972) it can be deduced that the **gross primary productivity (GPP)** of crops is linearly related to the amount of photosynthetically active radiation that is absorbed. It should be noted that this gross primary productivity (GPP) takes into account all plant parts plus roots as well as respiration energy. So it always overestimates the yield that farmers are interested in. However, this should not exclude the use of the GPP as a relative measure for the assessment of the site-specific situation regarding productivity.

The hypothesis is that a connection between reflectance sensing, absorbed radiation and finally the crop productivity exists. The relation between reflectance and absorbance is evident when regarding the fact that these two quantities together with the transmittance add up to 100, and that the transmittance in the visible range hardly counts within a well grown crop (Fig. 6.1, left).

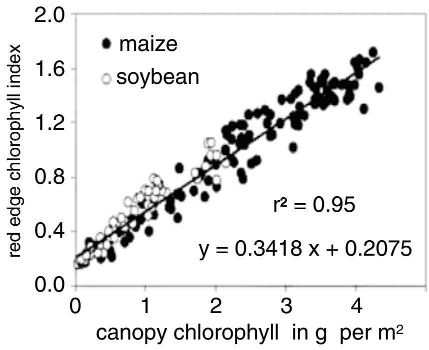


Fig. 6.9 Estimation of canopy chlorophyll for a maize- and a soybean crop by a red edge index (From Gitelson et al. 2005, altered)

The logical consequence for recording the GPP is that at first information about the canopy chlorophyll is obtained via a suitable reflectance index. Secondly, by multiplying the canopy chlorophyll with the **photosynthetically active radiation (PAR)**, the gross primary productivity is estimated (Peng et al. 2010). The first step requires a suitable reflectance sensing technique, *e.g.* using the green- or the red edge chlorophyll index (Fig. 6.9). Among these, a red edge index (formula: $\mathbf{R_{NIR}/R_{720\text{-}730} - 1}$) offers the perspective of a non-species specific use.

However, the use of the photosynthetically active radiation (PAR) as a **multiplicator** for the canopy chlorophyll inherently means that a temporally varying factor is involved. The canopy chlorophyll too changes during the growing season, but the PAR varies much more, namely diurnally and in addition with the weather. Frequent records and averaging would have to compensate for this.

A simpler approach is to use the canopy chlorophyll that is sensed by a green- or red edge index as a **direct proxy** of the gross primary productivity without multiplying it by the photosynthetically active radiation (Gitelson et al. 2008; Peng et al. 2010, 2011). Because the actual values of the chlorophyll indices already result from an interaction between the canopy chlorophyll and the radiation. So without any multiplication with the PAR, the effect of the radiation might be sufficiently included. Consequently, a simplified process of estimating the gross primary productivity seems viable. The path of its short sensing logic is:

Chlorophyll index⇨Canopy chlorophyll⇨Gross prim. productivity.

This procedure eliminates the short-term variations that might come from the multiplication with the PAR. However, the focus is on the results that can be obtained.

Sensed results were compared with data that were obtained via a so called “eddy covariance system” (Fig. 6.10). This method analyses the carbon dioxide fluxes around defined areas in the field and thus obtains information about the carbon fixation by the crop. The chlorophyll sensor was located on a vehicle, hence the results are based on proximal site-specific sensing. Yet similarly reliable information about the gross primary productivity can also be obtained with remote sensing techniques. Figure 6.11 shows the relation between a green chlorophyll index from satellite data and the gross primary productivity of maize derived from it. The carbon dioxide fluxes in the respective areas within the field again allowed the needed comparisons.

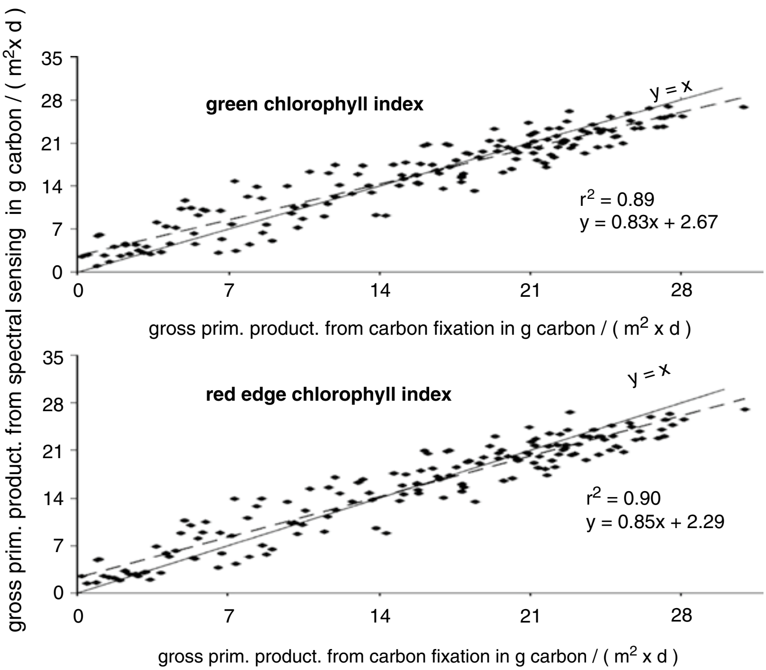
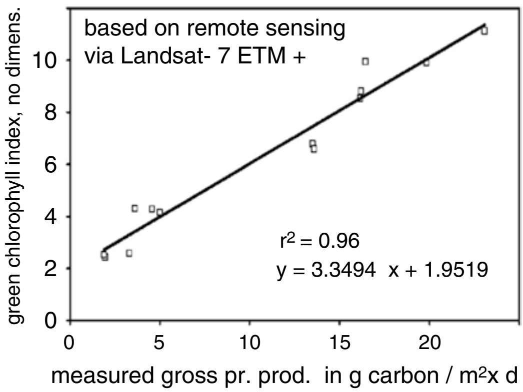


Fig. 6.10 Comparing the daytime gross primary productivity of maize that was either proximal sensed by chlorophyll indices or measured via fixation of CO_2 fluxes in the field. For details to the chlorophyll indices see Fig. 6.8 and text to it. The results refer to 16 irrigated and rainfed maize fields within the years 2001–2008 in Nebraska, USA (From Peng et al. 2011)

Fig. 6.11 Synoptic monitoring of gross primary productivity of maize using a green chlorophyll index based on Landsat data (From Gitelson et al. 2008, altered)



A prerequisite for productivity sensing from satellites is a **clear sky**. So depending on the respective climate, there may be temporal restrictions. And proximal sensing always facilitates high resolutions. However, the Landsat Thematic Mapper Plus satellite system – on which the comparison in Fig. 6.11 is based – also can provide a spatial resolution of 30×30 m. This probably suffices for most site-specific farm operations.

Another prerequisite for every method of crop canopy property recording via reflectance is that the amount of soil in the viewing area of the sensor is kept low enough. Because the reflectance from soil is completely different (Fig. 6.2). So closed canopies are needed. With closely spaced crops – *e.g.* small grains, colza, grass, clover and alfalfa – it is much easier to meet this premise than with widely spaced plants such as maize, beets and sunflower.

However, since the coefficients of determination (r^2) for sensing the gross primary productivity (GPP) are very high (Figs. 6.10 and 6.11), a small percentage of soil reflectance within the signals can be tolerated. Gitelson et al. (2008) even state that the effects of soil on the accuracy of GPP retrieval of maize are minimized once the canopy cover exceeds 60 %.

With proximal sensing and early growth stages of crops, **view directing** can help to avoid sensing errors that are caused by soil. This method aims at restricting the sensing view to small strips just above the plant rows and thus leaving out bare inter-row strips or at using an oblique view on canopies in order to avoid reflectance from soil. Yet with remote sensing, the use of such methods hardly seems possible. However an **elimination of soil errors** with row crops via special post-processing of signals might be feasible (Homayouni et al. 2008; Liu et al. 2008; Pacheco et al. 2008). Up to now, such post-processing to eliminate soil errors is not state of the art. It would lend itself for proximal as well as for remote sensing.

A point to consider is the frequency with which the gross primary productivity (GPP) should be monitored. High yielding crops often need several treatments with farm chemicals during the growing season. Accordingly, also several dates for recording the GPP might be reasonable. Whenever immediate processing of the signals and simultaneous use for the control of farming operations is feasible, proximal sensing during these operations would be desirable.

