CHAPTER A.II.

Contribution of Remote Sensing Techniques for monitoring Natura 2000 sites

Sander Mücher & Gerard Hazeu

II.1 Introduction

Remote sensing is becoming increasingly important in habitat mapping and monitoring due to the strong synoptic overview of its images in the temporal and spatial domain. ***Early applications pertained to the visual interpretation of aerial photography, but more recently satellite imagery with a huge range of spatial and temporal resolutions is in use that increases the applicability from entire ecosystems to specific vegetation types****. The newest developments are the use of UAVs (Unmanned Aerial Vehicles) at the most detailed spatial scale (up to centimeter pixel detail) to support vegetation surveyors. Besides this, more and more satellite imagery is becoming available as open data, such as the imagery from the European SENTINELS, next to a much longer tradition in open data policy for American satellite sensors such as MODIS and Landsat, to widen the opportunities for their applications. Some vegetation mapping projects apply aerial photographs or remotely sensed imagery only to divide the area of interest into homogenous vegetation mapping units that are further labelled in vegetation types by field surveyors, while other classification methods produce vegetation or habitat maps directly from imagery by combining imagery with ground truth data. The latter approach is gaining momentum in light of major technological improvements, but also because it can speed up the mapping process compared to traditional methods.*

Traditional vegetation and habitat mapping methods using visual interpretation of aerial photography in combination with field surveys work very well, but are often labor intensive and updating frequencies are normally low, while policies are demanding currently higher monitoring frequencies. Therefore terrain managers are looking for alternatives that can support the mapping and monitoring of vegetation in more efficient ways. New developments in remote sensing such as very high resolution (VHR) satellite imagery, LiDAR techniques that support the measuring of the vegetation structure and the application of UAVs that can fly at any requested time and spatial resolution and are not affected by cloud cover, can help to speed up the process of vegetation mapping and monitoring. Nevertheless, these methods are all quite new and are not yet that robust that they immediately convince vegetation surveyors and/or terrain managers who often lack the skills to apply these new methods. Using a mixture of remote sensing and field methods seems to deliver the best results. This requires ecologists and remote sensing experts to collaborate closely and review the newest methods and technologies. Some of these technologies and methods are demonstrated below, but first a short introduction to remote sensing.

Citation

Chapter A.II: Mucher, C.A. & Hazeu, G.W. (2021) Contribution of remote sensing techniques for monitoring Natura 2000 sites. In: Schmidt, A.M. & Van der Sluis, T. (2021). E-BIND Handbook (Part A): Improving the availability of data and information on species, habitats and sites.

The whole document can be downloaded under ecologic.eu/book/improving-the-availability-of-data-and-information

Early applications pertained to the visual interpretation of aerial photography, but more recently satellite imagery with a huge range of spatial and temporal resolutions is in use that increases the applicability from entire ecosystems to specific vegetation types.

II.1.3 Theory and definition

Remote sensing is the science of obtaining information about an object, an area, or phenomenon through the analysis of data acquired by a sensor that is not in contact with the object, area or phenomenon under investigation (*Lillesand et al., 2015*). The human eye only detects the reflective solar radiance, the part of the electromagnetic range in the band length range 0.4–0.7µm. But remote sensing technology allows for the detection of other reflective and radiant (including thermal) energy band-length ranges. **Sensors can be divided into two broad groups—passive and active**. The earliest example of this is photography. With airborne cameras we have long been able to measure and record the reflection of light off of earth features. While aerial photography is still a major form of remote sensing, newer solid state technologies have extended capabilities for viewing in the visible and near-infrared wavelengths to include longer wavelength solar radiation as well.

Definition of remote sensing

Remote sensing is the science of obtaining information about an object, an area, or phenomenon through the analysis of data acquired by a sensor that is not in contact with the object, area or phenomenon under investigation (*Lillesand et al., 2015*).

II.1.4 Sensor characteristics and important platforms of remotely sensed imagery (spaceborne, airborne [manned & unmanned])

The relevance of remote sensing as a source of information for e.g. grassland monitoring is conditioned by the following sensor characteristics:

- **spatial resolution** – determines the amount of information in a remotely sensed image of a given area;
- **temporal resolution** – revisit frequency (how often a satellite takes a picture of the same area) helps to distinguish abrupt and gradual changes, but also allows an improvement in the identification of grassland associations
- **spectral resolution** – helps to distinguish between plants of different species and their traits;

Next to the sensor characteristics that determine the application domain, it is very important to have a good pre-processing line, which includes radiometric calibration including atmospheric correction, and cloud masking. Furthermore you need a good post-processing line, which includes for example time compositing of products derived from the calibrated satellite imagery: images can be combined, for example to remove clouds (accumulating images of the same area to increase chances of cloud free observations) and to create 8-day, monthly and annual composite (of variables such as spectral indices, like NDVI, or variables like fAPAR, SST).

Spatial and temporal resolution

The spatial resolution of spaceborne sensors today ranges from one kilometre to about 40 centimetres (Figure II.1). In general, a distinction is made between:

- **Low Resolution** Optical Satellite Data: >= 1km spatial resolution by multi-spectral sensors like GOES, Meteosat, NOAA, SPOT-Vegetation.

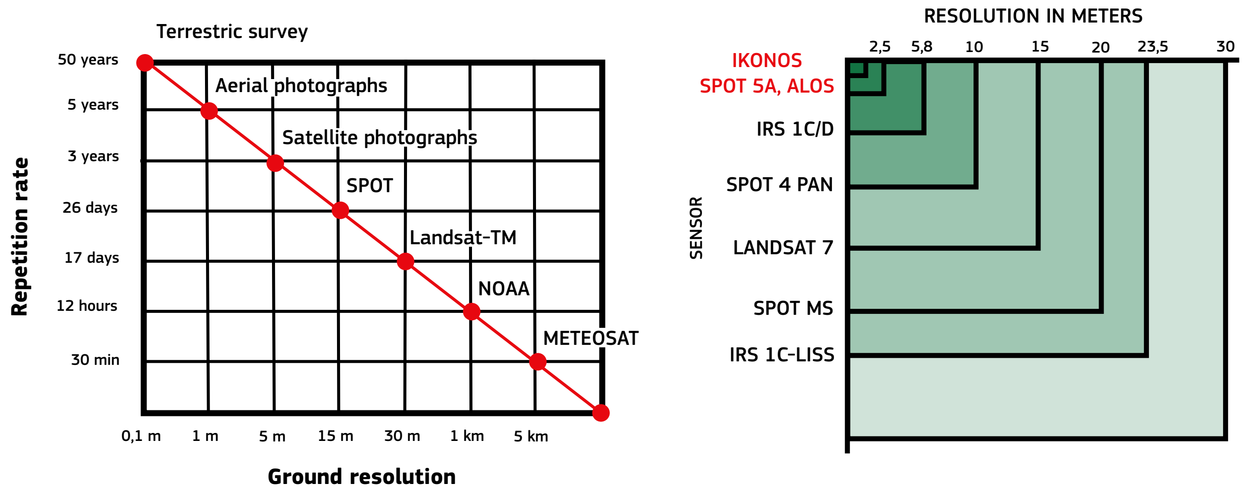


Figure II.1
Spatial and temporal resolution of satellite sensors.
Source: dib.joanneum.ac.at/edtr/satsys.html

- **Medium Resolution** Optical Satellite Data: 80–500m spatial resolution by multi-spectral sensors like MODIS, Landsat MSS, RESURS-01 (MSU-SK) and IRS-1C (Wide Field Sensor – WiFS).
- **High Resolution** Optical Satellite Data: 5–30m spatial resolution by panchromatic or multi-spectral sensors or analogue camera systems such as Sentinel-2, Landsat TM, SPOT PAN and MS, IRS-1C/D (PAN and LISS), KFA 1000, MK4, etc.
- **Very High Resolution** (VHR) Optical Satellite Data: 1–4m spatial resolution by panchromatic or multi-spectral sensors, e.g. Worldview-2 and Quickbird with half a meter resolution for panchromatic band and 2m for the multi-spectral bands.

See also Annex I for a long list of satellite sensors and their characteristics.

Airborne sensors can be distinguished in manned and unmanned sensors (better known as drones) and commonly have spatial resolutions between 40cm and 1cm.

There is a clear trade-off between spatial and temporal resolution. The higher the temporal resolution the lower the spatial resolution. The European Space Agency (ESA) is developing five new missions called Sentinels specifically for the operational needs of the European GMES programme. The Sentinel missions are based on a constellation of two satellites to fulfil revisit and coverage requirements, providing robust datasets for GMES Services. The Sentinels were launched from 2013 onwards. The mission orbits at a mean altitude of approximately 800 km and, with the pair of satellites in operation, has a revisit time of five days at the equator (under cloud-free conditions) and 2–3 days at mid-latitudes (source: www.esa.int/Our_Activities/Observing_the_Earth/GMES/Overview4).

Spectral resolution

An example of a typical spectrum for photosynthetic (green) vegetation is given in Figure II.2, but characteristic spectra relevant to land cover and habitat mapping are also available for non-photosynthetic (brown) vegetation, soils, water (in liquid and frozen form), bare areas and urban surfaces.

Within the vegetation (photosynthetic) spectra, characteristic features include the green peak, red edge and near infrared (NIR) plateau with absorption features (relating to moisture content) evident in the latter and also in the short-wave infrared (SWIR) wavelength regions. Reflectance in the visible regions is primarily a function of pigment concentrations in foliage whilst in the NIR and SWIR, the internal leaf structure and moisture content of the leaves respectively influence reflectance (*Swain & Davis, 1978*). In all cases, it should be noted that the reflectance of vegetation canopies is different from of individual components (e.g. leaves, branches), because of the different contributions to the reflectance from plant materials and also the underlying surface and shadowing as a function of canopy heterogeneity, which particularly influences the NIR and SWIR wavelength regions. The loss of pigments, cell structure and moisture content during senescence of leaves leads to the loss of most of the characteristic features of green leaves (with the exception of the water absorption features) and the transition to the spectral curve typical of non-photosynthetic vegetation.

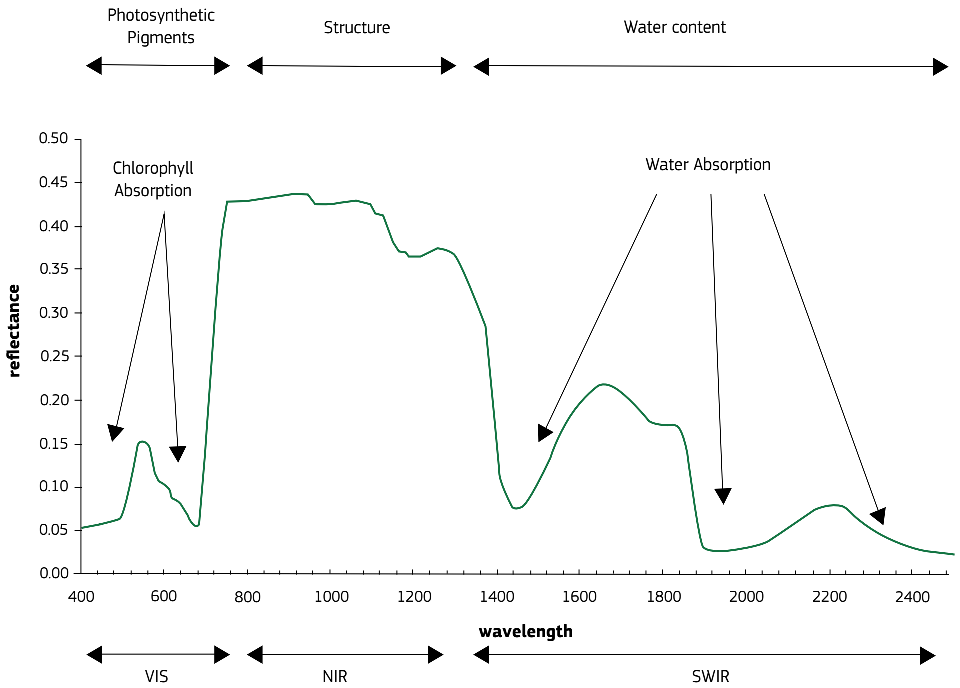


Figure II.2
Typical spectra for vegetation highlighting the main contributors to reflectance.

