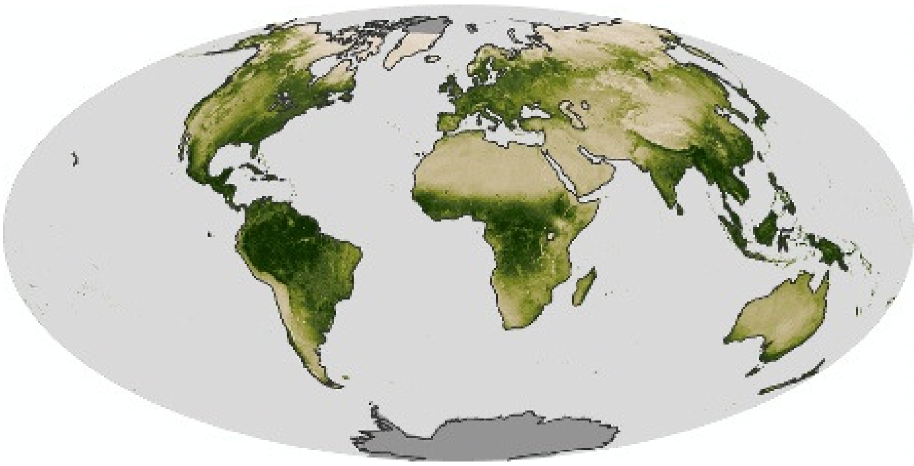
The application of remote sensing in vegetation science



Bachelor thesis by Nicky Lustenhouwer

October-December 2009

Student number: s1610422
Supervisors: Prof. dr. H. Olff & Drs. J.L. Ruifrok
Community and Conservation Ecology Group
Faculty of Mathematics and Natural Sciences
University of Groningen

Index

Abstract

Over the past decades, the discipline of remote sensing has become an essential tool in earth sciences for land-use studies, biogeography and many other applications. Remote sensing has also become of increasing interest to ecologists, especially for monitoring the presence, biophysical properties and seasonal dynamics of vegetation. Many applications of remote sensing in vegetation science are based on the fact that the amount of electromagnetic energy that is reflected by vegetation, depends on the biophysical and structural properties of the vegetation.

The goal of this study is to give an overview of the current and possible future applications of remote sensing in vegetation science. The basic principles of remote sensing are explained, as well as the different spectral, spatial and temporal scales at which remote sensing can be applied in vegetation ecology. Remote sensing can be used to measure a variety of vegetation properties. Mapping studies develop maps of vegetation distribution at the community and species level. By using spectral vegetation indices such as the NDVI, biophysical properties such as LAI, NPP and biomass can be estimated. The main research themes where these measurements are used range from studies of individual plants to ecosystems and relationships with the environment.

The many possibilities that remote sensing has to offer to vegetation science compensate easily for the existing limitations of this interesting technology.

[1] Image on the front page: global distribution of vegetation as measured by remote sensing in October 2009. (Source: http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=MOD13A2_M_NDVI#)

Introduction

Over the past decades, the discipline of remote sensing[2] has become an essential tool in earth sciences for land-use studies, biogeography and many other applications (de Jong et al. 2008). The field of remote sensing has also become of increasing interest to ecologists. Satellite-based observations are being used for fundamental ecological research as well as for applications in conservation biology (Kerr & Ostrovsky 2003). The use of satellite imagery can be an useful addition to ecological fieldwork, when studying large or inaccessible areas. Furthermore, the long time series of several satellite missions make it possible to look back in time, which can be very interesting in studying long-term processes such as vegetation succession.

Remote sensing is particularly useful in monitoring the presence, biophysical properties and seasonal dynamics of vegetation. The scientific basis of one of the most important satellite missions, the Landsat program, lies in the fact that photosynthetically active vegetation produces an unique electromagnetic reflectance spectrum (Cohen & Goward 2004). The fast development of remote sensing techniques has led to a renewed interest in vegetation patterns and processes, from a local to a global scale. Vegetation ecologists and remote sensing specialists are increasingly working together, analyzing the digital maps and imagery provided by remote sensing (Walsh & Davis 1994).

The goal of this study is to give an overview of the current and possible future applications of remote sensing in vegetation science. First of all, the basic principles of remote sensing are explained, such as the components of a remote sensing system and the presentation of remotely sensed data. After that the different spectral, spatial and temporal scales at which remote sensing can be used in vegetation science will be discussed. The third part of this review gives an overview of the vegetation properties that can be measured by using remote sensing. A distinction is made between mapping studies and estimations of biophysical variables. These measurements are integrated into a discussion of the main research themes in vegetation ecology where remote sensing can be applied. Finally, the possible limitations of remote sensing applications in vegetation ecology are described.

This review does not cover an inclusive list of all the possible applications of remote sensing in vegetation ecology; these are already endless and many hundreds to thousands of papers have been written that cover some part of the possibilities. It does, however, provide an insight into the basic principles of remote sensing and its main applications in vegetation science. The ecological reasoning behind the measurements and applications will be explained, to give vegetation ecologists who would like to know more about the potential of remote sensing a basis for a further understanding of the possibilities in their specific area of research.

[2] A definition of remote sensing and other terms can be found in Appendix II.

Introduction to remote sensing

To be able to understand the many possible applications of remote sensing in ecology, a deeper understanding of remote sensing technology is required. The basis of remote sensing is the detection of electromagnetic energy using a space borne or airborne sensor. A remote sensing system generally consists of four components: a source of electromagnetic energy, the interaction of this energy with the atmosphere and with an object of interest on the Earth's surface, and a sensor that can register the amount of reflected or emitted energy (de Jong et al. 2008).

The electromagnetic spectrum can be divided into two wavelength regions, the optical (~0.4-14µm) and microwave (~1mm-1m) wavelengths (Figure 1). Optical sensors usually register the amount of reflected radiation in the wavelength intervals of visible light (blue, green and red), near- and middle-infrared radiation and thermal radiation. Only a small portion of the microwave region of the electromagnetic spectrum is used by remote sensing, namely by radar technologies. This concerns a range of wavelengths from 0.75 to 30 cm (Figure 1). Optical and microwave remote sensing each have their own distinct sensors and applications (Turner et al. 2003).

The main sources of electromagnetic energy are radiation from the Sun, reflected by the object of interest on the Earth's surface, and the heat emitted by the Earth itself. However, artificial sources of energy also exist. The source of energy is used to divide remote sensing systems into active and passive systems. In passive systems, a sensor registers the amount of radiation from the Sun that is reflected by the object of interest. A wide variety of sensors is available. These measure different wavelength intervals of the electromagnetic spectrum ("bands" or "channels") and also differ in quality of registration. In active systems, an artificial energy source emits radiation, for example radar, and a sensor registers the amount that is reflected (de Jong et al. 2008; Turner et al. 2003).

The properties of the sensor used in a remote sensing system define the characteristics and therefore the applicability of the acquired data. A sensor records electromagnetic energy, converts it to an electrical pulse and stores it in a suitable format, which is usually a digital format. A sensor can be embedded in a scanner, an instrument (carried by a satellite or aircraft) which sweeps across a terrain and combines many small parallel images into one image (de Jong et al. 2008). The most basic form of remote sensing are cameras, used for taking aerial photographs. However, cameras can take a picture of only one part of the electromagnetic spectrum at a time.