However, this probably would exclude manual inspection and correction of the results by the farmer prior to the control operation. These human interactions – that might take care of *e.g.* respective soil and water situations – could easily be implemented by recording and mapping the canopy productivity results in a separate first step. Processing and combining the results could then take place in a second and stationary step, thus preparing a final control map for the third step, the respective site-specific operation. This **multi-step procedure** would lend itself for **remote productivity sensing**. A definite point for remote sensing is that is can be repeated rather easily any time, provided no clouds obscure the view. With ground based proximal sensing, this is not feasible because of the labor that is involved.

How can a farmer use the signals from productivity sensing for defining the yield expectations? The information about the gross primary production (GPP) indicates the respective situation at intermediate stages within the growing season. This can at best help to get an estimation. If GPP maps were obtained at two different growing stages early in the season, the question is, how the site-specific signals should be combined into a single map.

A logical reasoning for this would be to expect the final yield to be proportional to averages or sums of the GPP from the sensing dates. However, the time span and the temperature between two sensing dates should be considered. The longer the time span and the higher the temperature within limits is, the more growth can be expected. Following this logic, Raun et al. (2001) concluded that the sum of the signals from two reflectance sensing dates should be divided by the cumulative **growing degree days** between the readings. For these calculations that were based on winter wheat in Oklahoma, USA, a growing degree day was defined as the sum of the daily maximum- and minimum temperatures minus 4.4 in °C. It is obvious that details of this procedure for estimating the yield potential must be adapted to respective crops and to local conditions. Raun et al. 2001 used the described method for site-specific sensing with the normalized difference vegetation index (NDVI) during the second half of the tillering time span and obtained an accuracy of 83 %. For high yielding crops, a red edge index instead of the NVDI is recommended (see Fig. 6.7 and text to it).

Though yield estimating via reflectance is not yet state of the art, it probably will become an important method for getting logic to site-specific control algorithms and thus for providing more efficiency to several farming operations.

6.4 Fluorescence Sensing

The denotation "fluorescence" indicates a flowing or a flux of radiation that is emitted. The emitter can be plants or also dead material. However, the latter case is left out here.

Contrary to reflectance, the radiation does not originate from irradiance that is simply thrown back from the canopy. Instead, fluorescent radiation can be traced back to photons that did enter an absorption process in plants. However, the photons that enter such processes in plants and induce fluorescence and those that leave the canopy as fluorescent light are different. The light that excites plants to fluoresce always has shorter wavelengths than the fluorescence that finally results from it. The development of fluorescent light implicates a **prolongation of wavelengths**.

Common ranges for plant fluorescence are either the **blue to green region** extending from about 400 to 600 nm or the **red to far-red region** from approximately 650 to 770 nm wavelength. The blue-green fluorescence is induced by ultraviolet light, thus by light that is not used by photosynthesis. It is assumed that the blue-green fluorescence develops within phenolic materials in the cell walls of plants (Buschmann and Lichtenthaler 1998). The red to far-red fluorescence can also result from ultraviolet radiation, yet in addition it can come from light that entered a photosynthetic process and hence chlorophyll molecules. Consequently, it is named **chlorophyll fluorescence**. The visible wavelengths that induce the chlorophyll fluorescence can range from the blue to the red region. But the exciting wavelengths always are below those of the final fluorescence.

The fact that the fluorescence always has higher wavelengths than the respective exciting light means that – in terms of energy per photon – the fluorescent light is less valuable (Fig. 3.1). The chlorophyll fluorescence is regarded as a **by-product of photosynthesis** because it is a means of getting rid of surplus energy. A question is, however, why are plants wasting energy?

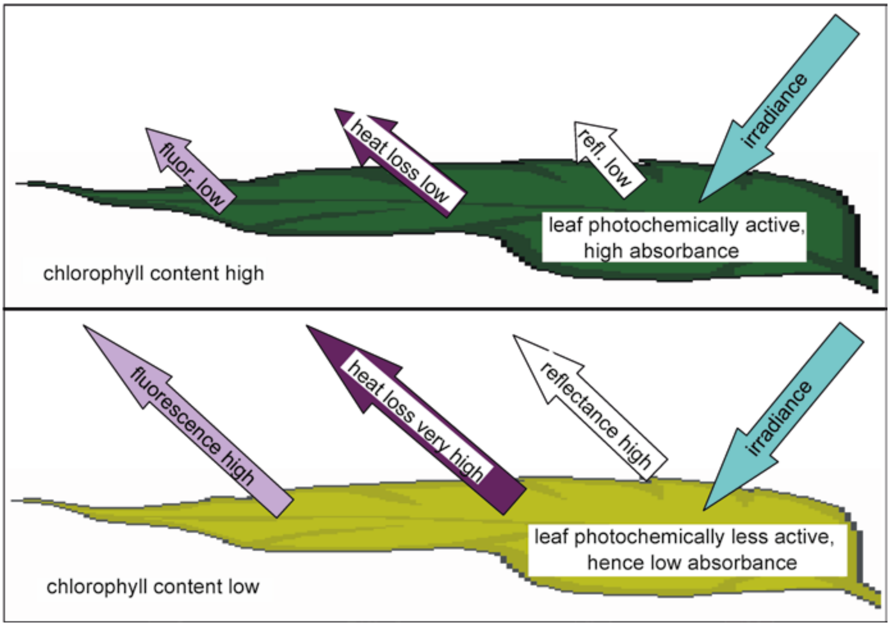


Fig. 6.12 Two leaves with differences in the chlorophyll content and hence also in the photosynthetic activity, the absorbance and the reflectance of photochemically active radiation. But there are also principal differences in the fluorescence and in the heat loss

Table 6.1 Use of absorbed light quanta[a]

Energy used for …	Optimal photosynthesis (%)	Blocked photosynthesis (%)
Photosynthesis	84	0
Heat loss	14	88
Chlor. fluorescence	2	12

[a]Compiled from data by Rosema et al. (1991)

Actually, plants are not wasting much of the solar energy that they receive if the growing conditions are good and the leaves are well equipped with chlorophyll. But the situation is quite different if photosynthesis is impeded or cannot take place at all though sufficient photosynthetic active radiation is available. For growing crops such situations can *e. g.* result from the lack or from a wrong supply of water or mineral nutrients. Diseases or pest infestations too can cause this. Hence plants need means to get rid of all or part of the solar energy if photosynthesis cannot take place. The dissipation of chlorophyll fluorescence and simply of heat to the environment serves this purpose (Fig. 6.12).

It seems reasonable to relate the thus dissipated energy to the energy of the absorbed light (Table 6.1). When the growing conditions are optimal, only 2 % of the absorbed energy is emitted as chlorophyll fluorescence. If on the other hand the photosynthetic process is completely blocked, the emitted chlorophyll fluorescence is six times as high. The heat dissipation as well goes up to the six-fold if no photosynthesis occurs. However, the absolute level of energy dissipation via heat is very much higher than via fluorescence. Under the same conditions, about seven times as much energy is lost via heat than via fluorescence (Table 6.1).

A prime objective in precision farming is obtaining site-specific information from the crop itself about the energetic efficiency with which the photosynthetic process is going on. Such information would supply essential knowledge for a logically controlled site-specific application of *e.g.* water and farm chemicals.

Theoretically, the dissipation either of **heat** or of chlorophyll **fluorescence** would be candidates for respective signals about the status of the photosynthetic process. From the amount of energy that is involved, it might be assumed that the heat dissipation could provide the best signals for this (Table 6.1). However, up to now, detecting the heat emission from plants in an accurate way is possible only in laboratories. For doing this with crop canopies in fields by remote or proximal sensing, no precise techniques exist. This has to do with the fact that the steadily changing weather affects the physical measuring conditions. Contrary to this for fluorescent radiation, remote sensing from aerial platforms and proximal sensing from farm machines in an online and on-the-go manner is state of the art.