A large number of studies have used spectral reflectance data to differentiate plant species and communities on the basis of differences in spectral reflectance, with this being attributed largely to differences in foliar chemistry, the internal structure of leaves, moisture content and the overall canopy structure (e.g. in terms of shadowing and relative amounts of plant components (e.g. leaves, branches). As examples, *Lucas et al., (2008)* extracted reflectance spectra (based on CASI data) from the sunlit portions of delineated tree crowns in Australia savannas, discriminating species of Callitris, Eucalyptus, Acacia and Angophora through discriminant analysis. *Lu et. al., (2009)* used hyper-spectral data to map the distribution of two spectrally similar grasses (*Miscanthus sacchariflorus* and *Phragmites australis*) in Japan on the basis of subtle differences in canopy density, leaf and canopy structure as well as biochemical properties. The benefits of using hyper-spectral data for mapping aquatic vegetation (e.g., different species of Spartina in San Francisco Bay, USA; *Rosso et al., 2005*), identifying and mapping invasive species (e.g. *Ustin et al., 2004*; *Hestir et al., 2008*; *Walsh et al., 2008*; *He et al., 2011*); and differentiating between trees of the same species that are of different ages and sizes have also been conveyed (*Christian & Krishnayya, 2009*).

II.1.5 Remote sensing for Natura 2000 surveying (status) & monitoring (changes)

The Habitats Directive requires EU Member States to maintain and restore all habitats and species of "community interest" listed in annexes to the Directive.

A study of *Lengyel et al. (2008)* of 148 habitat monitoring schemes across Europe found that the majority of the programs were launched to comply with EU Directives, thus underlining their importance in European assessments of habitat change. At that time, the member states were only able to produce robust trend figures on the range of about 1.7% of habitat types and for no more than 4% of the populations of species listed. Most countries did not produce trend figures at all (*European Topic Centre Biodiversity, 2008*). Due to the lack of such information, remotely sensed observations are increasingly being considered by EU Member States to satisfy their reporting obligations under the Habitats Directive (*Lengyel et al., 2008*; *Vanden Borre et al., 2011b*). For instance, an approach proposed by *Jongman et al. (2006)* is based on environmental stratification along with detailed field surveys in selected sites, with this utilising remote sensing data in conjunction with GIS databases and modelling. Remote sensing data is also being used by other countries across the world to satisfy their conservation reporting requirements.

Vanden Borre et al. (2011a) discussed the opportunities for remote sensing with over 30 monitoring experts from administrations in 13 EU Member States. They see clear opportunities for its application in their work processes, see box Remote sensing can help to measure habitat conservation status.

Aspects of habitat conservation status to be measured

Articles 11 and 17 of the Directive also require member states to report on five parameters of habitat conservation status every six years:

- habitat area and geographic range,
- habitat structure and function (quality),
- and future prospects for habitat survival in the member state (*European Commission, 2005; Vanden Borre et al., 2011a*).

Remote sensing can also provide methods to monitor specific biophysical and biochemical indicators of ecosystem functioning (e.g. leaf area index, normalised difference vegetation index; *Kerr & Ostrovsky, 2003*; *Mücher, 2009*). The strength of remote sensing is its ability to deliver quantitative measures of such parameters in a standardised manner with full coverage over larger areas, whereas field surveys can only deliver this through point sample measurements and subsequent interpolation. The provision of such data by remote sensing may open new ways of looking at the quality of Natura 2000 habitats (*Vanden Borre, 2011b*).

When we take grasslands as an example, remote sensing can contribute to:

» Identify spatially the **land cover class grassland** and in some cases **specific habitat type**. There are many different local and regional grassland classification schemes (floristic, habitat, climatic, management, use etc.). In most cases floristic composition plays an important role and this is not that easy to distinguish from satellite imagery.

» Identify **grassland quality parameters**. These parameters include amongst others LAI, fraction cover, canopy shade, gap fraction soil, biomass content, soil moisture (indirectly), canopy coverage etc. The biophysical parameters that can be retrieved from GMES data sources (e.g. GEOLAND-2) are amongst others:

  → LAI and FAPAR are also classical parameters to quantify green vegetation (so we refer in fact to green LAI or GLAI). They are strongly correlated with fCover (but the relation between LAI and fCover is far from linear). It is a direct input into grass vegetation density product.

  → fCover: fractional green vegetation cover (FVC) is a useful parameter for many environmental and climate-related applications. Comparing to previously used NDVI, it has several strong advantages: absolute parameter (sensor-independent), robustness to thin clouds, fully scalable at different spatial resolutions

  → Canopy Shade Factor (CSF): this parameter allows to characterize the amount level of shadows self-cast on the canopies, and so in many conditions to discriminate rough canopies (forests, shrub) from flat, homogeneous canopies (crops and grasslands)

  → fSoil: quantifies the gap fraction of soil in the image, and relies on the capacity to discriminate a third contributor that is brown or non-photosynthetic (NPV) vegetation. It can be most useful to identify intensive agriculture practices with bare soil event.

» **Changes in extent and quality** of the habitat type.

Literature review shows that remote sensing can play further a role in: grassland transpiration, grassland emissions and fluxes, grassland dynamics and phenology, grassland albedo, grassland productivity, chlorophyll and water content and vegetation condition and structure.

Remote sensing can help to measure habitat conservation status *(Vanden Borre et al., 2011a)*

Habitat area
The production of habitat distribution maps, at various scale levels, constitutes an obvious area of high potential for remote sensing, as experts indicated. The advent of hyperspatial and hyperspectral sensors has indeed greatly enhanced the possibilities of distinguishing related habitat types at very fine scales (*Turner et al., 2003*). The end-users need such maps in the first place for estimating and update the sampling frame (the statistical 'population') of habitats for which field sample surveys are in place. The use of remote sensing also provides a major opportunity for harmonising Natura 2000 habitat mapping throughout Europe.

Habitat structure and function (quality)
As stated already by *Vanden Borre et al. (2011b)* the usefulness of remote sensing for habitat quality assessment is less straightforward for many monitoring experts. However, airborne LiDAR data can provide much information about habitat structure and changes in the habitat structure, while hyperspectral and multispectral data can in most cases provide information about dominant species and changes in the coverage of those dominant species.

Change detection
Remote sensing is frequently identified as a powerful tool for detecting change (*Kennedy et al., 2009*; *Mücher et al., 2000*). Remote sensing driven change maps not only provide excellent instruments for estimating trends in range and area, but they also localise the areas where change has occurred. Monitoring experts highly value this asset, because it allows subsequent field work to concentrate on these areas, possibly yielding a significant increase in cost-efficiency. In the Netherlands we will probably see that habitat maps remain likely to be derived from conventional vegetation maps updated once in the 12 years, but that more frequent updates will be based on remote sensing products such as LiDAR data, very high resolution satellite imagery and aerial photographs.

II.2 Current use of Remote Sensing for Natura 2000 monitoring

II.2.1 State of the art of Remote Sensing for Natura 2000 monitoring

The state of the art of remote sensing for Natura 2000 monitoring is told based on examples from European and national projects that clearly explain how remote sensing is being exploited in Natura 2000 monitoring.

Below is an overview of techniques and tools for different purposes in relation to Natura 2000 monitoring. It provides a link to the paragraph which further describes or gives examples of the method.

Table II.1
Remote sensing tools and methods.

Tool	Scale	Purpose	Aspects of habitat conservation status that can be measured
MODIS	250m pixel size	Global monitoring and monitoring large areas. Typical MODIS products are: surface reflectance, surface temperature and emissivity, land cover, vegetation indices, e.g. NDVI, thermal anomalies /active fraction of photosynthetically active radiation (FPAR) / leaf area index (LAI), evapotranspiration, gross primary productivity (GPP) / net primary productivity (NPP), water, burned area, snow cover, sea ice, sea surface temperature.	» habitat area » habitat structure and **function** (quality), » **changes** in area and quality (structure and function)
Landsat TM	30m pixel size	Regional studies and recently also global studies, such as Global Forest Watch and Global Water Surface Explorer. Typical Landsat products are: surface reflectance, spectral indices such as NDVI, vegetation and moisture measurements, surface temperature, dynamic surface water extent, fractional snow covered area, burned area.	» **habitat area** » habitat structure and function (quality), » **changes** in area and quality (structure and function)
Sentinel	10m pixel size	Regional and global studies. Typical Sentinel products are: surface reflectance, land cover, vegetation indices, e.g. NDVI, leaf area index (LAI), water.	» **habitat area** » habitat structure and function (quality), » **changes** in area and quality (structure and function)
Aerial photos	20cm pixel size	Local and national studies, typically used for topographical surveying.	» **habitat area** » habitat **structure** and **function** (quality), » **changes** in area and quality (structure and function)
Airborne LiDAR and hyperspectral imagery & UAVs		Local studies such as specific Natura 2000 sites. Typical UAV (drone) products are: canapy.	» **habitat area** » habitat **structure** and **function** (quality) » **changes** in area and quality (structure and function)

Mapping and monitoring habitat area

In the following sections examples are given on the use of remote sensing data for the mapping and monitoring of habitat area. The first example is based on the interpretation of historical aerial photographs to detect land cover changes in and around Natura 2000 sites since the early fifties. The second example concerns the Copernicus European land cover monitoring activities. The third example concerns the mapping of ecosystems (MAES), the fourth example mapping and monitoring of habitats using very high resolution data.

a. Interpretation of land cover changes in and around Natura 2000 sites based on time series of historical aerial photographs

The EU project BIOPRESS funded within the EU Fifth Framework is taken as an example for the interpretation of land cover changes from historical aerial photographs in and around Natura 2000 sites. Historical aerial photographs from the 1950s provide useful information about the original state of natural areas before the process of land consolidation and the associated amount of land use changes. Moreover the land cover flows (transition from one land cover type in another land cover type) within and around protected sites also provide information about the effectiveness of protection. The BIOPRESS method was designed to produce land cover change information collected in an operational and consistent manner from samples (including transects) across Natura 2000 within the different biogeographical regions of Europe. Land cover was classified according to the CORINE Land Cover nomenclature with 44 classes at the highest level 3 (*Heymann et al., 1993*). Change was captured by means of 'backdating' where the older data set is compared against the most recent. Change was recorded at a scale of 1:100.000 within 73 samples of 30 by 30km, and 59 transects of 2 by 15km at a scale of 1:20.000 for aerial photographs of the reference years: 1950, 1990 and 2000. Figure II.3 shows an example for the Nitra site in Slovakia.