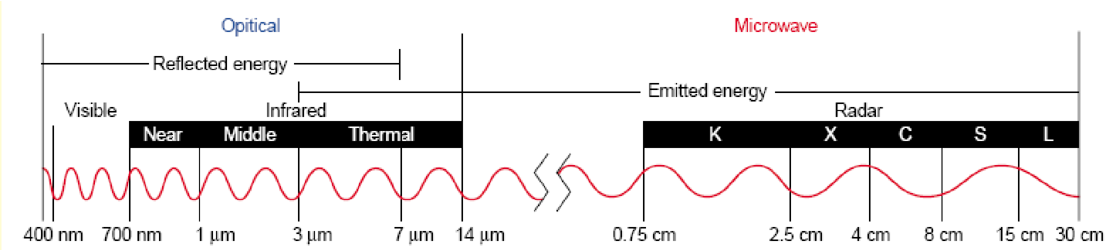


Figure 1. The electromagnetic spectrum. *(Turner et al. 2003)*

Multispectral scanners are usually mounted on satellites and take images of the same area at a small number of broad wavelength bands (Wadsworth & Treweek 1999). Examples of important satellite sensor systems that are discussed in this paper are the Landsat ETM+, SPOT-VGT, AVHRR, IKONOS and MODIS (Kerr & Ostrovsky 2003; Appendix I).

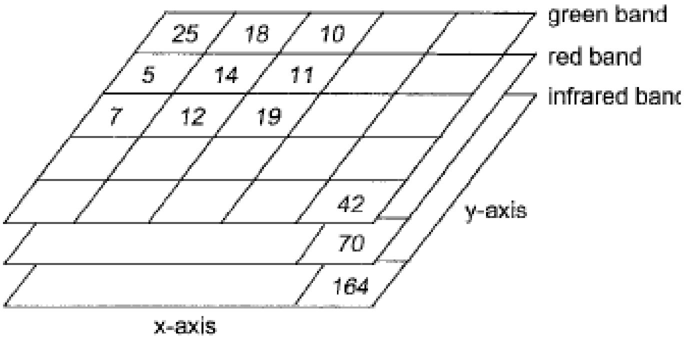
The majority of the energy that is sent form the source to the Earth's surface, never reaches the sensor again, because of interactions with the atmosphere and with the object of interest. Part of the radiation is absorbed by clouds or by the atmosphere. This absorption is wavelength dependent. The majority of UV-radiation, for example, is absorbed by the atmosphere. The parts of the spectrum that are transmitted by the atmosphere, are called atmospheric windows. The radiation that was not absorbed, can be scattered in many directions. The susceptibility to scattering differs among wavelengths. For example, the human eye registers the sky as blue, because blue light is scattered easily in the atmosphere. The amount of atmospheric absorption and scattering also depend on atmospheric conditions. Because these very in space and time, it can be very difficult to correct images for atmospheric distortion (de Jong et al. 2008).

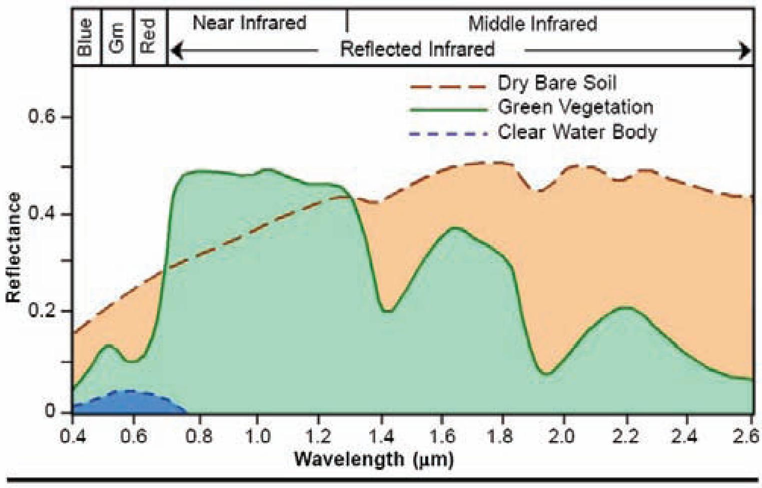
When the radiation reaches the Earth's surface, part of it is absorbed, transmitted or scattered by the objects on the surface. The amount of reflected radiation depends on the characteristics of the object of interest and on the wavelength of the radiation. Because the reflected energy is sent in many directions, only part of it reaches the sensor. This effect is stronger in areas with more variation in elevation (de Jong et al. 2008). Naturally, these and other limitations force remote sensing specialists to apply a lot of techniques and corrections to produce an image that is ready for use. For the purposes of this paper, it will be assumed that these technical problems have been overcome and that an already pre-processed image is ready to be analyzed.

Presentation of remotely sensed data

Remotely sensed data are usually stored in a matrix of pixels. The area of the square of surface corresponding to a digital pixel varies from a square meter to several square kilometers, depending on the sensor used. Digital remote sensing data can be visually presented in multiple ways, but the most natural way is by presenting it in a two-dimensional picture, called the image space. This method will be further clarified in the case of multispectral systems, because these are most commonly used in vegetation related remote sensing.

A multispectral scanner records, for each individual pixel, the amount of reflection of radiation in the different wavelength bands. A multispectral scanner consisting of seven bands, like the Landsat 7 ETM, will produce seven different images, one for each band (Figure 2). Because the human eye can only see combinations of three colors, a combination of three bands will have to be chosen to visualize in a picture. A true color picture will present the visual light bands of blue, green and red (band 1, 2 and 3) as blue, green and red in a picture. This is noted as "(RGB=123)".





Top: **Figure 2.** Digital representation of data *(Cohen et al. 1996)*
Bottom: **Figure 4.** Spectral signatures of dry bare soil, green vegetation and clear water. *(Govender et al. 2007)*

Figure 3. The Utrecht area, in true color (RGB=123; top) and false color (RGB=432; bottom). Vegetation is clearly red in the bottom picture. *(de Jong et al. 2008)*

False color pictures can reveal different kinds of information. When using the near-infrared (NIR), red and green bands (RGB=432), vegetation will turn red because of its high reflectance in NIR (Figure 3).It is also possible to see the difference between agricultural land and forest. The forest in Figure 3 has a darker red color, because it has more differences in elevation and therefore more scattering and less reflection (de Jong et al. 2008).

Because the amount of reflection at different wavelengths depends on the properties of the object of interest, it is possible to create different classes, for example different types of vegetation, soil and water. This is the basis of image classification, which aims to assign each pixel to a class, using a variety of statistical methods. Based on a classified image, it is possible to produce spectral signatures of each class (Figure 4). A spectral signature shows the reflectance of a single class at the different wavelengths. The typical spectral signature of vegetation has a small peak in the green and a high peak in the NIR region (Govender et al. 2007).