6.4.1 Fluorescence Sensing in a Steady State Mode

The methods for fluorescence sensing operate either in a **steady state**- or in a **non-steady state** mode. This refers to the radiation that induces the fluorescence and which either is temporally constant (= steady) or for which a change is programmed during the time of sensing. Whenever passive sensing based on natural light occurs, a steady state mode exists. Because practically within the sensing time for a signal, the natural light is constant.

But in case active sensing takes place since the induction is based on artificial radiation (*e.g.* by laser light), this can be done either in a steady state- or also in a non-steady state mode. The latter aims at detecting how the fluorescence behaves when the illumination changes and therefore often in denoted as a **"kinetic" sensing method**. It is explained in detail in the next section. This section deals with steady state methods.

There are many factors that influence the course of the fluorescence spectra such as the exciting radiation and plant species. Yet an important feature are the high levels or peaks in the red (F680) and far red (F735) wavelength region. With a low chlorophyll concentration, the peak in the red range dominates. But with a high chlorophyll content, the peak shifts to the far-red region (Fig. 6.13). This phenomenon is explained by **re-absorption of photons** from the fluorescent light (Lichtenthaler 1996; Buschmann and Lichtenthaler 1998). If the wavelength is below 700 nm, the fluorescent photons coming from internal leaf cells can be re-absorbed when hitting adjacent chlorophyll molecules. With a wavelength above

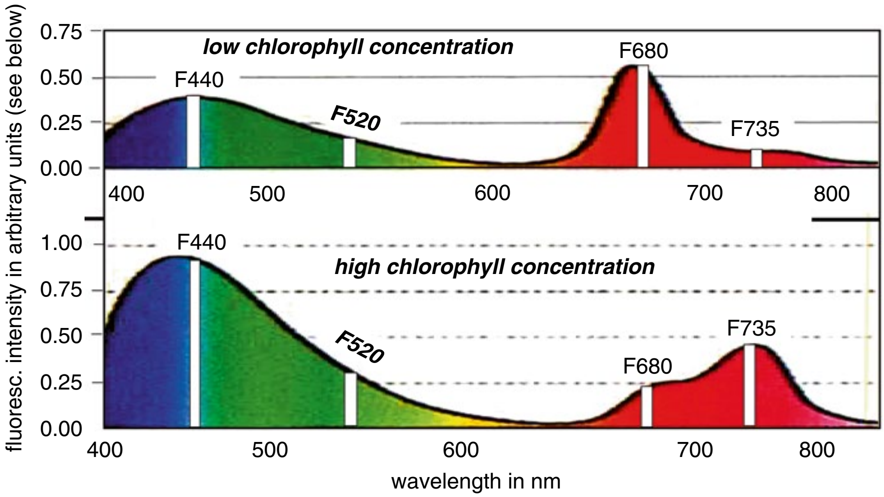


Fig. 6.13 Steady state fluorescence spectra of maize leaves with low or high chlorophyll concentrations that were excited by ultraviolet light. The *white*, *thin* columns represent wavelength bands that are suitable for plant stress detection (Compiled from data by Guenther et al. 1999 and Lichtenthaler 1996). For details to the units on the ordinate see Schwartz et al. 2006

700 nm, re-absorption is not possible. And the higher the chlorophyll content within the leaves, the more re-absorption occurs. This explains why the fluorescence ratio F680/F735 can be regarded as a reliable indicator of the chlorophyll concentration in leaves.

The ratio of the blue to green fluorescence bands (Fig. 6.13) is less influenced by growth conditions. The blue band (F440) referenced to the far red band is used as an indicator for the sensing of fungi infections (Thiessen 2002).

The wavelengths of reflectance and fluorescence can be the same. Hence techniques that enable to differentiate between both types of radiation are needed. In case of active sensing with artificial light, **modulation** of the exciting radiation allows for this. This modulation can be obtained via pulses of the inducing laser light.

But in case of passive sensing, when natural light induces fluorescence, a modulation technique is not available. In addition, the chlorophyll fluorescence emitted by vegetation represents a small part of the radiation (Table 6.1). The sun – when it is used for inducing – poses a dilemma. It stimulates the formation of fluorescence. But simultaneously, it masks the fluorescence with reflectance. In order to prevent that the fluorescence is obscured by the reflected light, the sensing is done within narrow wavelength ranges where the incident natural light is either completely excluded or at least attenuated. The solar spectrum has several such very narrow ranges that are the result of light **absorption** by atmospheric molecules. These narrow spectral ranges are known as **Fraunhofer lines**, named after the physicist von Fraunhofer.

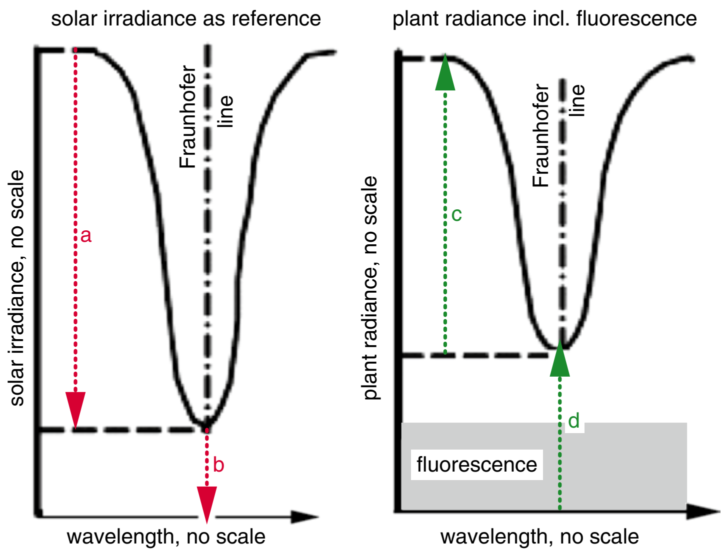


Fig. 6.14 Basics for passive sensing of the chlorophyll fluorescence of vegetation using Fraunhofer lines. The radiance that is coming from the plants (*right*) is compared to the irradiance (*left*) that hits an adjacent reference panel situated in the same illumination conditions. The radiations denoted with the letters *a*, *b*, *c* and *d* are sensed. The components *a* and *c* are recorded adjacent to the wavelength of the Fraunhofer line, whereas *b* and *d* are measured precisely in this line. It should be noted that adding the components a and b or alternatively c and d does not make sense since the wavelengths are different

In order to be useful, such a Fraunhofer line must be in a region where fluorescence recording makes sense. Within the red and far red range, such Fraunhofer lines exist

- at 656.3 nm wavelength due to absorption by hydrogen
- at 687.0 nm wavelength due to absorption by oxygen and
- at 760.0 nm wavelength again due to absorption by oxygen.

The 687 nm oxygen wavelength almost coincides with the red peak of the chlorophyll fluorescence spectrum that is recommended for plant stress sensing (Fig. 6.13, top). However, at this wavelength as well as at the 656.3 nm hydrogen wavelength, the absorption of solar radiation by the atmosphere is much less than at the 760.0 nm oxygen wavelength. It is for this reason that generally the 760.0 nm oxygen band is preferred (Liu et al. 2005; Maier et al. 1999; Moya et al. 2004), which still is rather near to the recommended band in the far-red range.

The basic measurements needed to detect sunlight-induced fluorescence in Frauenhofer lines are outlined in a simplified way by letters in Fig. 6.14. The left inverted Gaussian curve indicates the band of **irradiance** that is directed towards the canopy. The intensity of this irradiance decreases on its way through the atmosphere as a result of absorption, *e.g.* by oxygen. The vertical Frauenhofer line represents the wavelength that is the center of the attenuation.

The right inverted Gaussian curve (Fig. 6.14) stands for the **radiance** band that the plants emit, hence for **reflected plus fluorescent radiation**. This radiation that is directed away from the canopy is compared to the irradiance (left).

The purpose of recording radiation lateral to the Fraunhofer line is to obtain an estimate of the reflectance R without any contribution of fluorescence. The quotient c/a provides this reflectance R, which can be regarded as a coefficient of reflection (see Sect. 3.1). Since the solar irradiance hits a reference panel that is non-fluorescent, its component b in the Fraunhofer line cannot contain energy that is converted to fluorescence. This means that the product of reflectance R and component b provides the absolute reflection part precisely within the Fraunhofer line. And because the plant radiance within the Fraunhofer line d contains reflection as well as fluorescence f in absolute values, subtracting the product R × b from it provides finally the fluorescence.

$$\text{So fluorescence } f = d - R\ b = d - c\ b/a.$$

Moya et al. (2004) and Liu et al. (2005) have shown that this method provides good results. However, this method inherently does not allow to sense vegetation stress via the F680/F735 ratio that can be used with active sensing.