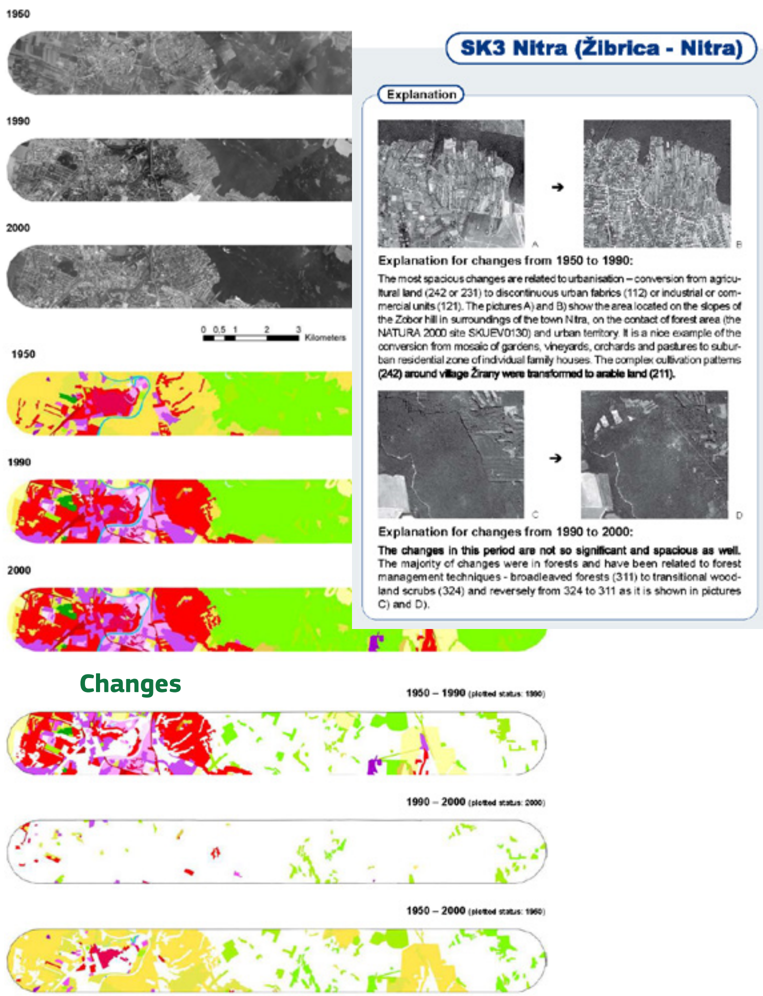


Figure II.3

Detected land cover changes in Slovakia in and around Natura 2000 site "Nitra" since the early fifties, based on historical aerial photographs (*Gerard et al., 2006*).

The degree of thematic detail and level of spatial detail of the land cover measured determines the type, amount and rate of change detected. Moreover the land cover flows can be associated with specific pressures such as urbanization, drainage, afforestation, deforestation, abandonment and intensification.

b. European Land monitoring in the framework of Copernicus

European Land monitoring in the framework of Copernicus consists of two components, the pan-European land monitoring and the local or hotspot land monitoring. The pan-European component includes as main products the CORINE Land Cover (CLC), High Resolution Layers and image mosaics. The CORINE Land Cover is provided for 1990, 2000, 2006, 2012, and 2018. This vector-based dataset includes 44 land cover and land use classes with 25ha as minimum mapping unit (MMU). The time-series also includes a land-change layer, highlighting changes in land cover and land-use (5ha MMU). The use of CLC for ecosystem mapping and assessment and the mapping of High Nature Value Farmland is described in Feranec et al., 2016. The high-resolution layers (HRL) are raster-based datasets which provides information about different land cover characteristics and is complementary to land-cover mapping (e.g. CORINE) datasets (100*100m aggregated products).

Five HRLs describe some of the main land cover characteristics: impervious (sealed) surfaces (e.g. roads and built up areas), forest areas, grasslands, water & wetlands, and small woody features (land.copernicus.eu/pan-european). Figure II.4 presents an example of the HRL Grassland for Czech Republic. The local component focuses on different hotspots, i.e. areas that are prone

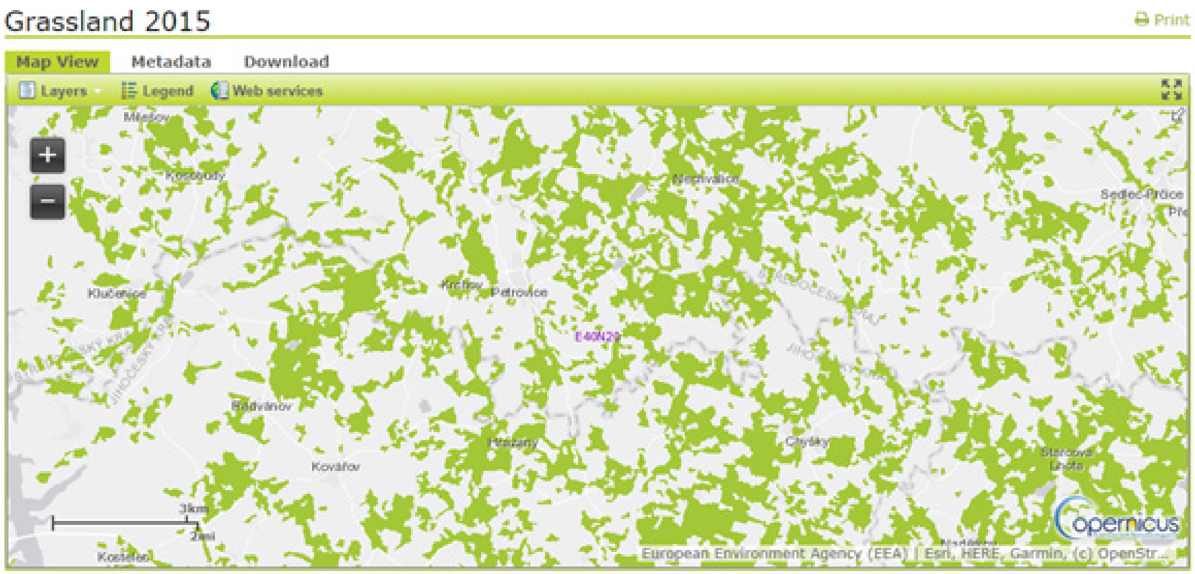


Figure II.4
Example for Czech Republic of the Copernicus High Resolution Layer grassland 2015, from: land.copernicus.eu/pan-european/high-resolution-layers/grassland/status-maps/2015

to specific environmental challenges and problems. It is based on very high resolution imagery (2,5x2,5m pixels) in combination with other available datasets (high and medium resolution images) over the pan-European area. The three local components are: Urban Atlas, Riparian Zones and Natura 2000. The rationale for the last two local components is provided by the need to monitor biodiversity at European level and to assess if the N2000 sites are being effectively preserved (land.copernicus.eu/local).

c. Ecosystem Types of Europe

The dataset combines the Copernicus land service portfolio and marine bathymetry and seabed information with the non-spatial EUNIS habitat classification for a better biological characterization of ecosystems across Europe. As such it represents probabilities of EUNIS habitat presence for each MAES ecosystem type. The Ecosystem Type Map (ETM) is produced by applying different mapping rules on input datasets.

The newest version, v3.1, is based on the following input datasets:

» Corine Land Cover 2012 accounting layer (instead of CLC 2012 status layer)

» HRL Forests 2012 (Forest Type, Tree Cover Density)

» HRL Imperviousness 2012

» OpenStreetMap (OSM) data 2015 (main roads, land use information)

And further integration of new available Copernicus data

» Urban Atlas 2012

» Riparian Zones 2012

» Natura 2000 2012

» HRL Grassland 2012

» HRL Permanent Water Bodies 2012

The resulting Ecosystem Type Map (v3.1) is displayed in the Figure II.5.

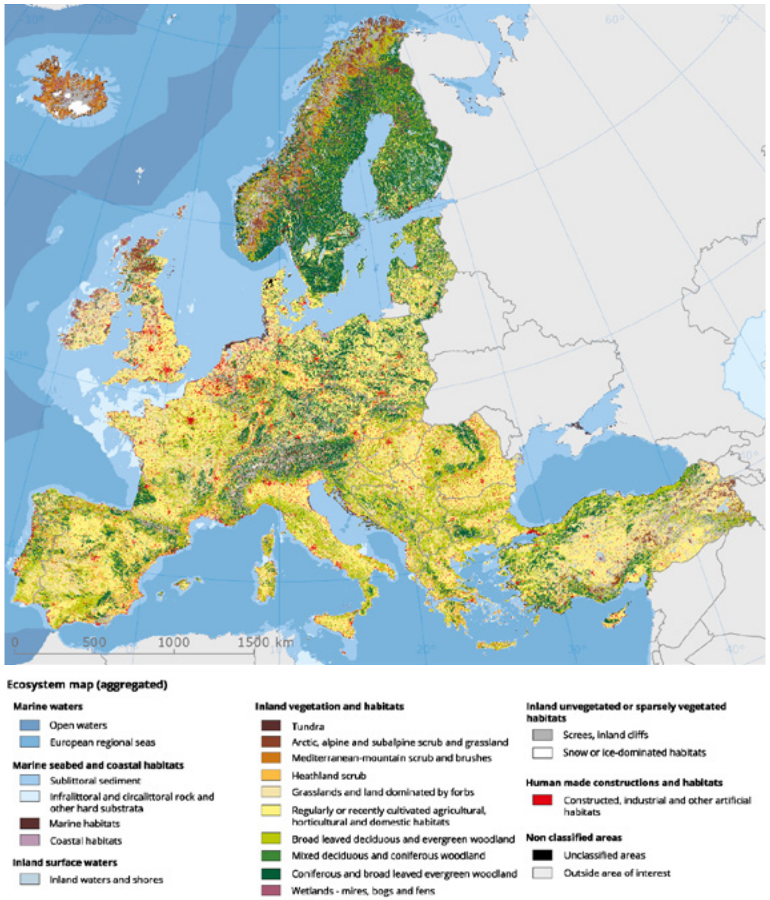


Figure II.5
Ecosystem Map (aggregated, v3.1) (*Weis & Banko, 2018*).

d. Earth Observation data for Habitat Mapping and Monitoring

To support decisions related to the use and conservation of protected areas and surrounds, the EU-funded BIO SOS project has developed the Earth Observation Data for HAbitat Monitoring (EODHaM) system for consistent mapping and monitoring of biodiversity. The EODHaM approach has adopted the Food and Agriculture Organization Land Cover Classification System (LCCS) taxonomy and translates mapped classes to General Habitat Categories (GHCs) from which Annex I habitats (EU Habitats Directive) can be defined (*Lucas et al., 2015*).

Although LCCS focusses on land cover and GHC on habitats, both LCCS and GHC categories have height information of the canopy as essential information. Input data sources for EODHaM are very high resolution (VHR) images, height information from LiDAR data, and ancillary information such as topographical maps (*Mücher et al, 2015*). The EODHaM system uses decision rules to derive GHC classes on the basis of spectral and height information (*Mücher et al, 2015*), see also Figure II.5 as an example.