Scales and sensors

Remote sensing can be used in vegetation science at a number of spectral, spatial and temporal scales. Because emerging new technologies are enabling more detailed coverage, the term “hyper” remote sensing is becoming common practice. Hyperspectral and hyperspatial systems create possibilities to accomplish ecological measurements directly from remotely sensed imagery (Chambers et al. 2007). This section gives an overview of the spectral, spatial and temporal scales of remote sensing in vegetation science, and concludes with an overview of the corresponding sensors.

Spectral scales

The spectral resolution of a remote sensing image refers to the number and width of the portions of the electromagnetic spectrum used by the sensor. A higher spectral resolution therefore means that you can discriminate better between different elements in a picture (Govender et al. 2007). Because of this reason, there is an increasing interest in hyperspectral imagery. Conventional multispectral scanners record the amount of reflectance in a small number of broad bands in the optical part of the spectrum. In contrast, hyperspectral systems measure the reflectance in approximately 200 narrow bands, thus constructing an almost continuous reflectance spectrum. This enables researchers to register many more individual properties of the objects of interest (Govender et al. 2007).

The potential of the use of hyperspectral imagery for identifying structural and physiological properties of vegetation has been the subject of many investigations over the last decade (Govender et al. 2007). The spectral signatures of both deciduous and coniferous canopies are for example determined by a combination of these factors. In tropical rainforest research, different absorption features can be distinguished, such as leaf pigments, canopy structure and water content (Chambers et al. 2007). Because of its detailed registration hyperspectral imagery also enables scientists to distinguish between individual plant species, for instance by studying the variability in leaf structure (Govender et al. 2007) or leaf phenology (Gillespie et al. 2008). Promising though hyperspectral remote sensing might seem, it still is a very new technology, even to remote sensing specialists. The higher costs of data and the special atmospheric corrections and expert knowledge needed are still limiting ecological research in this area (Shippert 2004).

Multispectral and hyperspectral remote sensing both operate in the optical part of the electromagnetic spectrum. In the microwave region, radar technologies are a promise for the future. A major advantage of radar is that radio waves can penetrate through cloud cover and canopies, which is especially valuable in tropical areas (Gillespie et al. 2008). The backscattering of radar waves depends on forest structure and moisture, enabling applications such as vegetation type mapping and biomass measurements (Chambers et al. 2007).

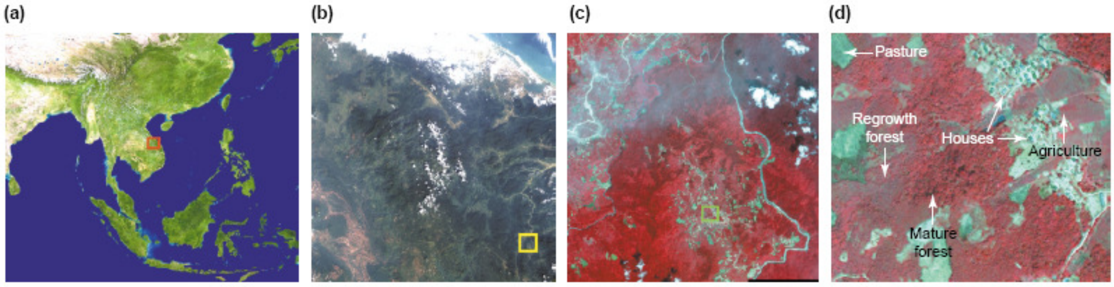


Figure 5. Satellite images from three sensors with local to global spatial resolutions. a) MODIS, south-east Asia. b) Landsat 7 ETM+, central Vietnam. c) IKONOS, 108.6 km^2 region in Vietnam (RGB=432). d) close-up with different land-uses. *(Turner et al. 2003)*

Spatial scales

The spatial resolution of an image is the amount of spatial detail that can be interpreted from the image. In an image with a higher spatial resolution, smaller objects can still be interpreted as separate entities. Because the smallest distinguishable object has to be bigger than a pixel, the pixel size determines the spatial resolution. The available sensors vary in pixel size from a square meter to several square kilometers and can therefore be used at different spatial scales, from local to regional and global (Figure 5). Airborne sensors generally have a higher spatial resolution than satellite sensors, because they are closer to the ground (Govender et al. 2007).

Hyperspatial sensors have a maximum spatial resolution of 1 m^2. These are usually part of commercial satellite systems that have emerged over the last decade, such as IKONOS and Quickbird. The introduction of fine spatial-resolution imagery has facilitated a shift in interest from the mapping of general vegetation types to identifying very specific classes such as tree species (Foody 2008). In a hyperspatial image, an individual tree crown is part of many pixels. This way, forest structure can be investigated at the scale of individual trees over large areas. Current methodological issues are the high cost and limited coverage of hyperspatial data and the validation of remotely sensed data with ecological field data, which are collected at a different spatial scale. An integration with hyperspectral imagery could help overcome these problems (Chambers et al. 2007; Kerr & Ostrovsky 2003).

Temporal scales

The available scientific and commercial satellite systems vary in temporal coverage. The revisit time of a satellite to the same area varies from twice-daily by the meteorological satellites carrying AVHRR sensors, to 26 days by the vegetation monitoring satellite SPOT (Appendix I). Hypertemporal systems have a maximal revisit time of one day. A regular coverage of the same area increases the change of obtaining cloud-free images (Chambers et al. 2007). Additionally, the history of a satellite mission is important. AVHRR data have been recorded almost daily for 25 years and are the only near-continuous, long-time source of measurements of key ecological parameters. Landsat sensors are used less because of their longer revisit time of 16-18 days, despite their longer history (since 1972) and better spatial resolution (Kerr & Ostrovsky 2003).

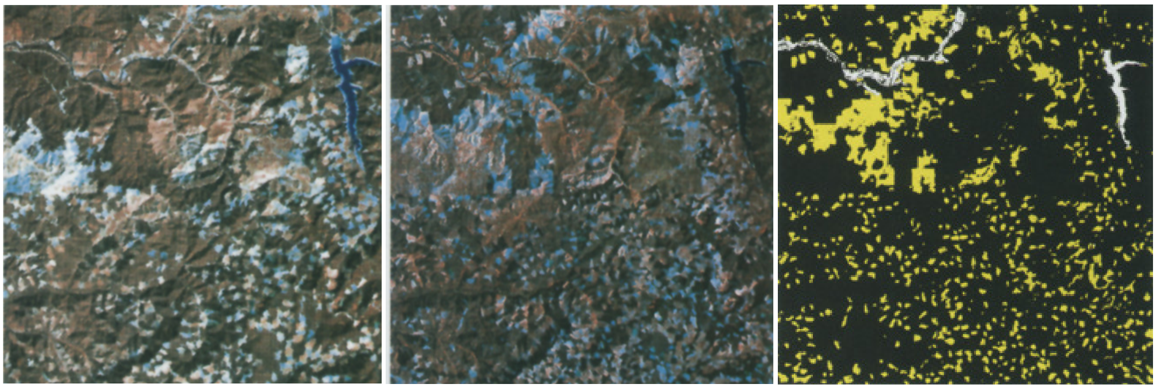


Figure 6. An example of change detection, applied in forestry. A three band, false color image of the same area in 1972 (left) and 1991 (middle). The right image was create by subtracting the 1991 image from the 1972 image. Yellow areas are harvested forest, black areas are non-harvested forest and white areas are no forest. *(Cohen et al. 1996)*

The long running-time of remote sensing programs is the basis of one of the major advantages of remote sensing for ecological studies: the ability to look back in time. Both the seasonal and inter-annual temporal dynamics of ecosystems can be characterized. The focus of intra-annual analyzes lies on phenological events, such as the variation in greenness of leaves over a year and the senescence of vegetation (Cohen & Goward 2004).