6.4.2 Fluorescence Sensing in a Non-Steady State Mode

This method goes back to Kautsky and Hirsch (1931), who watched the fluorescence intensity of leaves that were held in the dark and then suddenly were illuminated. It showed up that starting from a very low level, the fluorescence intensity rose steeply to a maximum. While the illumination continued, the fluorescence then fell gradually. This descent of fluorescence took several seconds and sometimes included smaller intermediate maxima. Finally – with the illumination still on – the fluorescence got to a steady state level (Fig. 6.15). This reaction of fluorescence to varying illumination often is called the **Kautsky effect**.

The physiological background of this phenomenon is that the photochemical factory of a plant needs adjustments and time to get to the steady state operational mode. The **initial rise** of the fluorescence intensity with the start of the illumination is attributed to progressive saturation of the photochemical system. And the **slow decrease** of the fluorescence intensity after having attained the maximum is most likely due to protection mechanisms since the plant has to avoid adverse effects of an excess of light.

The significance of the Kautsky fluorescence curve is that it allows to get information about the most important crop property – its photochemical devices – under fairly controlled conditions. Because the light that enters the process is artificially programmed. And simultaneously, the waste energy that the crop sheds as fluorescence is recorded. Temporal optical indices that represent variations in the rise, in the maximum or in the decay of the Kautsky fluorescence have been developed and can assist in assessing the photochemical situation (Buschmann and Lichtenthaler 1998; Thiessen 2002).

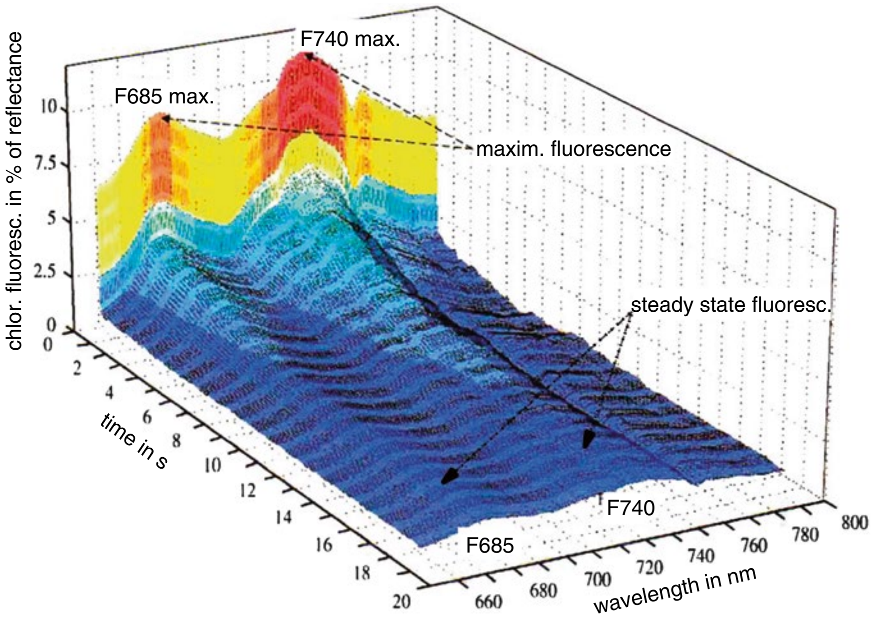


Fig. 6.15 Spectra of chlorophyll-fluorescence that were acquired from maize leaves after 5 min of dark adaptation in the laboratory. The illumination with a 300 W xenon arc lamp began at time 0 and was to simulate constant solar radiation following the dark adaptation. The initial rise of the fluorescence according to the Kautsky effect cannot be seen. But the gradual decrease to the final steady state fluorescence is apparent. The graph also points out the maxima of the chlorophyll fluorescence – as explained in Fig. 6.13 – at 685 and 740 nm wavelength (From Entcheva Campbell et al. 2008, altered)

6.4.3 Fluorescence or Reflectance

Principally, both active as well as passive sensing of chlorophyll fluorescence can be done on a site-specific basis. However, passive sensing in Fraunhofer lines is not yet used in farming operations whereas active sensing of the chlorophyll content via the red/far red fluorescence ratio is state of the art. An advantage of fluorescence sensing – when compared to chlorophyll sensing via reflectance – is that radiation from the soil does not result in errors. Because the soil does not emit fluorescent radiation. So contrary to chlorophyll sensing by reflectance, a not **closed crop canopy** is not a problem.

But whereas reflectance allows to sense the chlorophyll content within the leaves as well as the leaf-area-index, this is not *per se* possible by fluorescence. Even if fluorescence sensing is done in combination with a device that scans the complete field surface, it is the canopy surface that supplies the signals and leaves below it are disregarded. Hence fluorescence cannot as well provide information about the chlorophyll content per unit of field area and thus about the **longterm yield** potential of crops – as suitable reflectance indices can (see Sect. 6.3). However, a combined use of fluorescence- and reflectance sensing may be reasonable.

The **Kautsky method** is not easy to apply in an online and on-the-go mode in field operations since the sensing of its effect needs time. However, a similar stimulating effect on fluorescence can be obtained with very short **laser light flashes** that hit the canopy and saturate the photochemical system for a tiny time period of 1 s or less. A subsequent sensing time span of 1–2 s can be realized while a tractor passes along crop rows if recording takes place successively from the front to the rear of the machine. Interesting approaches along this line have been dealt with by Thiessen (2002) and Hammes (2005).

The sensing via signals of reflectance on the one hand or from steady state- or from non steady state fluorescence on the other hand has different objectives within plants. With reflectance sensing, the main objective is the biomass – precisely the leaf-area-index – in combination with the chlorophyll content of the leaves. The product of the leaf-area-index and the chlorophyll content within leaves – thus the chlorophyll content per unit field area – is the classical objective. With **steady state fluorescence**, the objective mostly is just the chlorophyll content within leaves *per se* and sometimes – in case of blue/green fluorescence – the phenolic material in cell walls. Finally, with the non steady state **Kautsky fluorescence**, the prime objective is the rate of electron transport within the photosynthesis. In this case, the biomass and chlorophyll situation is taken as it is.

These differences in sensing objectives have temporal implications. The biomass of crops and the chlorophyll content per unit field area are rather long-term phenomena. Compared to these, the electron transport in the photochemical systems is a very fast matter. And the chlorophyll content within leaves is – on a temporal basis – in between of these extremes.

From this follows that reflectance sensing provides information about crop properties on the basis of rather long time spans, *e.g.* from several days to a few weeks. The steady state fluorescence methods can supply signals that are related to properties for a few days. Finally, the Kautsky fluorescence is able to indicate immediate problems in plant physiology.

A need for rapid detection exists in case of many fungal infections of crops. A fast detection and immediate crop protection action can provide the opportunity of preventing additional infection cycles and hence save fungicides. Because of its physiological background, the Kautsky fluorescence can supply such immediate control information about infections. By using indices that were derived from the non-steady state Kautsky fluorescence, it has been possible to indicate fungal infections on leaves several days earlier than the human eye was able to detect them (Buerling et al. 2009; Moshou et al. 2009; Thiessen 2002). So the perspectives for early detection of fungi are good. However, on-the go detection from farm machines is not yet state of the art. And since different crops, several fungi and various environmental conditions are involved, there are still problems that must be solved.

Crop properties will probably exist as short-term and long-term phenomena. So both reflectance- as well as fluorescence sensing might be reasonable. Yet since fluorescence signals are much weaker than those from reflectance, the preferred recording mode for it in the near future will be proximal- instead of remote sensing.