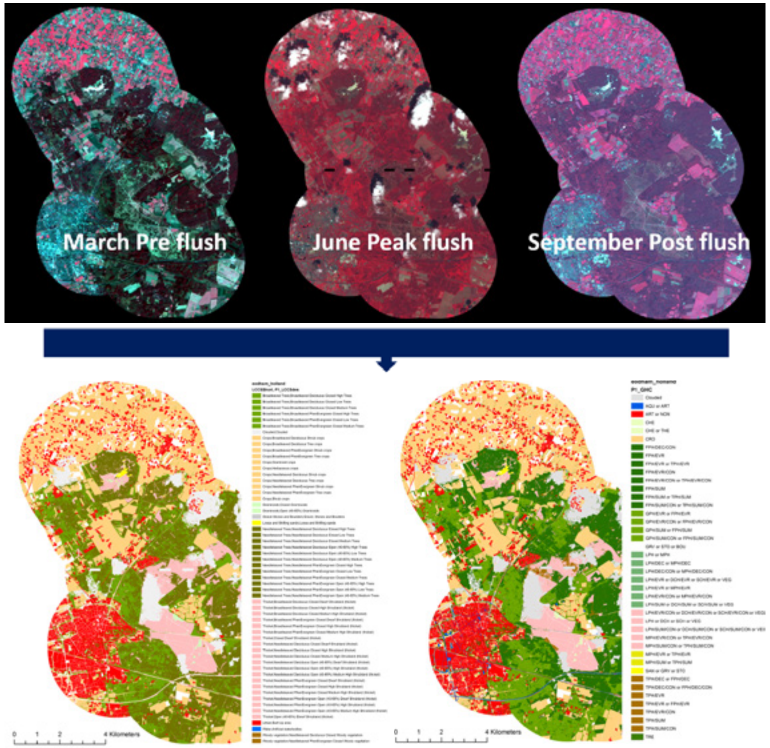


Figure II.6
Results of EODHam for a part of the Veluwe in the Netherlands. On the left the land cover classification at level 4 of FAO LCCS. In the right the habitat classification in terms of General Habitat Categories (*Mücher et al, 2015*).

Mapping and monitoring habitat quality

a. Remote sensing-enabled Essential Biodiversity Variables (RS-EBVs)

Essential Biodiversity Variables (EBVs) were proposed in 2013 by the biodiversity community to improve harmonization of biodiversity data into meaningful metrics (see chapter A.III Access to data and Information). The proposed EBVs have been grouped into six classes: genetic composition (not able yet with remote sensing data), species populations, species traits, community composition, ecosystem structure, and ecosystem function (see Figure II.6). This concept has taken root within wide segments of the theoretical and applied ecology communities. Furthermore, the idea behind the original EBV concept was that at least one EBV per class should be monitored, while keeping the set of EBVs limited is necessary to assure the usefulness of the EBV concept. Possible EBV's that capture biodiversity change on the ground and can be monitored from space range from leaf nitrogen and chlorophyll content to seasonal changes in floods and fires (*Skidmore et al., 2015*).

The RS-enabled EBVs can play a role in the monitoring of the quality of the habitats, next to the mapping and monitoring of habitat types. Nevertheless, much effort still has to be put in place to translate these remote sensing variables into useful information for ecologists in terms of habitat quality.

For example, *Vaz et al. (2015)* collected field data on five habitat quality indicators in vegetation plots from woodland habitats of a landscape undergoing agricultural abandonment. Their findings strongly suggest that some features of habitat quality, such as structure and habitat composition, can be effectively monitored from EO data combined with field campaigns as part of an integrative monitoring framework for habitat status assessment.

b. Mapping quality of heathland areas in terms of grass encroachment

Mücher et al. (2013) focused on the use of continuous fraction images for habitat quality assessment in a heathland site in the Netherlands (see Figure II.7). This combined application of techniques on hyperspectral imagery demonstrates the usefulness for mapping grass abundance (*Molinia caerulea*) in heathlands. It provides a better basis to monitor large areas for processes such as grass encroachment that largely determine the conservation status of Natura 2000 heathland areas. Timely, accurate and up-to-date spatial information on the encroachment of mosses, grasses, shrubs or trees (dominant species) can help conservation managers to take better decisions and to better evaluate the effect of taken measures.

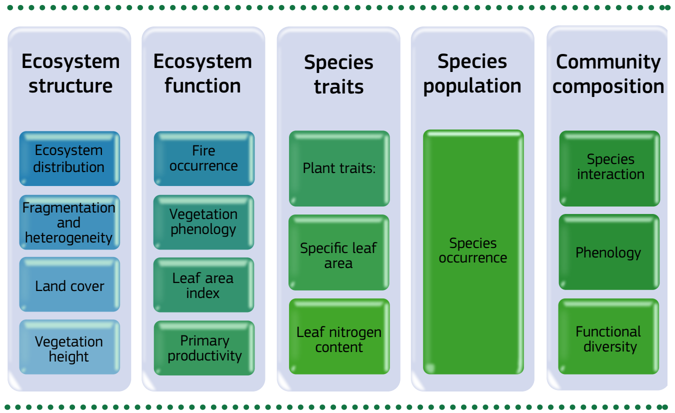
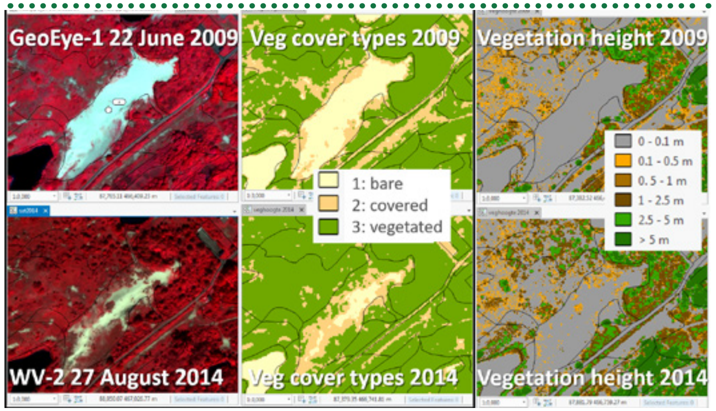
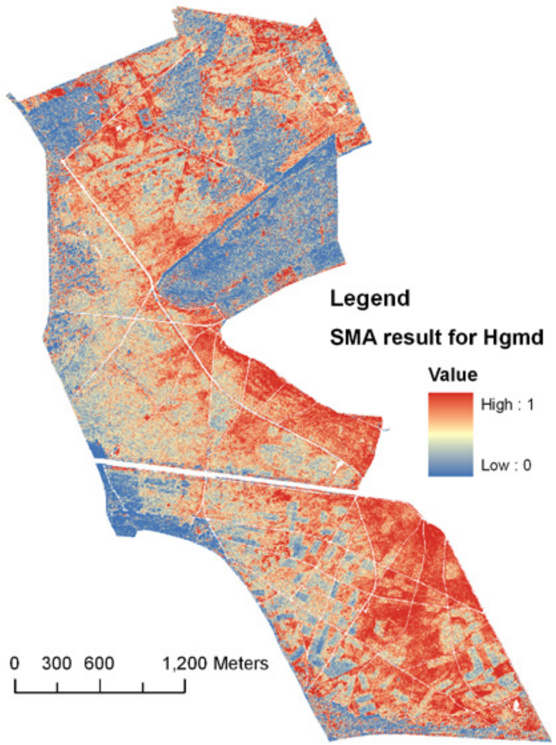


Figure II.7
A selection of proposed RS-Enabled Essential Biodiversity Variables (RS-EBVs) – Modified by E.Neinavaz from *Skidmore et al. (2015)*.

c. Monitoring shrub encroachment

Regular mapping of vegetation structure is of importance for biodiversity monitoring (*Mücher et al., 2017a*). In the Netherlands, vegetation structure mapping is in most cases still done in a traditional way based on field surveys in combination with visual interpretation of aerial photographs. This procedure is time consuming and often limited in its consistency and efficiency to cover large areas. Meanwhile space and airborne imagery are increasingly becoming available at affordable costs and with a high spatial resolution of approximately 50cm (*Mücher et al., 2017a*). Therefore, commonly shared Dutch open LiDAR-data such as AHN (LiDAR derived terrain models) in combination with commercially available very high resolution satellite data were used to develop methodologies that can help to increase the updating frequency of vegetation structure maps, based on respectively vegetation height and vegetation cover. LiDAR-data from AHN2 (2008) and AHN3 (2014) was combined with very high resolution satellite imagery from the similar time period in order to detect changes in vegetation structure at 1 metre spatial resolution (see Figure II.8). The existing habitat map was used to develop a protocol to find Grey Dunes (H2130) that showed significant changes in vegetation structure between 2008 and 2014 (see Figure II.9 as example). The Remote Sensing method can also be used for other vegetation structure – or habitat types but requires other specific decision rules in relation to vegetation height and/or vegetation cover which have to be agreed upon by the nature conservation community. Therefore, the developed Remote Sensing monitoring method for vegetation structure is only a start to enable national wide operational monitoring of the vegetation structure of all habitat types (*Mücher et al., 2017a*).





II.2.2 Recent developments

New high resolution satellite sensors and drones

A lot of remote sensing data sources with much higher spatial and temporal resolution have become available that can support Natura 2000 monitoring.

The observations from the different platforms are often integrated for upscaling and downscaling of the measurements and derived information (Figure II.10). In particular, the use of UAVs, better known as drones, is increasing rapidly for biodiversity monitoring, with spectral, spatial and temporal resolution often adjustable flexibly, but with limited coverage compared to other platforms.

The spatial resolution of most current multispectral spaceborne sensors is insufficient (~2–250m) to detect the presence of individual plants. However, most airborne sensors have a sufficiently high spatial resolution (pixels of 0.5–5m) to register small-scale variation in the vegetation. Spaceborne systems have the advantage of coming over at fixed intervals (ranging from a few days to a few weeks). This means that a new recording can be made regularly, so that the phenology can be visualized.

Figure II.8 (right)

Thematic fraction image for grass encroachment of heathlands concerning the Molinia dominated heathland (Hgmd), obtained by spectral mixture analysis (SMA) on an AHS hyperspectral image of October 2007. Red means almost 100% coverage with Molinia or other grasses, and blue means almost 0% coverage with Molinia, so it's good quality Heathland.

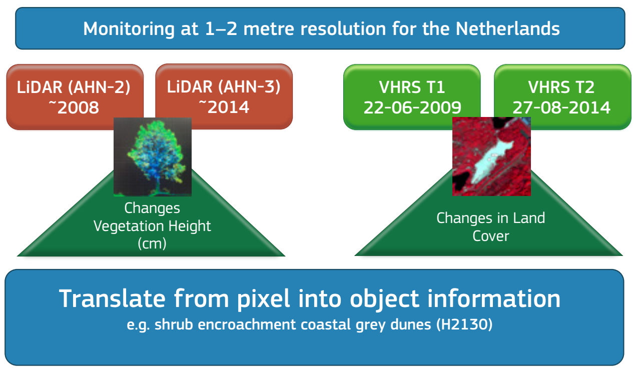
Figure II.9 (left)

An example of the monitoring of changes in vegetation structure for the Grey Dunes in the Netherlands, based on changes in vegetation cover and vegetation height (*Mücher et al., 2017a*).