The assessment of changes in vegetation state at various temporal scales is usually referred to as change detection. This application is widespread, for example in studying land-use changes, vegetation succession, climate change and the effects of a range of environmental parameters on vegetation (Cohen et al. 1996; Cohen & Goward 2004; Kerr & Ostrovsky 2003; Turner et al. 2003). To detect changes, an image can be analyzed on a pixel-by-pixel basis by simply subtracting the value of a pixel at one date from the value at another date (Figure 6). This is not only possible for the original images, but also after image transformations or classifications.

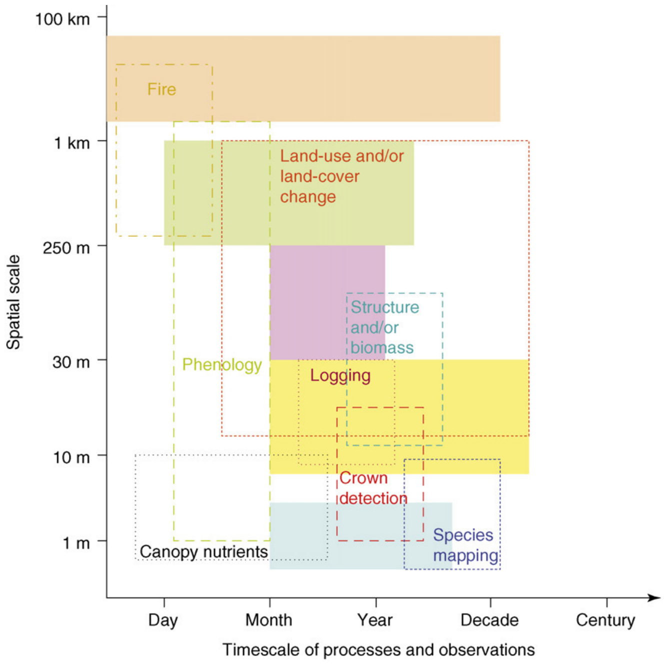


Figure 7. Different applications of remote sensing in tropical rainforest studies. The colored boxes show the spatial and temporal ranges of several sensors: GOES (red), MODIS (green), Radar and laser (pink), Landsat (yellow) and IKONOS (blue). *(Chambers et al. 2007)*

Remote sensing is available at a great variety of spectral, spatial and temporal scales. There is usually a trade-off between high resolution spatial, temporal and spectral imagery: no sensor has it all. For each ecological application, an unique combination of scales and sensors is suitable (Figure 7).

Vegetation properties that can be measured

Remote sensing can be used to measure a variety of vegetation properties. The most basic method is identifying plant communities or species to create a vegetation map. These mapping studies for instance investigate land-cover transitions, species distributions and landscape heterogeneity and fragmentation. Other studies use remotely derived indices and remote sensing models to estimate biophysical properties of vegetation, such as leaf area index, net primary production and biomass (Wulder et al. 2004). Many of these measurements are based on spectral vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). This section gives an overview of the vegetation characteristics that can be measured in mapping and biophysical studies and explains the basic methods to determine these characteristics.

Mapping studies

Mapping studies are based on land cover classification. The thematic classification of a remotely sensed image is the critical step in creating vegetation maps. Depending on the spectral and spatial scale of an image, vegetation communities or species can be identified and classified. High spatial resolution images, where the objects of interest are bigger than a single pixel, are especially suitable for classification (McDermid et al. 2005). Hyperspectral imagery enables the analyst to use the unique spectral properties of individual species and create more detailed classes of vegetation cover (Govender et al. 2007).

Land cover classification studies are common work in research management, for example in forestry. Many of these applications, such as assessing forest fragmentation, successional stage and the location of endangered plant species, are also interesting for vegetation ecologists (Cohen & Goward 2004). Land-use studies using multispectral scanners can identify the location of agriculture and built areas and of simple biome types such as broad-leaf and coniferous forests, wetlands, shrub lands and savanna (Figure 8).

With hyperspectral imagery, more detailed vegetation surveys are possible. The determination of the community composition or even the species distribution is based on the different spectral properties of plant species. The photosynthetic

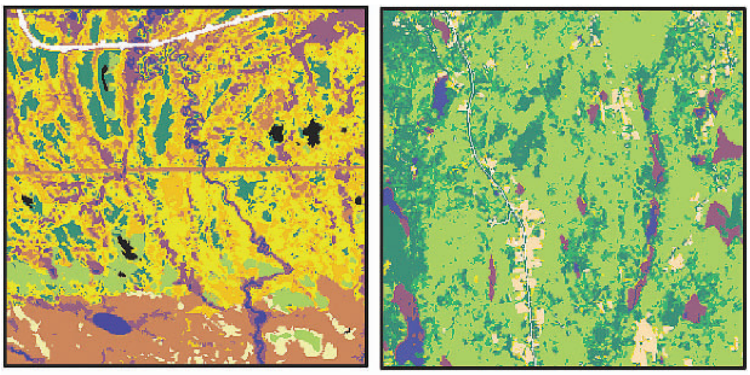


Figure 8. Maps of land and forest cover for 7-km by 7-km sections of boreal forest in northern Canada (left) and mixed deciduous evergreen forest in eastern Massachusetts (right), derived from Landsat ETM+ data. *(Cohen & Goward 2004)*

pigments, cell structure and water content of a plant determine the absorption and reflection of radiation in the optical wavelengths of the electromagnetic spectrum (Figure 9).

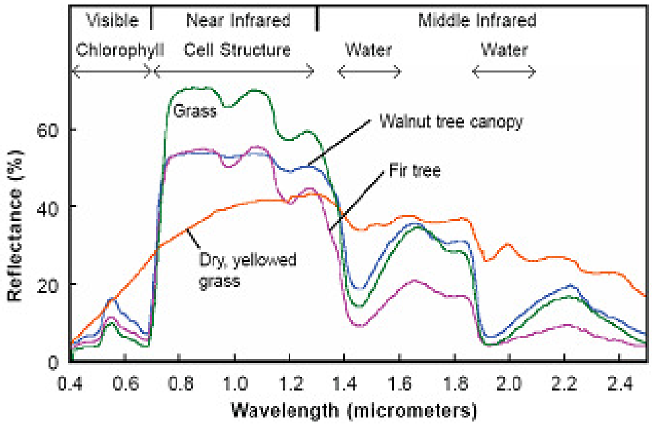


Figure 9. Reflectance spectra of different types of green vegetation compared to a spectral signature for senescent leaves. *(Govender et al. 2007)*

In green vegetation, the reflectance spectrum at the visible wavelengths (400-700 nm) is dominated by the strong absorption of light by photosynthetic pigments. A peak of reflection in the green wavelengths is typical for chlorophyll. Analysis of the relative contribution of chlorophylls and the other major plant pigment classes, carotenoids (yellow-orange) and anthocyanins (red-purple), can provide insight into photosynthetic activity and plant stress (Ustin et al. 2004).