6.5 Sensing the Water Supply of Crops by Infrared Radiation

The perspectives of crop development depend not only on the chlorophyll situation but equally well on the water supply. Hence information about the water supply is needed too for the control of several farming operations such as irrigation or the application of farm chemicals. And getting this information directly from the crop instead of from the soil has distinct advantages. This automatically takes into account the site-specific influence of water-tension within the soil on the supply of the plants. Depending on the respective soil texture, the water tension varies considerably and thus the amount of water available. Furthermore, when sensing the supply of the crop instead of the soil, the influence of the root development on the situation is taken care of without any attention. And the root development varies during the growing season as well as on a site-specific basis.

Signals can be derived either from **reflected radiation** or from **emitted thermal radiation**.

6.5.1 Sensing Water by Near- and Shortwave-Infrared Reflectance

The visible wavelengths can be left out for water sensing from crop canopies. Instead, the reflected infrared domain can be considered as basis for signals. As with many other applications for spectral sensing, generally the best results are not obtained with wide bands that extend over long wavelength ranges within the spectrum, but instead from narrow bands or indices that use them. Such **hyperspectral bands** ranging from 1 to 10 nm width allow to select the most sensible region within the spectrum and to avoid the weakening or averaging effect that inevitably is associated with wide bands.

Soil- and canopy sensing differ not only in the region of the spectrum that is used (Fig. 6.2). With soil sensing via reflectance, a fundamental problem is the fact that it is based solely on the top-surface that is hit by the radiation. In order to get information from below the surface, sensing of vertical soil profiles is necessary.

This can only be done via proximal sensing from terrestrial vehicles or from farm machines that cut a slit into the soil. This limitation does not exist for sensing of crops by infrared radiation because this penetrates well into the vegetation and is reflected back from various layers below the canopy surface. Consequently, canopy sensing – contrary to soil sensing – lends itself for proximal sensing as well as for remote sensing from satellites or from aerial platforms.

Which wavelengths of narrow band reflectance can indicate the crop water supply? Table 6.2 shows results of experiments, for which the coefficients of determination (r^2) were above 0.60. The bandwidths of the wavelengths listed were between 1.5 and 10.0 nm with one exception, for which the range is indicated.

Table 6.2 Spectroscopic sensing of water content of crop canopies (results listed by coefficients of determination r^2)

Reference	Plant species, sensing methods	Reflect. indices R with wavelength in nm	Coeffic. of determinat. r^2
Jones et al. (2004)	Maize	R1450	0.67
	(*Zea mays*)	R2250	0.61
	Sensing in the lab		
	Spinach	R960	0.94
	(*Spinacea oleracea*)	R1150 – 1260	0.93
	Sensing in the lab	R1450	0.85
		R1950	0.80
		R2250	0.79
Penuelas et al. (1993)	Gerbera, 3 varieties	R970/R900	0.79
	(*Gerbera jamesonii*)	R970/R900	0.86
	Sensing in the lab	R970/R900	0.84
Sims and Gamon (2003)	Means of 23 species,	R960	0.75
	Sensing in the field	R1180	0.81
Sonnenschein et al. (2005)	Wheat	R900/R970 static[a]	0.90
	(*Triticum aestivum*)	R900/R930 – 990 var[b]	0.90
	Sensing in the field		
	Wheat	R900/R981	0.90
	(*Triticum aestivum*)		
	Airborne sensing		
Yang and Su (2000)	Rice	R697	0.81
	(*Oryza sativa*)	R1508	0.90
	Sensing in the field	R2113	0.96

[a]Denumerator and denominator static as listed
[b]Denumerator static, denominator was varied between R930 and R990

The wavelengths of the successful narrow band indices are located in a rather wide range extending from 697 to 2,250 nm, thus within the **near-infrared region** (700–1,300 nm) and the **short-wave infrared region** (1,300–2,500 nm). Within the whole spectrum, the near-infrared radiation has the highest foliar reflectance due to scattering in the canopy, and the short-wave infrared region has ranges of high liquid water absorption. But it is not clear whether these special properties of liquid water are important. High coefficients of determination can be seen in the near infrared- as well as in the short-wave infrared region (Table 6.2). However, sensing in the near-infrared is less expensive because these sensors are mass-produced and less sensitive to temperature.

Generally, it can be expected that *ceteris paribus* sensing in laboratories provides higher accuracies than proximal sensing in fields while remote sensing from satellites or aerial platforms supplies the least precise results. However, such an effect of the sensing location is not indicated by the coefficients of determination in Table 6.2. This probably is due to the fact that just comparing results from several investigations – among them many varying factors such as *e.g.* plant species, wavelength, illumination, sensing distance – does not supply knowledge about the basic effects of single parameters. This knowledge can be derived from investigations that allow a system analysis, in which the effect of varying factors can be controlled.

The graphs in Figs. 6.16 and 6.17 have been obtained by using modern canopy reflectance models (Clevers et al. 2010). These models offer the advantage that the results are independent of site and plant species and thus fairly universally valid. For details to these models see Jacquemoud and Baret (1990) as well as Verhoef (1984). The graphs have been supplemented with data to remote sensing preferences.

Across the whole near-infrared and shortwave-infrared region, a decrease of the water content causes a rise in the reflectance (Fig. 6.16). This is important, particularly when crops grow older. Small differences in the water content due to short term weather variations in early growth stages are more difficult to detect. However, the visual inspection of the course of the reflectance curves does not provide reliable information about the best wavelengths for sensing. This knowledge can be obtained from calculations of the respective correlations. Details to this cannot be dealt with here, yet important results are indicated in Figs 6.16 and 6.17.

Accordingly, good spectral information about canopy water content can be obtained from features centered at either **970** or **1,200 nm wavelength**. These wavelengths are approximately at the bottom of the two dips within the near-infrared spectrum. For best results, either first derivatives or simple **wavelength ratios** from the slopes of the spectrum just adjacent to these wavelength centers should be used. Recommended ranges for the derivatives or the simple ratios are either the left or alternatively the right slope from the 970 nm centre and also the left slope from the 1,200 nm center.

The green framed columns in Fig. 6.17, bottom, show the recommended slope ranges. Some of the simple ratios in Table 6.1 correspond closely to these ranges.

For **sensing from satellites**, absorption of radiation due to water vapor in the atmosphere within some wavelength ranges needs attention. Because sensing in these regions results in very noisy or inaccurate signals, they should be avoided. Within the short- wave infrared region (1,300–2,500 nm), there are two ranges that are affected. In Fig. 6.16, these ranges are indicated by red columns. It is not accidentally that these ranges are also close to dips within the spectral curves. Because the dips are the result of high spectral absorption by liquid water in the canopy. And the red columns indicate high absorption, yet by water vapor. Precisely seen, however, the centers of **water vapor** absorption are shifted approximately 50 nm to shorter wavelengths when compared to the dips in the curves for the **liquid water** in the canopy (Clevers et al. 2008, 2010).

In the near-infrared region, there are only two very thin bands of atmospheric absorption by water vapor. These narrow bands of absorption by water vapor – that too are radiation barriers – are located rather closely to the recommended slope ranges for canopy water sensing (see red vertical lines in Fig. 6.17). The centers of these bands in the near-infrared – which should be avoided – are at 940 and 1,140 nm (Gao and Goetz 1990). Thus "hyperspectral precision" in selecting the wavelengths for remote canopy water sensing is needed.