Three types of sensor platforms

Remote sensing is the science of obtaining information about an object, an area, or phenomenon

1. **spaceborne** platforms, read satellites.
2. **airborne** platforms (including aircraft, helicopter, balloon or Unmanned Airborne Vehicles (UAV), and
3. **Ground-based** platforms, where the sensor is mounted on a mast or is held manually above the ground



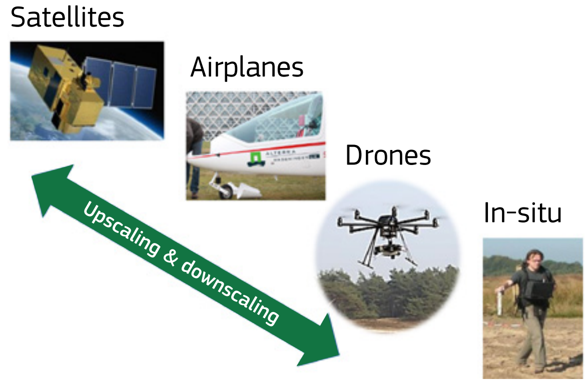


Figure II.10 (left)
Overview of the vegetation structure monitoring system based on the exploitation of LiDAR data and very high resolution satellite imagery (VHRS) (*Mücher et al., 2017a*).

Figure II.11 (right)
Multi-scale sensing approach with different remote sensing platforms: spaceborne, airborne and ground-based (Source: presentation Mucher).

An even higher spatial and temporal resolution than with airborne or spaceborne systems can be achieved with the use of UAVs. However, this also depends on the type of camera used. Different types of UAVs exist like multicopters and fixed wing airplanes having different capacities (camera load, flight time, easiness to maneuver) (Figure II.14). They can be equipped with different sensors (passive and active). The use of unmanned airborne vehicles (UAVs) or so-called drones that can carry a LiDAR camera is a recent development. Recently, the use and adoption of UAVs as a flexible sensor platform for monitoring has evolved rapidly. Potential application domains are e.g. agriculture (phenotyping of individual plants), coastal monitoring, archaeology, corridor mapping (power lines, railway tracks, pipeline inspection), topography, geomorphology, and construction site monitoring (surveying urban environments), next to forestry and vegetation monitoring. Until recently it was not possible to have a LiDAR camera on a UAV since the cameras were too heavy to be carried by a UAV.

Figure II.12
Multicopter with hyperspectral camera and a fixed wing drone with RGB camera (source presentation Mucher).

The detail of the recorded images also depends on the height that is flown. Table II.2 gives an overview of the possible pixel size and width of the recording at different heights. Another advantage of UAVs is that it can be flown completely autonomously.

Height (m)	Pixel size hyperspectral camera (cm)	Pixel size RGB camera (cm)
20	5.3	0.52
40	11	1.0
60	16	1.6
80	21	2.1
100	**27**	2.6
120	**32**	3.1

Table II.2
Examples of varying pixel resolution and image width with flight height for a hyperspectral and RGB camera.

Mapping and monitoring vegetation structure

Mapping and monitoring vegetation height can not only help to distinguish the different plant lifeforms but can also help to identify processes such as shrub and tree encroachment (*Mücher et al., 2017b*). Vegetation height is as such an important component of the structural aspect of ecological complexity. *Bunce et al. (2013)* emphasises the importance of habitat/vegetation structure in the development of biodiversity policies in their own right and also demonstrates that there are strong links between vegetation structure and occurrence of species. Only a very small part of all species can be monitored. Vegetation height is an important indicator as well in the definition of an ecosystem or habitat type. To enable the measurement of vegetation height, remote sensing can play a crucial role and can become an important information source.

New developments in remote sensing such as the use of very high resolution (VHR) satellite imagery and LiDAR (Light Detection And Ranging) techniques, next to the use of UAV platforms, can help to speed up the process of vegetation mapping and monitoring. Nevertheless, some of these methods are relatively new and require ecologists and remote sensing experts to collaborate closely and review the newest methods and technologies. Therefore this section discusses the potential use of passive optical sensors, RADAR and LiDAR technology for measuring vegetation height to support the monitoring of vegetation structure or in other words the EBV 'ecosystem structure' (*Mücher et al., 2017b*).

Sensor technologies for mapping and monitoring vegetation structure

- Passive sensor technologies
- Radar technology
- LiDAR technology
  - → UAV LiDAR (drones)
  - → Airborne LiDAR
  - → Spaceborne LiDAR

a. Passive sensor technology

Several studies have employed passive satellite sensor data to estimate vegetation height. A wide variety of features have been extracted from passive sensors of spatial resolutions ranging from several centimetres to some tens of metres. *Donoghue and Watt (2006)* approximated mean vegetation height for plots of 0.02ha using directly the mean reflectance values from spectral bands of Landsat Enhanced Thematic Mapper Plus (ETM+) and IKONOS images (*Mücher et al., 2017b*).

b. RADAR technology

RADAR (Radio Detection And Ranging) is an important tool for detecting the structure and height of vegetation because of its ability to penetrate clouds, to provide a signal from the geometric properties of the vegetation and to generate images over large areas. The RADAR signal, back-scatter and interferometric phase, depends on the physical structure and dielectric properties allowing an indirect measurement of vegetation structure. Since the early 1990s several studies have demonstrated the relationship between RADAR backscatter and vegetation structure and height (e.g. *Dobson et al., 1995*, *Joshi et al., 2015*). Interferometric SAR (InSAR) allows a more direct estimation of height and the vertical distribution of vegetation (*Florian et al., 2006*, *Papa-thanassiou et al., 2008*, *Treuhaft and Sinqueira, 2004*).

c. LiDAR technology

The following subsections deal with LiDAR technology from different platforms that all have their own merits for surveying, they concern respectively airborne and spaceborne LiDAR scanning.

Airborne LiDAR
From the perspective of ecological research, LiDAR can be considered as a relatively new tech-nology (*Carson et al., 2004*). LiDAR was originally introduced to generate more accurate digital elevation models (DEMs) (*Evans et al., 2006*) but has recently become an effective tool for natural resources applications (*Akay et al., 2008*). Scopus presents very well the steep increase in publications per year between 2000 and 2015, respectively from around 10 in 2000 to 400 publications in 2015 (search "LiDAR AND vegetation").

Airborne LiDAR offers the possibility to collect structural information over larger spatial extents than could be obtained by field surveys (*Bradbury et al., 2005*). LiDAR, in contrast to optical re-mote sensing techniques, can be expected to bridge the gap in 3D structural information, includ-ing canopy shape, number of vegetation layers and individual tree identification at the landscape scale (*Graf et al., 2009*).

UAV LiDAR (drones)
Before, LiDAR measurements were made only from manned helicopters or airplanes. Attaching a LiDAR sensor to a moving UAV platform allows 3D mapping of larger surface areas (*Mücher et al., 2017b*). The big advantage of the use of a UAV is its flexibility to be used in space and time. The major limitation compared to manned airborne laser scanning is still limited in its areal coverage, not only due to the technological capabilities but also due to aviation regulations which does not allow in most cases to fly beyond line of sight. The use of unmanned LiDAR Scanning (ULS) cer-tainly has advantages compared to the more static terrestrial laser scanning (TLS) or large-scale systems using manned platforms (*Mücher et al., 2017b*): UAV is more flexible in its use, but LIDAR allows a larger area to be covered, and better timing of (repeated) data acquisition.

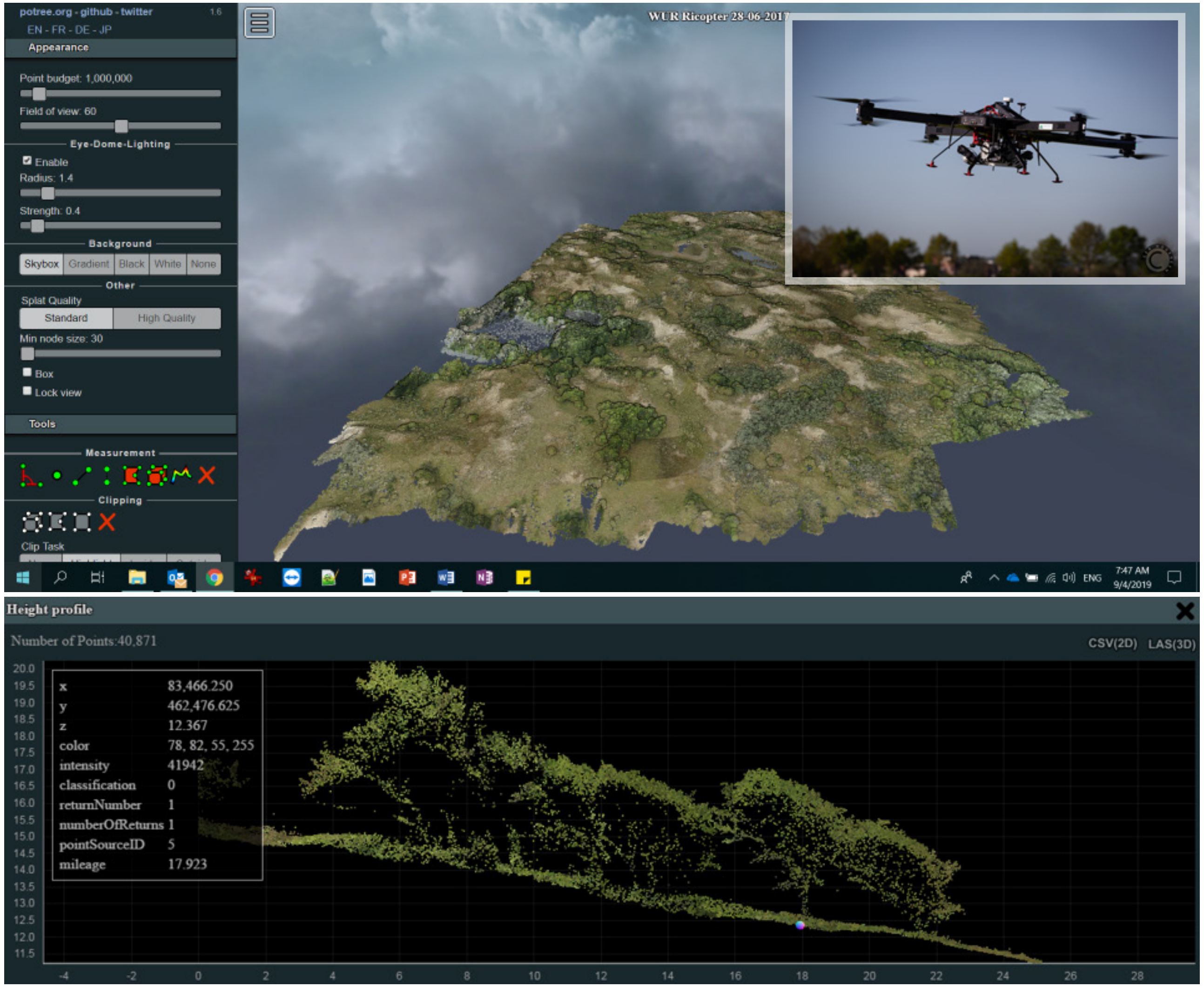


Figure II.13

Example of a line transect through a LiDAR point cloud, visualized in 3D, as taken by an UAV LiDAR camera (Acquired with VUX-SYS camera mounted on RiCopter).

However only a limited number of manufacturers can provide at the moment such integrated UAV-LiDAR systems *(Mücher et al., 2017b)*. See Figure II.13 as an example of ULS.

Spaceborne LiDAR

NASA's GLAS instrument (Geoscience Laser Altimeter System) on the spaceborn ICESat platform (Ice, Cloud, and land Elevation satellite), launched on 12 January 2003, is a good example of a promising technique from space. Although the main objective of the GLAS instrument was to measure ice sheet elevations and changes in elevation through time, it was also very successful in measuring forest height. Amongst others *Hayashia et al. (2013)* showed that ICESat/GLAS data provides useful information on forest canopy height with an accuracy RMSE of 2.8m. New advanced sensors to be launched in the next couple of years will provide increasingly accurate information on traits such as vegetation height and plant-species characteristics. These include the NASA Global Ecosystem Dynamics Investigation Lidar (GEDI), successfully launched in 2018 from Cape Canaveral.