The near infrared region (NIR, 700-1100 nm) is characterized by limited biochemical absorption and high reflection. A small amount of radiation is absorbed by water and structural compounds such as cellulose and lignin. The high reflectance is caused by the internal structure of plant cells: the way in which radiation is scattered depends on the location of cell walls and air and water spaces (Ustin et al. 2004). There is a lot of structural variability between species. However, species identification can still be difficult because the NIR reflectance is also influenced by plant stress and canopy architecture. On the other hand, the fact that vegetation under stress has a different spectral signature can be very helpful in analyzing vegetation disturbance when studying a single species (Govender et al. 2007).

The middle infrared region (1100-2500 nm, also called shortwave infrared), is also characterized by much reflection and few absorption. However, two clear water absorption bands exist at 1.4 and 1.9 nm (Figure 9). In dry leaves, the reflection is determined by structural compounds and plant biochemicals, which have broad overlapping reflectance spectra over the whole region (Ustin et al. 2004). The middle infrared region is especially important in the study of forest vegetation. It explains most of the variation in Landsat TM data associated with forest structure and is an important region for the estimation of LAI and forest volume. Many of these applications are based on the sensitivity of the middle infrared region to moisture (Cohen & Goward 2004).

The spectral signatures of plants that have been produced using the methods above, can be compared to spectral libraries, in order to quickly identify species and produce vegetation maps (Turner et al. 2003). However, expert ecological knowledge of the relevant species or ecosystems can still be needed to improve the quality of the produced map (Schmidt 2003).

Biophysical studies

In addition to its important role in the development of vegetation maps, remote sensing has been a tool in research on a range of biophysical vegetation properties, such as primary productivity, leaf area index (LAI) and chlorophyll content. Vegetation indices (VIs) have played a central role in the estimation of these variables by remote sensing, because of their relation to the absorption of photosynthetic active radiation (PAR) by chlorophyll (Pettorelli et al. 2005). Therefore, the principles behind VIs and their relation to photosynthesis and other biophysical processes will be described.

As noted before, vegetation typically has a very low reflection of red light and a very high reflection of NIR radiation. This great contrast in reflection within a small range of wavelengths is the basis of VIs. These are usually calculated by taking the ratio between the values of reflection in the NIR and the red bands of an image. The most-used vegetation index is the NDVI:

$$NDVI = \frac{\rho NIR - \rho Red}{\rho NIR + \rho Red}$$

where ρNIR is the reflection in the near-infrared part of the spectrum and ρRed is the reflection in the red part of the spectrum. The resulting NDVI values range from -1 to +1. The higher the value, the greater the difference between NIR and red reflection. This means that high positive NDVI values correspond to high amounts of photosynthetic active vegetation. Water has a negative NDVI value, because it absorbs more NIR radiation than red light. Soils generally have slightly positive values (Glenn et al. 2008). The spectral profiles of vegetation, water and soil are shown in figure 4.

The NDVI can be interpreted and used in multiple ways. The contrast between red and NIR reflectance in vegetation originates from a combination of leaf chlorophyll content, leaf area and canopy cover and structure. Hence, the most direct way to consider the NDVI is as a measure of the overall presence of healthy vegetation in an area (Glenn et al. 2008). In this context, NDVI values were originally used to create vegetation maps and to monitor phenological events, such as the beginning of the growing season (Pettorelli et al. 2005). Figure 10 shows the course of NDVI values during a growing season in Norway.

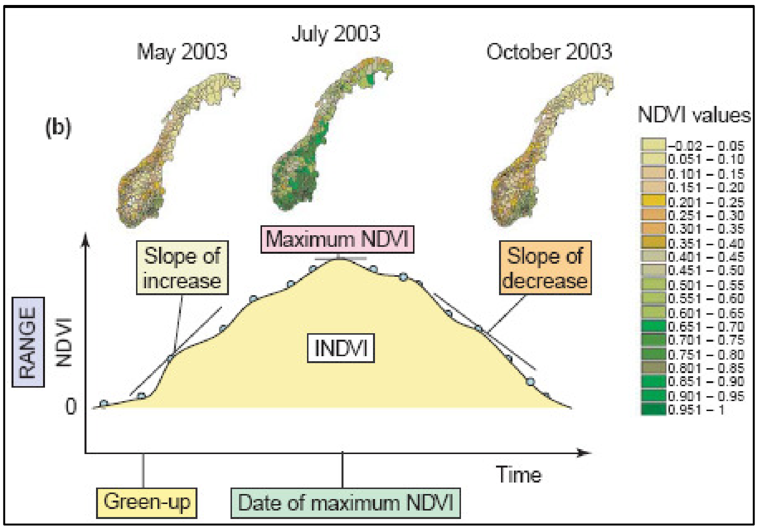


Figure 10. Different indices derived from NDVI time series, and maps of NDVI values for Norway in spring, summer and autumn. The INDVI is the sum of NDVI values over a year. The date of green-up marks the beginning of the growing season. *(Pettorelli et al. 2005)*

However, VIs are also used as indirect estimates of biophysical vegetation properties. The difference in red and NIR reflectance partly originates from the absorption of red light by chlorophyll; this means that VIs are strongly related to the fraction of photosynthetic active radiation (fPAR) absorbed by vegetation. VIs are therefore used in the study of processes related to fPAR (Pettorelli et al. 2005). The fPAR and the photosynthetic capacity of a plant are naturally linked. However, plant transpiration can also be studied, because both processes are determined by stomatal conduction (Glenn et al. 2008).

Remote sensing is used to estimate many variables in physiological models, such as the LAI, net primary productivity (NPP) and biomass (Wulder et al. 2004). Unfortunately, the LAI cannot be measured directly by satellite sensors. Because both LAI and VIs are related to light absorption by a canopy (Glenn et al. 2008), there is usually a significant correlation between LAI and NDVI (Turner et al. 2004). There are however many possible causes of errors, such as differences in leaf angle between species and different methods of ground measurements (Glenn et al. 2008), insufficient temporal or spatial scales of measurement and the presence of underlying vegetation (Wulder et al. 2004), and the nonlinear relationship between NDVI and LAI (Turner et al. 2004). Estimates of LAI by NDVI should therefore be analyzed critically, and have to be combined with field data (Glenn et al. 2008).