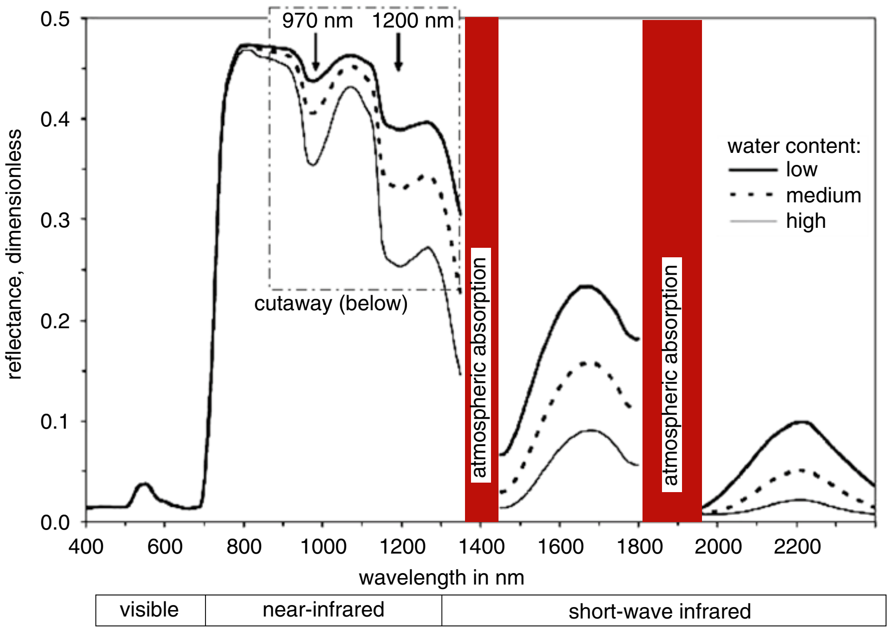


Fig. 6.16 Canopy water content, reflectance and sensing barriers (*red columns*) due to atmospheric water vapor (From Clevers et al. 2010, altered and supplemented)

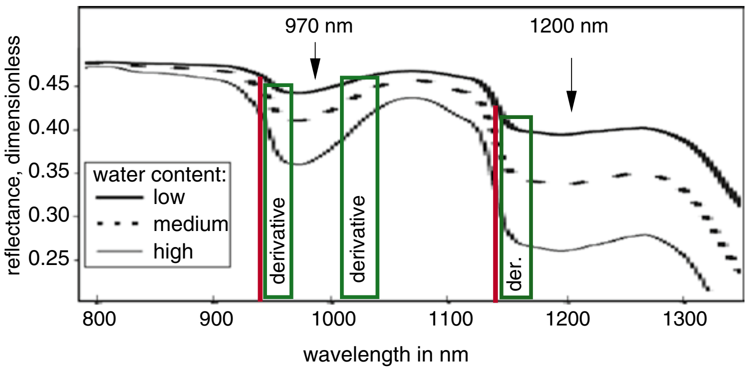


Fig. 6.17 Enlarged cutaway from the figure on top with changed scales showing the locations of recommended bands for canopy water sensing and of barriers (in *red*) due to atmospheric water vapor. Either first derivatives or simple wavelength ratios based on narrow bands from within the *green* framed columns should be used (Drawn from data by Clevers et al. 2008 and 2010)

Summing up, it can be concluded that the perspectives for site-specific canopy water sensing look good. However, canopy water sensing is not yet state of the art. It could be practiced either in a proximal sensing mode simultaneously with other farming operations or in a remote mode, *e.g.* from satellites. The proximal sensing mode lends itself primarily for the direct control of farming operations, whereas remote sensing is especially suited for tactical inspections of large fields within a short time. The steadily increasing number of satellites improves the perspective to perform such remote tactical inspections frequently and hence to sense the occasionally fast changing water situations. This might be valuable for site-specific irrigation practices.

6.5.2 Sensing Water by Emitted Thermal Infrared Radiation

This method of sensing the water supply of crops relies on the **transpiration** that takes place at the surface of leaves. The sensing signals are based on the cooling effect of water transpiration on the canopy. The energy for converting the liquid water to the gaseous state causes a cooling of the canopy. Because of this, on a very hot day it can be more comfortable for humans to be inside a dense forest.

The more water is transpired, the more the canopy temperature is below the temperature of the surrounding air. The **crop water stress index (CWSI)**, developed by the U.S. Water Conservation Laboratory in Arizona (Jackson et al. 1981) depends on this.

The main criterion of the crop water stress index therefore is the **temperature difference** between the canopy leaves and the air. If a crop has water stress and therefore cannot transpire, there is hardly any difference between leaf- and air temperature. The red upper baseline in Fig. 6.18 stands for this situation. For the not water stressed crop, the transpiration depends on the relative humidity of the air. The lower the relative humidity is, the more the crop transpires. And the more the crop transpires, the lower the temperatures of the leaves. The green lower baseline (Fig. 6.18) represents the case of the fully transpiring, non water stressed crop. The vertical distances between the upper and lower baseline define the differences of the temperature span between leaves and air that occur when non transpiring crops on the one hand with fully transpiring plants on the other hand are compared. It should be realized that this comparison is about **differences of differences**.

The graphical interpretation of a specific case starts with a point of the actual situation, *e.g.* point B in Fig. 6.18. This point has a respective leaf- minus air temperature. In addition, it is located at a distinct distance to the lower baseline. This distance to the lower baseline represents the absolute situation. However, this absolute situation should be referenced or normalized. The **normalization** is done by dividing the absolute situation for point B by the total distance between the upper- and the lower baseline. This quotient is the crop water stress index (CWSI), which has differences of differences in the numerator as well as in the denominator (Fig. 6.18). A CWSI of 0 indicates that a crop is fully transpiring and hence is well supplied, whereas a value of 1 means maximal water stress. Generally, watering is recommended when the CWSI value for maize is above 0.22 (Irmak et al. 2000).

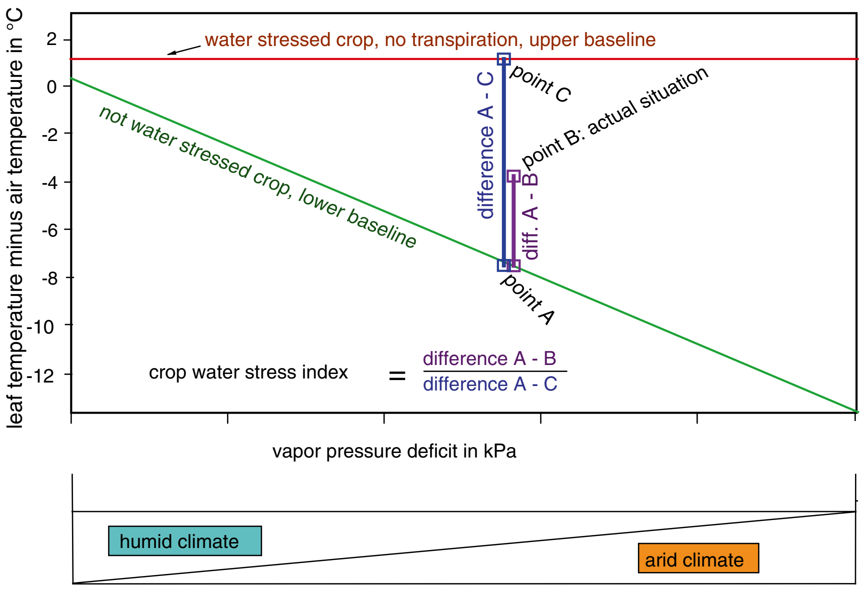


Fig. 6.18 Graphical interpretation of the crop water stress index

Sensing by the crop water stress index has distinct advantages.

- The first advantage is that the sensing criterion – the transpiration – is a result of the plants own internal moisture control system. The transpiration reflects **response of the crop** to the existing water supply. This response is probably more pinpointed than other human estimation of the needed moisture.
- The second advantage has to do with the physical quantity that is involved. Recording temperatures is easily possible in a non-contact, site-specific mode, either by proximal on-the-go sensing or as well by remote recording (Sadler et al. 2002).

However, fact is also that sensing of the canopy- as well as of the air temperature plus the vapor pressure deficit alone does not suffice for the recording of the crop water stress index. The positions of the upper and lower baseline (Fig. 6.18) must be precisely defined. Theoretically, these positions depend on several meteorological factors – among others wind speed – and on crop properties. Rather complicated approaches have been proposed for determining the positions of the baselines (Jackson et al. 1988; Payero and Irmak 2006). A rather simple recommendation (Alchanatis et al. 2010; Moeller et al. 2007) that is empirically based is:

- to define the **upper baseline** by adding 5 °C to the sensed air temperature and subtracting this sum from the respective leaf temperature (see ordinate in Fig. 6.18)

- to define the **lower baseline** by using the temperature of an artificial wet reference surface – such as a small wet foam mat floating in water – instead of the leaf temperature. The air temperature is then subtracted from the temperature of this artificial wet reference surface. The latter provides for more stable temperatures than moist leaves do.