Use of machine learning to map individual species

The exploitation of machine learning or artificial intelligence has improved with the increase in computational power, and provides the basis for more complicated image classifications that enables the recognition of objects such as human individuals but provides also opportunities to map individual plant species (in case of larger plants with distinct features). In general, machine learning explores patterns and regularities within the data in order to make predictions on new data based on what is learnt by analysing available known data. Since the accuracy can be improved with experience, machine learning performs the best when it can incorporate large training datasets.

Below is an example of a deep learning approach to identifying marsh marigold (*Caltha palustris*) from RGB drone imagery over the wetland forest Biesbosch National Park in the Netherlands (Figure II.14). The study (*Alkema, 2019*) attempts for species recognition from UAV images, to potentially assist or replace field inventories. The bright yellow flowers of marsh marigold and reflective leaves allow for relatively easy recognition in the field, and as an indicator species its presence or absence gives insight in the status of the surrounding swampy habitat.

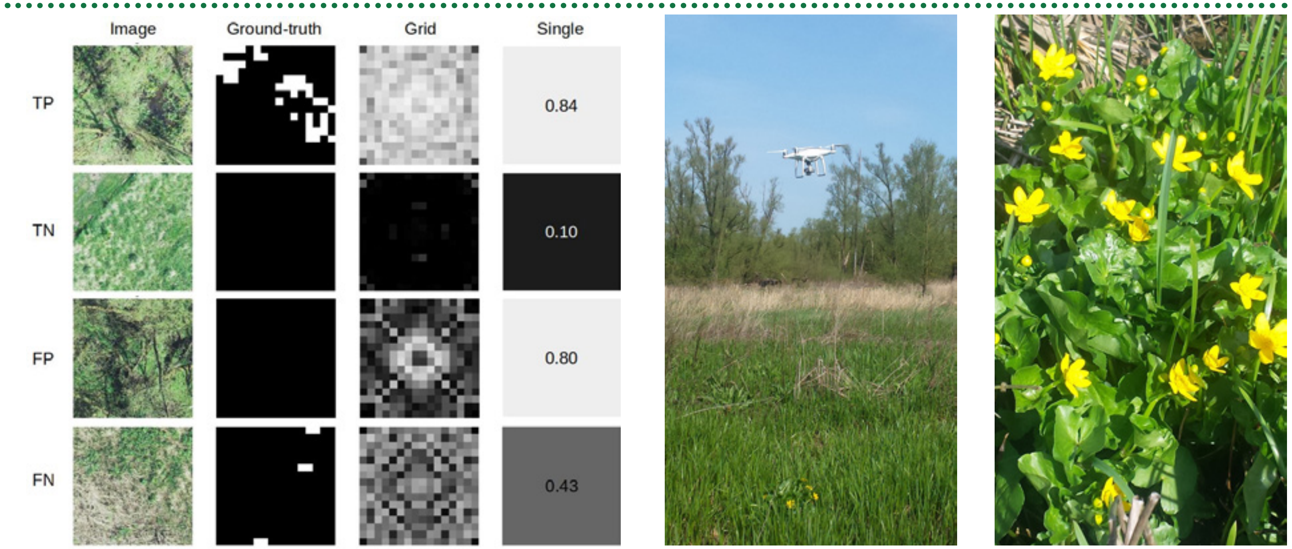


Figure II.14

Examples of correct and false predictions of the grid (3rd column) and single prediction models (4th column). True positive (TP), true negative (TN), false positive (FP) and false negative (FN) outputs are depicted next to the corresponding UAV images and ground-truth masks, given a threshold of 0.5 (*Alkema, 2019*).

II.3 Key findings and recommendations

The purpose of this report is the provision of services to advise the Commission, Member State authorities and other stakeholders on the better use of scientific knowledge and scientific networks in support of the implementation of the nature directives with a specific focus on evidence-based improvements in the Birds and Habitats Directives (BHD) implementation. Evidence-based improvements can be supported to a large extent by remotely sensed observations, and concerns this chapter. **Remote Sensing holds promise as a supporting technique for Natura 2000 habitat monitoring** (*Mücher et al. 2013*; *Vanden Borre et al. 2011b*), in many cases in terms of changes in habitat area and in some cases in terms of changes in habitat quality. But at the same time, the accuracy of remote sensing products vary a lot depending on the habitat type and its size, making the RS products not always useful. RS definitely provides a powerful tool for detecting land use changes (*Feranec et al. 2016*; *Hazeu et al. 2014*; *Hazeu et al. 2002*; *Van der Zanden et al. 2013*).

Remote sensing has a strong, yet underexploited potential to assist in the monitoring of protected areas. However, the data generated need to be utilized more effectively to enable better management of the condition of protected areas and their surroundings, prepare for climate change, and assist planning for future landscape management (*Nagendra et al. 2013*). More interaction between the remote sensing and conservation community is needed to fine-tune the site managers needs in terms of remote sensing products. This interaction is also needed because most RS products are not perfect and need to be exploited in the appropriate manner by ecologists and terrain managers. The RS community needs to simplify access to the original imagery and derived products to make the full potential of RS available for the TM community (*Geller et al. in Walters and Scholes, 2017*).

Remote sensing is generally most useful when combined with in situ observations and ecological knowledge. The in-situ observations are needed as ground-truth to enable training of the classifications and for assessing RS accuracy. RS can provide excellent synoptic spatial and temporal coverage, for example, though its usefulness may be limited by pixel size which may be too coarse for some applications. On the other hand, in-situ measurements are made at very fine spatial scales but tend to be sparse and infrequent, as well as difficult and relatively expensive to collect. Combining RS and in-situ observations takes advantage of their complementary features (*Geller et al. in Walters and Scholes, 2017*). Finally, remote sensing data can also be collected from terrains where in-situ measurements are difficult.

Remote sensing plays a major role in mapping and understanding (terrestrial) biodiversity. It is the basis of most land cover/land use maps, provides much of the environmental data used in species distribution modelling, can characterise ecosystem functioning, assists in ecosystem service assessment, and is beginning to be used in genetic analyses. RS data are usually combined with physical data such as elevation or climate (which in fact may be derived from RS data) and, increasingly, with socio-economic data (*Geller et al. in Walters and Scholes, 2017*).

Key findings

- » Remote Sensing holds promise as a supporting technique for Natura 2000 habitat monitoring
- » Remote sensing has a strong, yet underexploited potential to assist in the monitoring of protected areas.
- » Remote sensing is generally most useful when combined with in situ observations and ecological knowledge
- » Remote sensing plays a major role in mapping and understanding (terrestrial) biodiversity

Early applications pertained to the stereoscopic visual interpretation of aerial photography and were a great step forward in vegetation monitoring. More recently, satellite imagery with a large range of spatial and temporal resolutions is available and enables applications for entire ecosystems. Traditional vegetation mapping methods that use visual interpretation of aerial photography in combination with field surveys are, and have always been, working very well. But they are often also labour intensive and temporal frequencies are low, while policies are currently demanding higher temporal monitoring frequencies. Therefore, terrain and nature managers are looking for alternatives that can support the mapping and monitoring of vegetation in more efficient ways.

II.3.1 Current limitations

Mutual understanding and technical skills

An important barrier for site or terrain managers (TM) to use RS products is dealing with the **"unknown" of RS products**. A lot of people are still reluctant to use these tools (scepticism about technological innovation) which is slowing down their take-up for nature conservation management. For them RS techniques are mainly related to scientific purposes. For others, there is just an over-expectation of their results. So overall, there is a lack of understanding on the utility of these RS products/tools. Therefore it is needed to engage terrain managers in using RS products so they understand the possibilities and limitations of the RS products and tools. Why change your daily work routine if it works as you do now? It is often not (directly) clear what it could mean in their daily work. A huge difference exists between what can be done versus what is needed/expected by terrain managers (TM). Communication and mutual understanding between TM and RS community is of utmost importance. In order to resolve misunderstandings and perceived mismatches, increased cooperation and communication between producers and final users is needed. On the one hand, this can be achieved by setting up facilities for an enhanced sharing of ideas and results. On the other hand, end-users need to get involved in the development of remote sensing products as early as possible (*Vanden Borre et al., 2011b*).

Next to these barriers of mutual understanding there are **limitations of more technical nature**. The products are sometimes too complex and not easy to understand as the huge amount of data make it not easy to analyse the data and recognize the patterns. Remote sensing, as a science, is a very diverse field. For site managers mostly unfamiliar with the large variety of imagery and methodologies that are available, it will be impossible for them to find the most suitable method for their needs. Next to that, the specific requirements and applications in the field of habitat monitoring are equally diverse. Standardised RS products will therefore rarely suit the specific requirements (*Vanden Borre et al., 2011b*). Furthermore, the RS products need to be interpreted for which specific skills (or training) are needed. Also the liability of image availability is often questioned, and the necessity to work with and to buy new (complex) software and hardware is also often seen as an obstacle.

Current limitations

- Mutual understanding and technical skills
- Costs of remote sensing products
- Products mismatching expectations

Costs

RS needs to be combined with field visit to train your classification and/or verify your products. This is one of the reasons why it is difficult to say if RS products are cheaper than field visits. Detailed cost-effectiveness studies in this area were not found. RS cannot completely replace field visits. Also RS products can be used to fill the data gaps between specific moments in which field visits took place.

The cost of RS products is nowadays mainly related to setting-up the IT infrastructure for storage and processing, the interpretation and calibration of the products.

Next to the costs discussion, RS products sometimes cannot be replaced by field visits. RS products can look back into time, i.e. show the historical situation if RS imagery is available, while field visits show only the current situation.

Products mismatching expectations

Operational RS products at the regional/national scale are often focused on land cover/land use. The mapping and monitoring of the extent and quality of habitats in N2000 sites is limited compared to land cover and land use classifications. Moreover, legal regulations can hamper the use of remote sensing. For example, in the Netherlands habitat maps have to be derived from conventional vegetation maps, meaning that remote sensing is not allowed to replace traditional field surveys. On the other hand, remote sensing is still able to make more frequent updates in between the traditional updates implemented approximately once in 12 years. At the site level more examples are available regarding the added value of RS in habitat mapping. However, at e.g. plant species level (rare species) RS products are insufficient. In general it can be stated that large scale (and dynamic) habitats are more suitable for mapping by RS. The spatial resolution of the RS product must meet a certain 'intrinsic scale' that characterizes a specific habitat. This 'intrinsic scale' is habitat dependent (*Vanden Borre et al., 2011b*). As there are no standards defining spatial reference sizes for habitat mapping this knowledge gap makes standardisation of monitoring methodologies difficult. Matching appropriate RS observations to ecological processes or species distributions often requires a multi-scale approach where one spatial and temporal scale provides information on a portion of an ecological process or species' life-history while other scales are required to observe another portion (*Geller et al. in Walters and Scholes, 2017*). Another source for a mismatch of expectations mentioned by *Vanden Borre et al. (2011b)* is that habitat typologies are not harmonised making data compatibility and integration difficult. A standard habitat typology with a biotic and abiotic description could be of help to interchange remote sensing methods and products.