The NDVI is frequently used to estimate NPP (Cohen & Goward 2004; Kerr & Ostrovsky 2003; Walsh & Davis 1994; Wulder et al. 2004). An important factor in the correlation between NPP and NDVI is the strong correlation between NDVI and fPAR (Kerr & Ostrovsky 2003). This can be shown in a series of equations. NPP is defined as the gross primary production (GPP) minus plant respiration. GPP can be calculated as follows (Glenn et al. 2008):

GPP = Light use efficiency (LUE) x fPAR x PAR

This means that the amount of CO_2 that is fixed by a plant during photosynthesis is calculated by multiplying the conversion efficiency of PAR, the fraction of PAR that is absorbed and the amount of PAR available to the plant. Because of the strong correlation between NDVI and fPAR, this can also be written down as (Glenn et al. 2008):

GPP = LUE x NDVI x PAR → NPP= LUE x NDVI x PAR – Plant respiration

The light use efficiency mentioned above is also an interesting parameter for vegetation ecologists. However, it is currently not estimated by using remote sensing, but by using models including a variety of parameters estimated for different biomes (Glenn et al. 2008).

The third important parameter that can be estimated using the NDVI is biomass. The reasoning behind this is easy, because the increase in biomass of a plant depends on its photosynthetic activity and the resulting primary production. The NDVI is above all a measure of the amount of healthy vegetation present in a pixel, e.g. of the amount of plant biomass present. To quantify the amount and temporal variability in biomass, a number of additional indices have been developed, such as the Integrated NDVI (INDVI) and the Annual Maximum NDVI (Figure

10). Turner *et al.* (2004) note that the NDVI is mainly sensitive to green leaves, and less to other parts of vegetation such as stems and roots. Radar technologies are more sensitive to these structural properties of vegetation. However, both NDVI and radar show an asymptotic relationship with biomass.

LAI, NPP and biomass are certainly not all the biophysical vegetation properties that can be estimated using the NDVI or remote sensing in general. Other measurable vegetation characteristics mentioned in literature include evapotranspiration, specific leaf area, canopy cover, canopy nutrient and moisture content, drought responses and crown area (Chambers et al. 2007; Cohen & Goward 2004; Govender et al. 2007; Pettorelli et al. 2005; Walsh & Davis 1994). In most of these cases, the estimations should be analyzed critically to avoid misinterpretations because of non-linear or area-dependent relationships, the effects of underlying soil characteristics or many other possible causes of errors and uncertainties. Glenn et al. (2008) therefore advise to use VIs only as a measure of canopy light absorption. Some issues can be overcome by using other VIs, that were developed to overcome some limitations of the NDVI. Nevertheless, the NDVI remains the most used and most studied spectral vegetation index (Kerr & Ostrovsky 2003).

Main application themes

The previous sections have shown that remote sensing can be applied in vegetation ecology at a range of spectral, spatial and temporal scales. This results in a combination of maps, measurements and models of a great number of vegetation properties. This final section gives an overview of the main research themes in vegetation ecology were remote sensing technologies are applied, from the study of the characteristics of individual plants to ecosystem properties and the relation between vegetation and the environment.

The reflectance spectra of vegetation are determined by a combination of structural and biochemical properties. This means that at the level of individual plants, plant ecophysiology and vegetation structure can be studied. An example of the use of remote sensing in determining vegetation structure is the investigation of the size distribution of individual trees in tropical rainforests. The results provide insight into forest structure and development over large areas (Chambers et al. 2007). The study of biophysical (LAI, NPP, biomass) and biochemical (chlorophyll, water and nutrient content) properties of plants is important in determining ecosystem condition and the presence of environmental stress (Ustin et al. 2004).

Remote sensing is used in particular in studies at the scale of communities or ecosystems, because of its information cover of large and inaccessible areas (Foody 2008). Land-cover studies and classifications are used to study spatial patterns of vegetation, such as vegetation cover, heterogeneity measures and fragmentation (Cohen & Goward 2004). Multi-date measurements provide insight into the temporal dynamics of vegetation cover and thus enable studies of vegetation succession. Hypertemporal imagery is also widely used to study phenological events. Because of the application of remote sensing, the attention in phenological studies has shifted from individual plants to the phenology of entire ecosystems (Reed et al. 1994). The NDVI is a measure of the photosynthetic activity of vegetation and is therefore an important tool in the study of phenological processes. Reed et al. (1994) have developed 12 measures, derived from NDVI data, to assess different aspects of phenology (Table 1). These phenological measures can especially be useful in monitoring ecosystem responses to environmental change.

The effect of the environment on vegetation is the third major research area were remote sensing is applied. Data of vegetation distributions can be analyzed in combination with data of physical environmental gradients, such as variation in elevation and temperature. Variation in topography causes variation in water, nutrient and energy availability. Consequently, digital elevation models are used in many studies considering the relation between vegetation and abiotic environmental factors (Walsh & Davis 1994). Raynolds et al. (2008) found a positive relationship between the NDVI and land surface temperature in arctic vegetation (Figure 11). This result is important for the understanding of the distribution of arctic vegetation and to predict in which arctic areas the vegetation composition will change most due to climate change.

The study of the influence of climate change and other (human or natural) disturbances on vegetation is a research area where remote sensing can be valuable from a conservation point of view. Remote sensing can provide both evidence for climate change and a way to monitor the consequences. By analyzing NDVI values of 1981-1999, the length of the growing season and the annual primary productivity have been shown to increase (Kerr & Ostrovsky 2003). Other disturbances that can be identified and monitored using remote sensing are fire, deforestation, drought and frost (Kerr & Ostrovsky 2003; Pettorelli et al. 2005). The possibility to create detailed maps by using remote sensing, enables vegetation ecologists to monitor the distribution and health of vegetation that is threatened by the increasing human impact on nature.

Metric	Phenological interpretation
Temporal NDVI metrics	
Time of onset of greenness	Beginning of measureable photosynthesis
Time of end of greenness	Cessation of measureable photosynthesis
Duration of greenness	Duration of photosynthetic activity
Time of maximum NDVI	Time of maximum measureable photosynthesis
NDVI-value metrics	
Value of onset of greenness	Level of photosynthetic activity at beginning of growing season
Value of end of greenness	Level of photosynthetic activity at end of growing season
Value of maximum NDVI	Maximum measureable level of photosynthetic activity
Range of NDVI	Range of measureable photosynthetic activity
Derived metrics	
Time-integrated NDVI	Net primary production
Rate of greenup	Acceleration of photosynthesis
Rate of senescence	Deceleration of photosynthesis
Modality	Periodicity of photosynthetic activity

Table 1. 12 measures of phenological phenomena, derived from NDVI time series. *(Reed et al. 1994)*

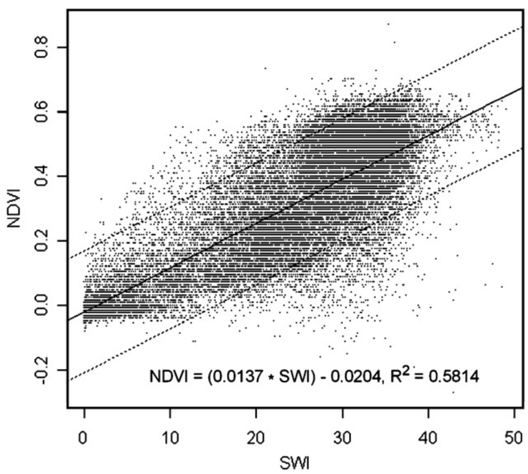


Figure 11. Regression analysis of NDVI as a function of summer warmth index (SWI), a measure of land surface temperature. Regression line ± 1 S.D. *(Raynolds et al. 2008)*

Limitations

Remote sensing offers seemingly endless possibilities for the study of vegetation patterns and properties. However, vegetation ecologists face many problems and challenges when applying remote sensing to their research. The field of remote sensing has been the domain of remote sensing geologists for decades, and acquiring the required technical expertise as an ecologist can be a severe obstacle (Turner et al. 2003).

