INTRODUCTION TO CROP GROWTH MONITORING AND MODELING ON THE BASE OF SPECTRAL RESPONSE OF CANOPIES

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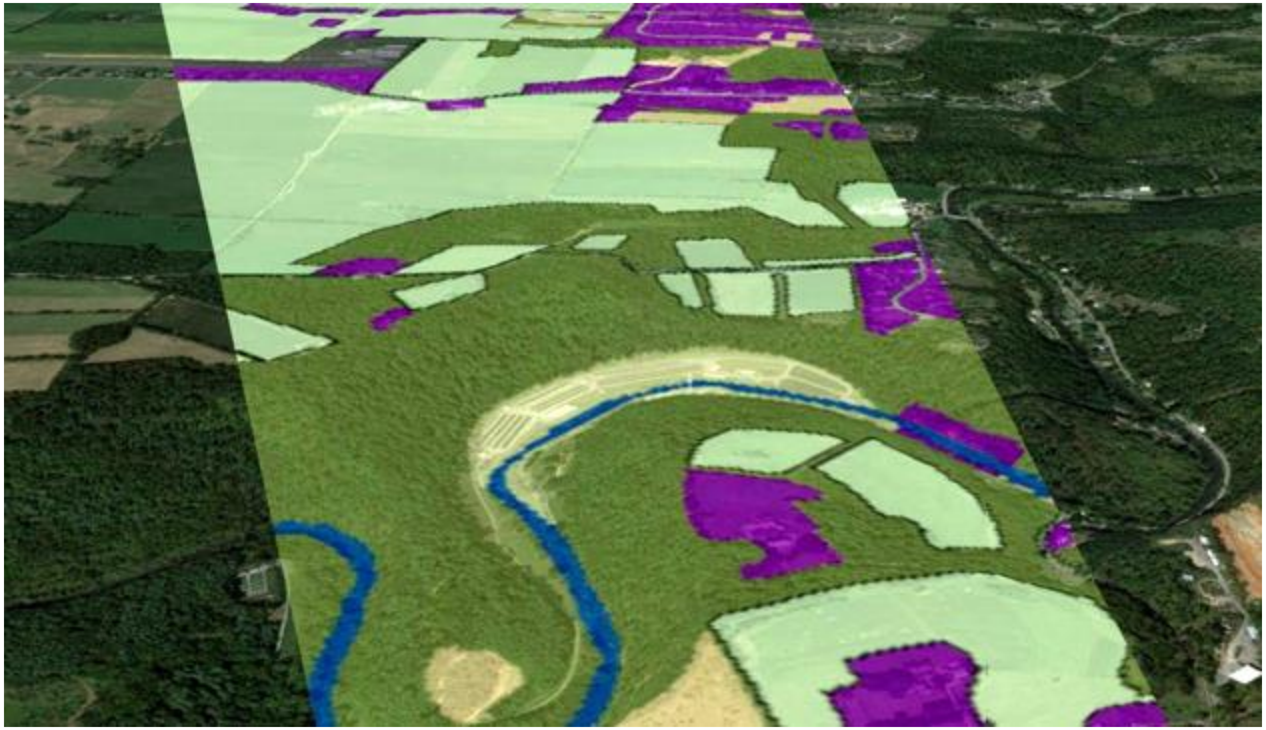
Co-funded by the Erasmus+ Programme of the European Union

Joint Project: Capacity Building in the Field of Higher Education ERASMUS+ 2018

SPECTRAL PROPERTIES OF VEGETATION AND SOIL



Factors affecting EMR radiation

EMR measured has to pass through the Earth's atmosphere. Its passage through the atmosphere will modify its spectral distribution, intensity, frequency, and direction, among other things.

It depends on:

- kind of substance (chemical composition…)
- physical condition (moisture content, surface compaction, etc.)
- the state of surroundings (on the permeability of the atmosphere, etc.)

Spectral reflectance

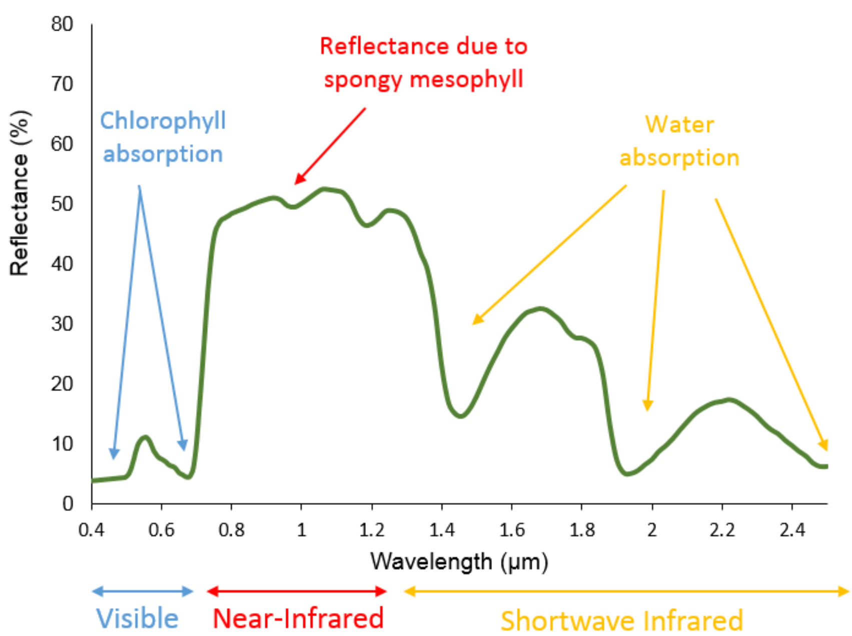
The amount of reflected radiation can be characterized by the so-called spectral reflectance ρ (λ), which can be defined as the ratio of the reflected radiation (Mr) and the incident radiation intensity (Mi) at a certain wavelength (λ), expressed eg in percent, ie:

$$\rho(\lambda) = \frac{M_r(\lambda)}{M_i(\lambda)} * 100\ [\%]$$

In spite of all the influences caused by the atmosphere and the interaction of radiation on the Earth's surface, despite all the effects caused by the physical state of the objects, it can be stated that each substance on the Earth's surface is characterized by its own **spectral properties**.