In *Corbane et al. (2015)* it is stated that the immense versatility of remote sensing technique and products has led to numerous potential approaches, but all of them are to a great extent affected by a series of potential flaws (*Grillo and Venora, 2011*):

» the large variability in the quality of input variables in terms of their semantic, thematic and geometrical accuracy;

» the possible variability of the spectral, spatial and temporal resolutions of the input datasets used across different studies;

» the (non-) availability of remote sensing data and ancillary data, with standardized metadata formats and pre-processing protocols, which are a prerequisite for the transferability of the methods between the sites;

» the (non-)availability of ground truth data in a suitable format for remote sensing applications (which differs from purely vegetation-based field mapping).

The difficulty of habitats mapping, in addition to the issues described above, is related to the following (see *Corbane et al., 2015*):

» the mismatch between the tremendous progress in RS applications to habitat mapping and the capabilities of Thematic Mapper,

» the difficulty to standardise monitoring methodologies due to the lack of typical surface area range in which most patches of a given habitat occur (see ‘intrinsic scale’),

» the broad definition of habitats or lack of a standardised typology (co-occurrence in mosaic patterns, based on descriptive information, heterogeneity (number of species involved)), and

» the missing link between land cover and habitats.

Furthermore, it is recognised that small scale sites can be better mapped by field observations. Increasing the level of detail in which habitats are described/defined the more difficult they can be mapped by RS. Also RS products cannot fulfill the needs for habitat modelling.

A risk exists that excitement over the RS technologies, encouraged by donors keen to show their support for innovation, may lead to practitioners deciding on which tools to use before they have decided on what they want to measure. **Remote sensing therefore needs to be applied only when appropriate to the local situation and when it can be used to answer specific monitoring questions** (*Stephenson, 2019*). The decision to use technology should also be based on project objectives and the availability of appropriate budgets and technical skills (*Schmeller et al., 2017*).

Summary of potential future developments for new other products

» Increase of update frequency of products due to developments in processing and availability of imagery

» Complete integration of remote sensing products with in-situ data (e.g. vegetation relevés, species presence)

» Integrated camera systems (e.g. LiDAR and hyperspectral)

» Pocket drones with integrated camera systems that can do instantaneous habitat mapping

» Non-disturbing drones

» ‘Everybody’ has their own drone

» Good & light batteries for drones

» Toolboxes & apps with free available high resolution RS products (e.g. temperature, flooding, soil moisture, vegetation structure, land cover, etc.) accessible, and all in one projection

» All RS products downloadable for own (further) processing

II.3.2 Future outlook

At the moment RS products and/or tools are mostly used by site managers for comparing sites, transferring knowledge across sites, early warning of effects of change in/outside the N2000 sites etc. For this they most commonly use aerial photos. To enhance the integration of remote sensing and habitat monitoring *Vanden Borre et al. (2011)* mentioned harmonisation and standardisation of approaches, development of readily useful products, and a fair validation of traditional and remote sensing products. Most importantly though, there is a need for a more active involvement from both parties, especially the monitoring community, in order to develop products that really suit the needs of their future users.

In the realisation of these potential products cloud processing/storage, better viewing tools and the application of machine learning (ML) will play a significant role.

Possible new products in the near future having different opportunities for realization

- Remote sensing based habitat maps for most Annex I habitat types (Natura 2000)
- Habitat maps every 6 years from RS (with 10m resolution)
- Species mapping with drones
- RS measures of abiotic site conditions (soil moisture, temperature, trophic levels, salinity)
- High resolution LiDAR products for vegetation structure everywhere including individual trees, height and diameter trees, and dead wood
- RS derived alert services
- Copernicus products linked to ecosystem and climate services

II.4 References

Akay, A.E., H. Oğuz, et al. (2008). Using LiDAR technology in forestry activities. Environmental Monitoring and Assessment: 1–9.

Alkema (2019). Aerial Plant Recognition Through Machine Learning; A deep learning approach to identifying marsh marigold (Caltha palustris) from UAV imagery in Biesbosch National Park, the Netherlands. Thesis Report GIRS-2019-24, Wageningen University, Wageningen.

Bengio, Y., Simard, P. & Frasconi, P. (1994). Learning long-term dependencies with gradient descent is difficult. IEEE Transactions on Neural Networks. Volume 5 Issue 2, March 1994, Pages 157–166.

Bradbury, R.B., Hill, R.A., Mason, D.C., Hinsley, S.A., Wilson, J.D., Baltzer, H., Anderson, G.Q.A., Whittingham, M.J., Davenport, I.J. & Bellamy, P.E. (2015). Modelling relationships between birds and vegetation structure using airborne LiDAR data: a review with case studies from agricultural and woodland environments. IBIS 147 (3).

Bunce, R.G.H., Bogers M.M.B., Evans, D., Halada, L., Jongman, R.H.G., Mucher, C.A., Bauch, B., de Blust, G., Parr T.W. & Olsvig-Whittaker L. (2013). The significance of habitats as indicators of biodiversity and their links to species. Ecological Indicators, Special Issue: Biodiversity Monitoring, Vol. 33 (2013) 19–25.

Carson, W. W., H. E. Andersen, et al. (2004). LiDAR applications in forestry – An overview, Denver, Colorado.

Christian, B. & Krishnayya, N.S.R. (2009). Classification of tropical trees growing in a sanctuary using Hyperion (EO-1) and SAM algorithm. Current Science, 96, 1601–1607.

Corbane, C., Lang, S., Pipkins, K., Alleaume, S., Deshayes, M., García Millán, V.E., Strasser, T., Vanden Borre, J., Spanhove, T. & Förster, M. (2015). Remote sensing for mapping natural habitats and their conservation status – New opportunities and challenges. International Journal of Applied Earth Observation and Geoinformation 37 (2015) 7–16.

Dobson, M.C., et al. (1995). Estimation of forest biophysical characteristics in northern Michigan with SIR-C/X-SAR, IEEE Trans. Geosci. Remote Sens., 33, 877–895, doi:10.1109/36.406674

Donoghue, D.N.M. & Watt, P.J. (2006). Using LiDAR to compare forest height estimates from IKONOS and Landsat ETM+ data in Sitka spruce plantation forests. Int. J. Remote Sens. 27(11): 2161–2175.

EC (1979). Council Directive 79/409/EEC of 2 April 1979 on the conservation of wild birds. Document 31979L0409.

EC (1992). The Habitats Directive, Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

EC (2009). The Birds Directive , Directive 2009/147/EC on the conservation of wild birds.

EC (2005).

ETC-BD (2018).

Evans, D.L., Roberts, S.D., et al. (2006). LiDAR – A new tool for forest measurements? Forestry Chronicle 82(2): 211–218.

Feranec, J., Soukup, T., Hazeu, G. & Jaffrain, G. (2016). European Landscape Dynamics: CORINE Land Cover Data. CRC Press, Boca Raton, 337 Pages – 52 Color & 45 B/W Illustrations, ISBN 9781482244663

Florian, K., Kostas, P. P. Irena, H. & Dirk, H. (2006). Forest height estimation in tropical rain forest using Pol-InSAR techniques, paper presented at International Conference on Geoscience and Remote Sensing Symposium, IEEE, Denver.

Gerard, F., Thompson, A., Manchester, S., Smith, G., Wadsworth, R., Swetnam, S., Petit, S., Gregor, M., Luque, S., Huitu, H., Köhler, R., Olschofsky, K., Hazeu, G., Mücher, C.A., Halada, L., Bugár, G. & Pino, J. (2006). Land Cover Change in Europe from the 1950'ies to 2000. Aerial photo interpretation and derived statistics from 59 samples distributed across Europe. Edited by Raul Köhler, Konstantin Olschofsky and France Gerard.. Book published by University of Hamburg, World Forestry Institute, Germany. ISBN 80- 89088-46-5, 364 pp.

Gerard, F., Petit, S., Smith, G., Thomson, A., Brown, N., Manchester, S., Wadsworth, R., Bugar, G., Halada, L., Bezák, P., Boltiziar, M., Badts, E., Gregor, M., Hazeu, G., Mücher, C.A., Wachowicz, M., Huitu, Tuominen, S., Köhler, R., Olschofsky, K., Ziese, H., Kolar, J., Sustera, J., Luque, S., Pino, J., Pons, X., Roda, F., Roscher, M. & Feranec, J. (2010). Land cover change in Europe between 1950 to 2000 determined employing aerial photography. Progress in Physical Geography, Vol. 34(2), 2010, pp. 183–205.

Graf, R.F., Mathys, L., et al. (2009). Habitat assessment for forest dwelling species using LiDAR remote sensing: Capercaillie in the Alps. Forest Ecology and Management 257(1): 160–167.

Grillo, O. & Venora, G. (2011). Biodiversity Loss in a Changing Planet, URL http://www.intechweb.org/books/show/title/biodiversity-loss-in-a-changing-planet.

Hayashia, M., Saigusaa, N., Ogumab, H. & Yamagata, Y. (2013). Forest canopy height estimation using ICESat/GLAS data and error factor analysis in Hokkaido, Japan. ISPRS Journal of Photogrammetry and Remote Sensing 81, 12–18.

Hazeu, G.W., J.A. Klijn, W. Knol & E.J. Lammerts (2002). Een eiland in beweging; veranderingen in het Terschellinger landschap over anderhalve eeuw aan de hand van oude topografische kaarten en luchtfoto's. Wageningen, Alterra. Alterra-rapport 501, 72 blz, 19 fig.; 5 tab.; 31 ref.

Hazeu, G.W., Milenov, P., Pedroli, B., Samoungi, V., van Eupen, M. & Vassilev, V. (2014). High Nature Value farmland identification from satellite imagery, a comparison of two methodological approaches. International Journal of Applied Earth Observations and Geoinformation 30, 98–112.

He, K.S., Rocchini, D., Neteler, M. & Nagendra, H. (2011). Benefits of hyperspectral remote sensing for tracking plant invasions. Diversity and Distributions, 17, 381–392.

Hestir, E.L., Khanna, S., Andrew, M.E., Santos, M.J., Viers, J.H., Greenberg, J.A., Rajapakse, S.S. & Ustin, S.L. (2008). Identification of invasive vegetation using hyperspectral remote sensing in the California Delta ecosystem. Remote Sensing of Environment, 112, 4034–4047.

Heymann, Y., Steenmans, C., Croisille, G. & Bossard, M. (1993). CORINE land cover project: technical guide. Luxembourg: European Commission, Environment, Nuclear Safety and Civil Protection.

Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., Mücher, C.A., Howard, D.C. & Mateus, V.L. (2006). Objectives and applications of a statistical environmental stratification of Europe. Landsc. Ecol. 21, 409–419.

Joshi, N.P., Mitchard, E.T.A., Schumacher, J., Johannsen, V.K., Saatchi, S. & Fensholt, R. (2015). L-Band SAR Backscatter Related to Forest Cover, Height and Aboveground Biomass at Multiple Spatial Scales across Denmark. Remote Sens., 2015, 7, 4442-4472.

Kennedy, R. E., Townsend, P. A., Gross, J. E., Cohen, W. B., Bolstad, P., Wang, Y. Q., et al. (2009). Remote sensing change detection tools for natural resource managers: Understanding concepts and tradeoffs in the design of landscape monitoring projects. Remote Sensing of Environment, 113, 1382–1396.