The financial consequences of using remote sensing also have to be taken into account. Although field work can be very time consuming and expensive, remote sensing comes with its own costs of data and special software- and hardware tools. However, an increasing amount of data from governmental satellites is available for free online and the costs of commercial satellite data are also decreasing (Turner et al. 2003). Nevertheless, data continuity is not guaranteed, because the future of some satellite missions, particularly Landsat, is uncertain (Foody 2008).

Remote sensing measurements always have to be validated by 'ground-truth information', to confirm that the image indeed shows the supposed objects or properties in reality. This can for instance be done by field measurements (Turner et al. 2003). It can be difficult to combine ecological field data and remote sensing data of different spatial scales. Luckily, the difference in spatial scale between field data and remote sensing data is currently declining because of the development of hyperspatial remote sensing (Kerr & Ostrovsky 2003).

Hyperspatial, -spectral and -temporal remote sensing and other new technologies such as radar are still in the development phase (Turner et al. 2003). As a consequence, the problems of data costs, data volumes and complicated data processing mechanisms are greater than for conventional methods. For this reason, multispectral systems are still favored above hyperspectral imagery (Govender et al. 2007). The exciting possibilities of hyperspectral imagery and other state of the art techniques are not yet available to a broad range of scientists.

Last but not least, the use of spatial data from ecological and remote sensing sources requires advanced statistical analyzes and error modeling. There are different methods to estimate uncertainties and an integrated spatial statistical approach is needed to accurately determine uncertainties and errors (Goodchild 1994).

The term remote sensing is often used in combination with GIS. A GIS (Geographical Information System) is a system for the input, storage, manipulation and output of spatial data. A GIS is therefore a much broader concept than remote sensing (Foody 2008). Although there are many possible data sources for a GIS, remote sensing is important because it can give a synoptic overview of very large areas. Integrating GIS and remote sensing can be problematic, because each technology has developed separately, including its own methods of data analysis and representation (Goodchild 1994). However, for the purposes of this paper it is sufficient to consider remote sensing as a source of vegetation data, that can be processed using either specific remote sensing tools or a GIS.

Conclusion

Ecologists are increasingly applying remote sensing technologies to the study of vegetation. Many applications of remote sensing in vegetation science are based on the fact that the amount of electromagnetic energy that is reflected by vegetation, depends on the biophysical and structural properties of the vegetation.

A variety of scientific and commercial satellite sensors provide remotely sensed data at different spectral, spatial and temporal scales. Hyperspectral imagery enables the analyst to better discriminate between individual plant features than with conventional multispectral scanners. Spatial scales range from several meters to thousands of kilometers and remote sensing can therefore be applied from a local to a global scale. The temporal coverage of several decades by some remote sensing systems offers ecologists the unique possibility to look back in time. Both the intra-annual (phenology) and interannual (change detection) dynamics of vegetation can be studied. There is usually a trade-off between high spectral, spatial and temporal resolution imagery; every ecological study requires its own set of sensors.

Remote sensing can be used to measure a variety of vegetation properties. Mapping studies can create vegetation maps at the community or even at the species level. With hyperspectral imagery, individual plant species can be discriminated based on the differences in reflection in the visible and near- and middle infrared regions of their spectral profile. The study of biophysical vegetation properties largely depends on estimations from vegetation indices. Because these are related to fPAR, they can be used to study processes related to photosynthesis and plant transpiration. The most used and well-studied vegetation index is the NDVI. This index can best be seen as a direct measurement of the overall presence of healthy vegetation. However, it is also frequently used to estimate biophysical variables such as LAI, NPP and biomass.

The main research themes in vegetation ecology where remote sensing can be applied concern studies of individual plants, ecosystems and environmental variables. Interesting applications can be found in plant ecophysiology, vegetation structure, the spatial and temporal dynamics of vegetation, phenology and the distribution of vegetation along environmental gradients. Remote sensing is also useful for the conservation of vegetation biodiversity, by enabling studies of the effects of climate change and other human or natural disturbances.

Naturally, remote sensing also has several limitations, especially for ecologists who are new to this originally geological field. Technical skills and special statistical methods have to be mastered and the costs of data and software can be high. High resolution methods could be valuable tools in vegetation science, but are still in the development phase. Moreover, remotely sensed data still need to be validated by field measurements. The possibilities that remote sensing has to offer to the many aspects of vegetation science described in this review are, however, more than worth the effort.

References

Chambers,J.Q., Asner,G.P., Morton,D.C., Anderson,L.O., Saatchi,S.S., Esp+¡rito-Santo,F.D.B., Palace,M. & Souza,J. 2007. Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. Trends in Ecology and Evolution 22: 414-423.

Cohen,W.B. & Goward,S.N. 2004. Landsat's role in ecological applications of remote sensing. BioScience 54: 535-545.

Cohen,W.B., Kushla,J.D., Ripple,W.J. & Garman,S.L. 1996. An introduction to digital methods in remote sensing of forested ecosystems: Focus on the pacific northwest, USA. Environmental Management 20: 421-435.

de Jong, S. M., Addink, E., Zeijlmans, M. & Nijland, W. Remote Sensing - A tool for environmental observations. 2008. Department of Physical Geography, Faculty of Geosciences, Utrecht University. Lecture Notes Remote Sensing Course GEO2-4208 . Ref Type: Report

Foody,G.M. 2008. GIS: Biodiversity applications. Progress in Physical Geography 32: 223-235.

Gillespie,T.W., Foody,G.M., Rocchini,D., Giorgi,A.P. & Saatchi,S. 2008. Measuring and modelling biodiversity from space. Progress in Physical Geography 32: 203-221.

Glenn,E.P., Huete,A.R., Nagler,P.L. & Nelson,S.G. 2008. Relationship between remotely-sensed vegetation indices, canopy attributes and plant physiological processes: What vegetation indices can and cannot tell us about the landscape. Sensors 8: 2136-2160.

Goodchild,M.F. 1994. Integrating GIS and remote sensing for vegetation analysis and modeling: methodological issues. Journal of Vegetation Science 5: 615-626.

Govender,M., Chetty,K. & Bulcock,H. 2007. A review of hyperspectral remote sensing and its application in vegetation and water resource studies. Water SA 33: 145-151.

Kerr,J.T. & Ostrovsky,M. 2003. From space to species: ecological applications for remote sensing. Trends in Ecology and Evolution 18: 299-305.

McDermid,G.J., Franklin,S.E. & LeDrew,E.F. 2005. Remote sensing for large-area habitat mapping. Progress in Physical Geography 29: 449-474.

Pettorelli,N., Vik,J.O., Mysterud,A., Gaillard,J., Tucker,C.J. & Stenseth,N.C. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends in Ecology and Evolution 20: 503-510.