Provided the baselines are well defined, the crop water stress index can be regarded as a prime choice for estimating the water situation of crops (Meron et al. 2010). However, there are still limitations for its use in practice. An important limitation is that very erroneous signals result if the radiation hits soil or plant residues instead of active leaves. Hence closed canopies offer ideal conditions. But these might not exist in early growing seasons or with widely spaced crops. Correctives that can provide a remedy are either narrowing the sensors view to rows of crops in case of proximal sensing or alternatively sorting out soil data via post-processing by means of reflectance signals. For details to this see Sect. 6.3.

The crop water stress index or similar thermal indices are occasionally used for the control of large area irrigation in dry regions, yet presently barely ever employed in regions with humid climate. Of course, in humid regions there is less water stress of crops. But it is also more difficult there to get precise signals. This is because the lower the vapor pressure deficit is, the smaller the differences of the temperature spans are, which are the basis of the crop water stress index (Fig. 6.18). Advances in measurement techniques may help to get precise signals even under more humid conditions.

The water situation should be sensed under uniform conditions of illumination. In order to get signals from the time when the maximal expression of water stress exists, the sensing should be done around noon and possibly when the sky is clear. Remote sensing facilitates getting signals that are based precisely on the same time within the whole field, but the delivery of the results might delay the application. With proximal sensing the situation is *vice versa*.

A challenging perspective would be **site-specific irrigation** based on either the crop water stress index or on water sensing via reflectance. This could save water or improve yields in many cases. Real-time control should be aimed at since irrigation is a timely matter.

Provided the signals were available, the site-specific irrigation control for systems with center pivoting or linearly moving booms could be realized via nozzles thats either pulse or which have variable orifices. With **pulsing nozzles**, the "on" to "off" time ratio controls the water supply. In case of nozzles with **variable orifices**, moving a coned pin towards the direction of the orifice varies the flow rate. For actuating the site-specific irrigation by these devices, a sophisticated telemetric control network is feasible. Details to this have been dealt with by Camp et al. 2006; Pierce et al. 2006 and Sadler et al. 2000.

However, there still are obstacles to real time site-specific irrigation. At least this holds for site-specific irrigation that relies on sprinkler systems and is based on sensing the water supply via radiation. The path of the radiation that senses the moisture status should not be obstructed by water drops. These would cause large sensing errors. So any real-time control system for sprinklers will have to provide separate paths for the radiation that is used for sensing on the one hand and for the water drops on the other hand.

Guiding the water from the sprinkler boom down into the canopy via vertical flexible hoses would do away with this problem. This technique also reduces evaporation losses. However, it results in line watering instead of treating the whole area and is hardly used in large scale farming.

In short, site-specific irrigation in real-time based directly on the water supply of crops or soils for large scale farming is not yet state of the art (Evans and King 2010, 2012) though it is an urgent matter because of the increasing lack of water. Principally, site-specific irrigation could also rely on maps of **topography** and **soil texture**. Both factors can influence the water supply of crops. However, the direct control via the water stress of crops should be preferred.

6.6 Sensing Properties of Crops by Microwaves

Microwaves operate with the longest waves that are used for sensing – hence the name might be misleading (Fig. 3.1). The historical explanation for the name is attributed to the fact that microwaves are shorter than radiowaves. Compared to sensing by visible and infrared reflectance, observations in the microwave region are complementary and also more complex. And applications are still more limited, but they are growing.

A fundamental advantage is that microwaves can penetrate the atmosphere including clouds during day and night. Only heavy rain or snow can prevent the use. As far as the transmission through the atmosphere is concerned, microwaves are predestined for remote sensing. Yet the crop properties that can be detected are quite different from those sensed by visible and infrared radiation. Whereas the latter waves can sense chlorophyll, water and leaves, the main objectives of recording via microwaves up to now are canopy structure, vegetation type and biomass.

Satellites operate on artificially created microwaves, which are commonly called **radar-waves**. Some radar-wave configurations that are used on modern satellites are listed in Table 6.3.

Table 6.3 Frequencies and wavelengths of radar bands within the 0.4–15 GHz range[a]

Letter designation	Frequency in GHz	Wavelength in cm
P-band	0.44	68
L-band	1.28	23
S-band	3.0	10
C-band	5.3	5.7
X-band	9.6	3.1

[a]Extracted from Ulaby et al. 1996 and altered. S-band wavelength corrected. Data refer to synthetic aperture radar (SAR). Additional bands can be available

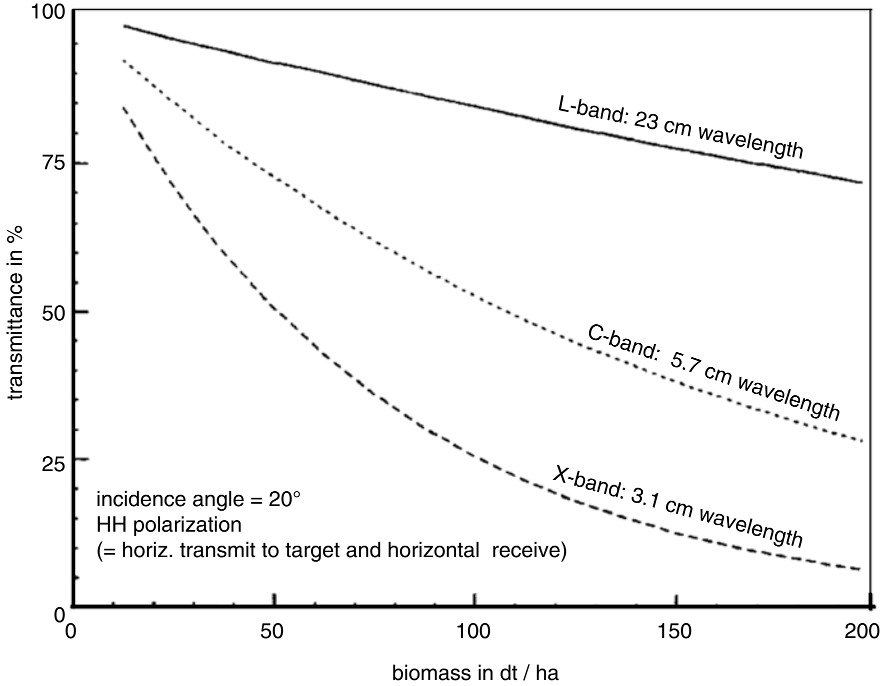


Fig. 6.19 Transmittance of radar waves though a grass canopy (From Ulaby et al. 1996, altered)

Radarwaves might penetrate crop canopies deeper than visible radiation. A rule of thumb is that for radar waves the **penetration depth** in crops is about half the wavelength (Heinzel 2007), whereas with soils it is one fifth of it (Sect. 5.2.3.2). Hence the penetration in crops is approximately 2–3 times deeper than in soils. But this is rather a rough estimation. It is not the wavelength alone that determines the penetration. Among others, the biomass of a crop (Fig. 6.19) and its water content are important.

For microwaves, a plant canopy acts similar to a three-dimensional water-bearing structure. Within this structure, especially the leaves are the carriers of water. It is mainly the effect of the **water** on the reflection that allows to sense crop properties. And regarding this water effect, the basic functioning of microwaves within canopies is very similar to that within soils. Instead of the term "reflection", for microwaves generally the notation "**backscatter**" is used. It is the backscatter that can supply signals about crop properties via remote or proximal sensing. For details to the measuring of the backscatter see Fig. 5.18.

When a canopy is closed and the radar wavelength is approximately the same size as the leaves, not much of the radiation energy may reach the soil underneath. Yet depending on the crop and its canopy, long waves may get to the soil. So if the objective is to sense only the crop without any interference by the soil below, limitations in the length of the waves might be necessary. If the signals received are partly from the crop and to some extent are influenced by the soil below, it is very difficult to interpret them.

Polarization of microwaves has become an important feature when regarding the ability to sense crop properties. Whereas for non polarized microwaves the photons vibrate around the axis of propagation in all directions at random – though the wavelength is uniform – with polarized microwaves the vibrations are restricted to a common plane (Fig. 3.6). This plane might be horizontally (H) or vertically (V) oriented. Yet the waves that are sent to the canopy and those that are returned to the receiver might not be in the same plane. Only those microwaves, which get back to the recording receiver after a **single reflection** on the surface of the canopy, maintain their original polarization or their plane of vibration. These waves are recorded by the receiver as "**like-polarized**" and represent **surface scattering**. However, this type of scattering occurs mainly with short waves.