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

Lengyel, S., Déri, E., Varga, Z., Horváth, R., Tóthmérész, B., Henry, P.-Y., Kobler, A., Kutnar, L., Babij, V., Seliˇskar, A., Christia, C., Papastergiadou, E., Gruber, B. & Henle, K. (2008). Habitat monitoring in Europe: a description of current practices. Biodivers. Conserv. 17, 3327–3339.

Lillesand, T.M., Kiefer, R.W. & Chipman, J.W. (2015). Remote sensing and image interpretation. Seventh edn. Hoboken, N.J.: John Wiley & Sons.

Lu, S., Shimizu, Y., Ishii, J., Funakoshi, S., Washitani, I. & Omasa, K. (2009). Estimation of abundance and distribution of two moist tall grasses in the Watarase wetland, Japan, using hyperspectral imagery. Isprs Journal of Photogrammetry and Remote Sensing, 64, 674–682.

Lucas, R.M., Blonda, P., Bunting, P.F., Jones, G., Inglada, J., Arias, M., Kosmidou, V., Petrou, Z., Manakos, I., Adamo, M., Charnock, R., Tarantino, C., Mücher, C.A., Kramer, H. Jongman, R., Honrado, J. & Mairota, P. (2015). The Earth Observation Data for Habitat Monitoring (EODHaM) System. International Journal of Applied Earth Observation and Geoinformation 37 (2015) 17–28.

Mallet, C. & Bretar, F. (2009). Full-waveform topographic lidar: State-of-the-art. ISPRS Journal of Photogrammetry and Remote Sensing, 64 (1), 1–16.

Mora, B., Wulder, M.A., White, J.C. & Hobart, G. (2013). Modeling Stand Height, Volume, and Biomass from Very High Spatial Resolution Satellite Imagery and Samples of Airborne LiDAR. Remote Sens. 2013, 5, 2308–2326.

Mücher, C.A., Kramer, H., van der Wijngaart, R. & Huiskes, R. (2017a). Ontwikkelen Remote Sensing monitoringssystematiek voor vegetatiestructuur. Pilot studie: detectie verruiging Grijze Duinen (H2130) voor het Natura 2000-gebied Meijendel-Berkheide. Wageningen, Wageningen Environmental Research, Rapport 2838, 46 pp.

Mücher, C.A., Calders, K., Zisis, I.S. & Reiche, J. (2017b). Ecosystem Structure. Chapter 2.5 of Biodiversity Sourcebook. In: GOFC-GOLD (2017) A Sourcebook of Methods and Procedures for Monitoring Essential Biodiversity Variables in Tropical Forests with Remote Sensing. Eds: GOFC-GOLD & GEO BON. Report version UNCBD COP-13, GOFC-GOLD Land Cover Project Office, Wageningen University, The Netherlands. ISSN: 2542–6729.

Mücher, C.A., Roupioz, L., Kramer, H., , Bogers, M.M.B., Jongman, R.H.G., Lucas, R.M., , Petrou, Z., Kosmidou, V.E., Manakos, I., Padoa-Schioppa, E., Adamo, M. & Blonda. (2015). Synergy of Airborne LiDAR and Worldview-2 satellite imagery for land cover and habitat mapping: a BIO_SOS-EODHaM case study for the Netherlands. International Journal of Applied Earth Observation and Geoinformation 37 (2015) 48–55.

Mücher, C.A., Kooistra, L., Vermeulen, M., Vanden Borre, J., Haest, B. & Haveman, R. (2013). Quantifying structure and function of Natura 2000 heathland habitats using spectral mixture analysis and segmentation techniques on hyperspectral imagery. Ecological indicators, Special Issue: Biodiversity Monitoring, Vol. 33 (2013) 71–81.

Mücher, C. A. (2009). Geo-spatial modelling and monitoring of European landscapes and habitats using remote sensing and field surveys. Ph.D. thesis, Wageningen University.

Mücher, C. A., Steinnocher, K. T., Kressler, F. P. & Heunks, C. (2000). Land cover characterization and change detection for environmental monitoring of pan-Europe. International Journal of Remote Sensing, 21, 1159–1181.

Nagendra, H., Lucas, R., Honrado, J. P., Jongman, R. H. G., Tarantino, C., Adamo, M. & Mairota, P. (2013). Remote Sensing for Conservation Monitoring: Assessing Protected Areas, Habitat Extent, Habitat Condition, Species Diversity, and Threats. Ecological Indicators 33 (2013).

Papathanassiou, K.P., Kugler, F., Lee, S., Marotti, L. & Hajnsek, I. (2008). Recent advances in Polarimetric SAR Interferometry for forest parameter estimation, paper presented at Radar Conference 2008, IEEE, Rome.

Petros Patias, Natalia Verde, Maria Tassopoulou, Charalampos Georgiadis & Dimitris Kaimaris (2019). Essential Variables: Describing the context, progress and opportunities for the Remote Sensing Community. Proceedings Volume 11174, Seventh International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2019); 111740C (2019)., https://doi.org/10.1117/12.2533604. Event: Seventh International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2019), 2019, Paphos, Cyprus.

Rosso, P.H., Ustin, S.L. & Hastings, A. (2005). Mapping marshland vegetation of San Francisco Bay, California, using hyperspectral data. International Journal of Remote Sensing, 26, 5169–5191.

Schmeller, D.S. (2008). European species and habitat monitoring: where are we now? Biodivers. Conserv. 17, 3321–3326.

Schmeller, D.S., Böhm, M., Arvanitidis, C., Barber-Meyer, S., Brummitt, N., Chandler, M. et al. (2017). Building capacity in biodiversity monitoring at the global scale. Biodiversity and Conservation 26: 2765–2790.

Skidmore, A.K., Pettorelli, N., Coops, N.C., Geller, G.N., Hansen, M., Lucas, R., Mücher, C.A., O'Connor, B., Paganini, M., Pereira, H.M., Schaepman, M.E., Turner, W., Wang, T. & Wegmann, M. (2015). Agree on biodiversity metrics to track from space. NATURE, 23 July 2015, Vol. 523, pp 403–405.

Stephenson, P.J. (2019). Integrating Remote Sensing into Wildlife Monitoring for Conservation. Environmental Conservation.

St-Onge, B., Vepakomma, U., Hu, Y., Wulder, M., Wynne, R. & Nelson, R.F. (2005). Mapping above ground forest biomass using lidar data and multispectral images.

Srivastava, R.K., Greff, K. & Schmidhuber, J. (2015). Training very deep networks. International Conference on Learning Representations.

Swain, Ph. H. & Davis, S.M. (Eds) (1978). Remote Sensing: The Quantitative Approach. NewYork: McGraw-Hill, 396pp.

Treuhaft, R.N. & Siqueira, P.R. (2000). The vertical structure of vegetated lad surfaces from interferometric and polarimetric radar. Radio Science 25, 141–177.

Turner, W., Spector, S., Gardiner, 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.

Vanden Borre, J., Haest, B., Lang, S., Spanhove, T., Förster, M. & Sifakis, N. I., (2011a). Towards a wider uptake of remote sensing in Natura 2000 monitoring: Streamlining remote sensing products with users' needs and expectations.

Vanden Borre, J., Paelinckx, D., Mücher, C. A., Kooistra, L., Haest, B., De Blust, G. & Schmidt, A. M. (2011b). Integrating remote sensing in Natura 2000 habitat monitoring: Prospects on the way forward. Journal for Nature Conservation, 19(2), 116–25. doi:10.1016/j.jnc.2010.07.003.

Van der Zanden, E.H., Verburg, P.H. & Mücher, C.A. (2013). Modelling the spatial distribution of linear landscape elements in Europe. Ecological Indicators 27, 125–136.

Vaz, A.S., Marcos, B., Goncalves, J., Monteiro, A., Alves, P., Civantos, E. & Honrado, J.P. (2015). Can we predict habitat quality from space? A multi-indicator assessment based on an automated knowledge-driven system. International Journal of Applied Earth Observation and Geoinformation, 37, 106–113. doi:10.1016/j.jag.2014.10.014

Walsh, S.J., Mccleary, A.L., Mena, C.F., Shao, Y., Tuttle, J.P., Gonzalez, A. & Atkinson, R. (2008). QuickBird and Hyperion data analysis of an invasive plant species in the. Galapagos Islands of Ecuador: Implications for control and land use management. Remote Sensing of Environment, 112, 1927–1941.

Walters, M. & Scholtes R.J. (eds.) (2017). The GEO Handbook on Biodiversity Observation Networks.

Weis and Banko (2018). Ecosystem Type Map v3.1 – Terrestrial and marine ecosystems. Technical paper N° 11/2018, EEA, European Topic Centre on Biological Diversity.

Annex I: Examples of useful satellite imagery

Satellite sensor	Launch	Number of bands	Spatial resolution [m]	Revisit time (days)	Biophysical parameters
WorldView-2	2009	8 (B,G,R,coastal, yellow,NIR,Red-Edge, NIR2)	0.46 (pan) 1.8 (ms)	1.1	Reflection, NDVI, LAI, leaf chlorophyll (and nitrogen) concentration Classification
WorldView-3	2014	8 (B,G,R,coastal, yellow,NIR, RedEdge,NIR2) 8 SWIR 12 CAVIS	0.31 (pan) 1.24 (ms) 3.7 (short wave IR)	<1	Reflection, NDVI, LAI, leaf chlorophyll (and nitrogen) concentration Classification
QuickBird	2001	4 (B,G,R,NIR)	0.65 (pan) 2.6 (ms)	1–3.5	Reflection, NDVI, LAI Classification
GeoEye-1	2008	4 (B,G,R,NIR)	0.4 (pan)	~3	Reflection, NDVI, LAI
GeoEye-2 (WorldView-4)	2016		0.3 (pan) 1.2 (ms)	<3	Reflection, NDVI, LAI, leaf chlorophyll (and nitrogen) concentration Classification
Ikonos	1999	4 (B,G,R,NIR)	1 (pan) 4 (ms)		Reflection, NDVI, LAI Classification
RapidEye (5 satellite constellation)	2008	5 (B,G,R,NIR, RedEdge)	5 (ms)	1	Reflection, NDVI, LAI, leaf chlorophyll (and nitrogen) concentration Classification
Pleiades-1A & B (2 satellite constellation)	2011/2012	4 (B,G,R,NIR)	0.5 (pan) 2 (ms)	1	Reflection, NDVI, LAI Classification
SkySat-1 & 2	2013/2014	4 (B,G,R,NIR)	0.9 (pan) 2 (ms)		
SPOT-6 & 7 constellation	2012/2014	4 (B,G,R,NIR)	1.5 (pan) 8 (ms)	1	
Landsat-8	2013	11 (VNIR,SWIR,TIR)	15 (pan) 30m (ms) 100m (TIR)	16	Reflection, NDVI, LAI, temperature Classification
Aster	1999	3, 6, 5 (VNIR,SWIR,TIR)	15 (VNIR) 30 (SWIR) 90 (TIR)		
Sentinel-2A & B (2 satellite constellation)	2015/2016	13 (VNIR, NIR, SWIR)	10, 20, 60	< 5	Reflection, NDVI, LAI, leaf chlorophyll (and nitrogen) concentration Classification

B: blue, G: green; R: red; NIR: near infrared; pan: panchromatic; ms: multi-spectral; VNIR: visible and near infrared; SWIR: shortwave infrared; TIR: thermal-infrared

Different satellite sensors are acquiring information with different spectral, temporal an spatial resolution making them suitable for monitoring specific biophysical parameters.