Raynolds,M.K., Comiso,J.C., Walker,D.A. & Verbyla,D. 2008. Relationship between satellite-derived land surface temperatures, arctic vegetation types, and NDVI. Remote sensing of environment 112: 1884-1894.

Reed,B.C., Brown,J.F., Vanderzee,D., Loveland,T.R., Merchant,J.W. & Ohlen,D.O. 1994. Measuring phenological variability from satellite imagery. Journal of Vegetation Science 5: 703-714.

Schmidt,K.S. 2003. Hyperspectral Remote Sensing of Vegetation Species Distribution in a Saltmarsh. Wageningen University Dissertation.

Shippert,P. 2004. Why use hyperspectral imagery? Photogrammetric Engineering and Remote Sensing 70: 377-380.

Turner,D.P., Ollinger,S.V. & Kimball,J.S. 2004. Integrating remote sensing and ecosystem process models for landscape- to regional-scale analysis of the carbon cycle. BioScience 54: 573-584.

Turner,W., Spector,S., Gardener,N., Fladeland,M., Sterling,E. & Steininger,M. 2003. Remote sensing for biodiversity science and conservation. Trends in Ecology and Evolution 18: 306-314.

Ustin,S.L., Roberts,D.A., Gamon,J.A., Asner,G.P. & Green,R.O. 2004. Using imaging spectroscopy to study ecosystem processes and properties. BioScience 54: 523-534.

Wadsworth,R. & Treweek,J. 1999. Sources of data. Geographical Information Systems for Ecology, pp. 63-75. Addison Wesley Longman Limited.

Walsh,S.J. & Davis,F.W. 1994. Applications of remote sensing and geographic information systems in vegetation science: Introduction. Journal of Vegetation Science 5: 610-613.

Wulder,M.A., Hall,R.J., Coops,N.C. & Franklin,S.E. 2004. High spatial resolution remotely sensed data for ecosystem characterization. BioScience 54: 511-521.

Appendix I - Sensors overview

(Satellite-)Sensor	Spectral resolution	Spatial resolution (m)	Temporal resolution	Vegetation application examples
Landsat 7 ETM+	Blue	30	16 days	Differentiation of vegetation from soils
	Green			NDVI measurements
	Red			Chlorophyll absorption
	NIR			Biomass surveys
	MIR (x2)			Vegetation moisture measurements
	Thermal	60		Plant heat stress
	Panchromatic	15		Hyperspectral studies
MODIS	36 bands	250/ 500/ 1000	1-2 days	Large-scale surveys; NDVI measurements
NOAA-AVHRR	Red	1100 / 4000	twice-daily	Global vegetation monitoring; forest fire activity; NDVI measurements
	NIR			
	MIR			
	Thermal			
SPOT-VGT	Blue	2,5 / 10 / 1150	26 days	Detection of very low vegetation cover
	Red			Plant canopy characterization
	NIR			Canopy structural properties
	MIR			Canopy structure, leaf water content
IKONOS	Blue	4	1.5-3 days	Hyperspatial measurements: e.g. identification of individual tree crowns
	Green			
	Red			
	NIR			
	Panchromatic	1		Hyperspectral and –spatial applicatons
Quickbird	Blue	2,4	2-4 days	Hyperspatial measurements: e.g. identification of individual tree crowns
	Green			
	Red			
	NIR			
	Panchromatic	0,60		Hyperspectral and –spatial applicatons
Hyperion	Panchromatic	30	16 days	Hyperspectral applications

Adapted from Kerr & Ostrovsky 2003; Gillespie et al. 2008; Turner et al. 2003

Abbreviations

Landsat ETM+	Landsat Enhanced Thematic Mapper Plus
MODIS	Moderate-resolution Imaging Spectroradiometer
NOAA-AVHHR	National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer
SPOT-VGT	Satellite Pour l'Observation de la Terre - Vegetation

Appendix II – Glossary

Active system	A remote sensing system with an artificial energy source that emits radiation and a sensor that measures the amount reflected.
Band/Channel	A broad wavelength interval of the electromagnetic spectrum, for example all the blue visible light, in which the amount of radiation is measured by a multispectral sensor. Multispectral sensors typically have 4 to 7 bands.
Change detection	The comparison of remotely sensed images from at least two different dates, for instance to assess changes in vegetation state.
Hyperspectral system	A remote sensing system with a sensor that measures the reflectance in approximately 200 narrow bands, thus constructing an almost continuous reflectance spectrum. These systems are still in the development phase.
Image classification	This technique aims to assign each pixel in an image to a class, using a variety of statistical methods. The goal is to visualize the location of different objects or properties, for example to create vegetation maps.
Image space	The presentation of remotely sensed data in a two-dimensional picture, divided into pixels. The pixels contain the value of reflection for each band.
INDVI	Integrated NDVI; the sum of NDVI values over a year and therefore a measure of the annual biomass production.
Microwave region	The part of the electromagnetic spectrum containing the wavelengths from 1mm to 1m. Radar uses a part of the microwave region (0.75-30 cm)
Multispectral system	A remote sensing system with a sensor that measures the reflectance in a small number of broad bands. These are the older, most common systems.
NDVI	Normalized Difference Vegetation Index; a measure of the overall presence of healthy vegetation in an area. Also used to estimate biophysical variables such as LAI, NPP and biomass. It is the most-used and -studied vegetation index.
Optical region	The part of the electromagnetic spectrum containing the wavelengths from 0.4 to 14μm. This concerns visible light, near-infrared (NIR), middle-infrared (MIR) and thermal radiation. This region is the focus of most remote sensing studies.
Panchromatic	The sensors of hyperspectral systems, with approximately 200 narrow bands, are also called panchromatic sensors.
PAR	Photosynthetic active radiation; the part of the electromagnetic spectrum that is available to vegetation for photosynthesis. fPAR is the fraction of PAR that is actually absorbed by a plant.
Passive system	A remote sensing system with a sensor that measures the amount of solar radiation that is reflected by objects on the Earth's surface.
Remote sensing	The science or technique to observe the Earth from space or from the air, by producing images using (part of) the electromagnetic spectrum (Wadsworth & Treweek 1999)
Sensor	A device that measures the amount of electromagnetic radiation that is reflected or emitted by an object of interest on the Earth's surface. In a remote sensing system, sensors can be airborne or space borne.
Spatial resolution	The amount of spatial detail that can be interpreted from an image. The spatial resolution of a sensor is noted as the length of one side of a square area on the Earth's surface, corresponding to one digital pixel.
Spectral resolution	The amount of variation in spectral profile that can be discriminated between different objects of interest. The spectral resolution of as sensor refers to the number and width of the portions of the electromagnetic spectrum measured.
Spectral signature	A graph showing the typical reflection pattern of a class of interest (for example vegetation) in a range of wavelengths.
Temporal resolution	The frequency at which a sensor records the same location on Earth, and the running time of the program to which the sensor belongs.
Vegetation index	Indices used to determine certain properties of vegetation, such as the density or biophysical properties. They are usually based on the ratio between the values of reflection in the NIR and the red bands of an image.