When very short waves are excluded, the majority of the waves are thrown back and forth within the crop before eventually being scattered towards the receiver. The result is that these waves – at least partly – get back to the receiver in a depolarized state. This means, the original polarization is lost. The depolarization does not alter the wavelength. And depolarization hardly occurs with waves that hit soil instead of a crop.

Hence the amount of depolarization can help to discriminate between soil and vegetation. A radar receiver can detect the amount of depolarization and thus record **volume scattering**. For this, the emitter of the satellite might just send polarized radiation within a vertical plane and receive in a horizontal plane, or vice versa. This would be a "**cross-polarized**" operational mode, which would indicate about volume scattering.

The main orientation of the plants can affect the backscatter. For many grain crops, the stems and its leaves are mostly oriented in a vertical direction, though this might depend on the growth stage If the incident radiation has a plane of polarization that is parallel instead of cross to the main orientation of the plants, the backscatter is lower. Hence using horizontally as well as vertically oriented polarizations can allow discriminating between crops according to their canopy structure or their habitus.

Another factor that affects the radar backscatter of crop canopies as well as of soils is the incidence angle. This is the angle with which the radiation coming from the satellite hits the earth.

Which crop properties can be sensed by means of radar waves when the present possibilities of varying frequencies or wavelengths, of different polarizations as well as incidence angles are exploited? Details to this question have been dealt with by Brisco and Brown 1998; Gherboudj et al. 2011; Jiao et al. 2010; Mattia et al. 2003; McNairn et al. 2009; Shimoni et al. 2009; Steingiesser and Kühbauch 1998. Summing up, the situation is:

- Chlorophyll content cannot be recorded.
- Indication of the crop water content is unstable. The results for water sensing via infrared radiation are better (Sect. 6.5).

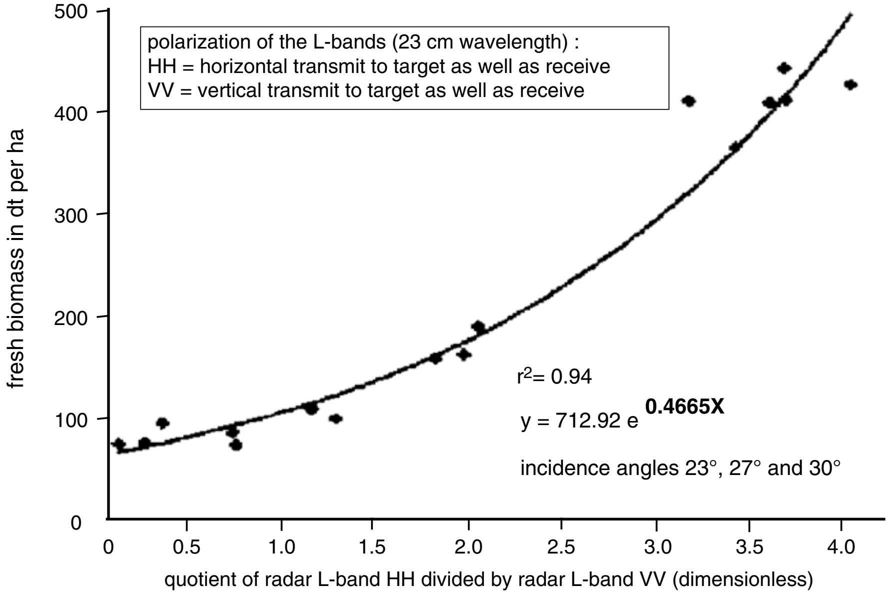


Fig. 6.20 Estimating the biomass of winter barley via a quotient of like-polarized radar waves and remote sensing from satellite (From Kühbauch and Hawlitschka 2003, altered)

- Recording of the height and the biomass of vegetation is possible. Non-polarized radiation might just provide rough estimates, whereas fully exploiting the potentials of polarization allows precise indications (Fig. 6.20).
- Leaf-area-index can be indicated if the wavelength fits to the crop. With maize, the L-band (23 cm wavelength) provided good results whereas the X-band (3.1 cm wavelength) completely failed (Jiao et al. 2010).
- Crop classification for wide area monitoring and mapping is possible. This is the main present application. Supplementing the indications based on radar by estimations that rely on visible and infrared radiation is not necessary.

Modern radar satellites can provide the spatial resolution that is needed for site-specific farming. The resolutions that can be obtained go down to a few m. And regarding the temporal resolution, the prospects too are good because the number of satellites is increasing. This means that temporal limitations for receiving information about crop properties via remote microwave sensing probably will not exist any more in the future. The information can be supplied day and night irrespective of clouds and haze. Only heavy precipitation might prevent the use. Because of the almost unlimited temporal possibilities, proximal sensing of crop properties via radar does not seem attractive. At least not as long as proximal sensing needs the attention of a driver and therefore is difficult to repeat any time.

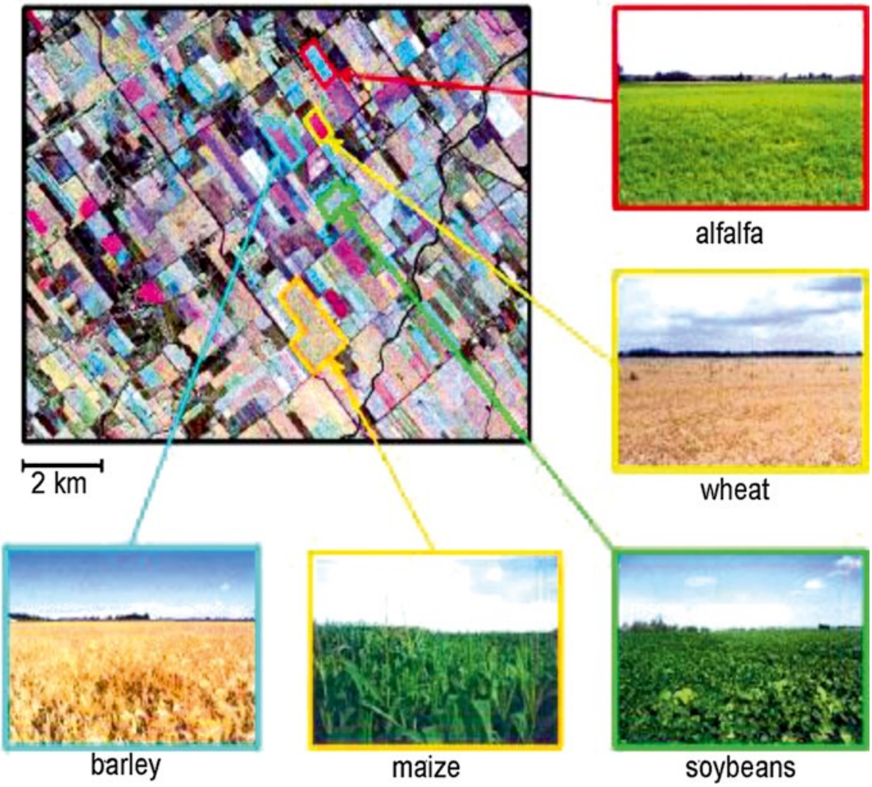


Fig. 6.21 Georeferenced and mapped crops (*top left*) that were classified via polarized radar from satellite within a wide area (From Pottier and Ferro-Famil 2004, altered)

Up to now, the most frequent agricultural application of remote sensing via radar waves is **crop classification** (Fig. 6.21). It provides a fast record about the areas of crops that are growing within wide regions. This information is used by governmental departments, farm agencies and agribusiness institutions for planning purposes.

Monitoring and mapping the **condition of crops** – *e.g.* by recording the site-specific biomass or leaf-area-index several times during the season – could be a domain of application within single farms as well. It might be questioned whether it suffices to record the biomass or the leaf-area-index or whether in addition the chlorophyll within the leaves should be detected, as it is possible when using visible and infrared radiation. The answer to this question might – on the one hand – depend on crop type. Because precise yield estimates during the growing period for grain crops might require more information than those for forage crops. On the other hand, the operational possibilities must be considered. Because in maritime areas, long time spans can occur during which clouds prevent any remote sensing from satellites for visible and infrared radiation.

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