Spectral behavior – spectral response

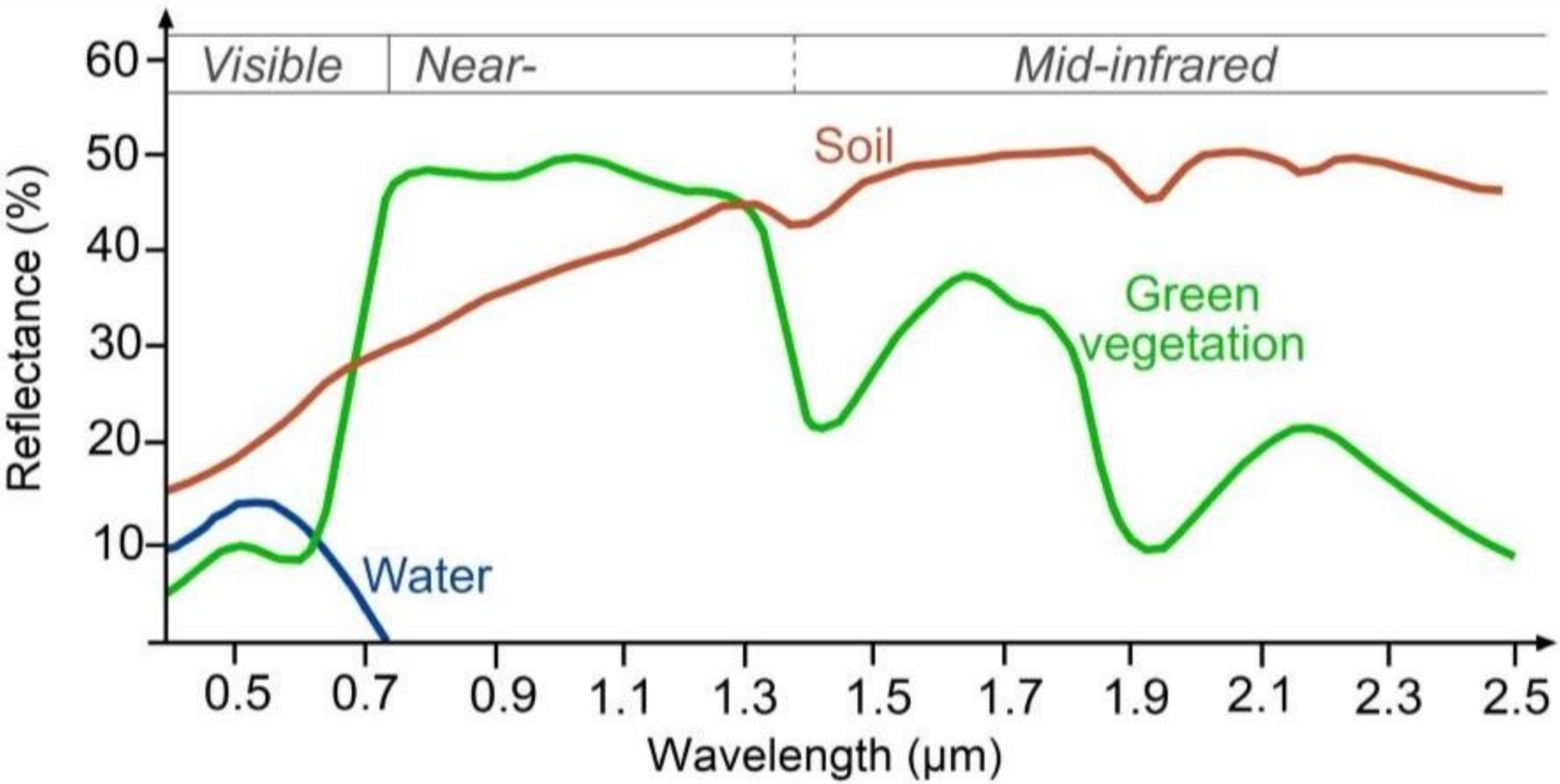
Most types of surfaces have a different shade of gray or other color in their images from different parts of the spectrum - they reflect different amounts of radiation.
Whether an object is visible in a particular image is determined by the amount of reflected radiation.



Spectral properties of objects

- For each object, a dependency between its reflectance and wavelength can be compiled, and the course of this dependence will be more or less typical of this object.
- This characteristic is called the so-called **spectral reflectance curve**.
- The reflectance curve is a expression of the so-called spectral properties of objects. The shape of the curve has a great influence on the selection of the wavelength in which the object data is to be retrieved.
- The spectral response curves always have a typical course for the same object class (vegetation, bare soil).

Spectral response of selected types of surfaces

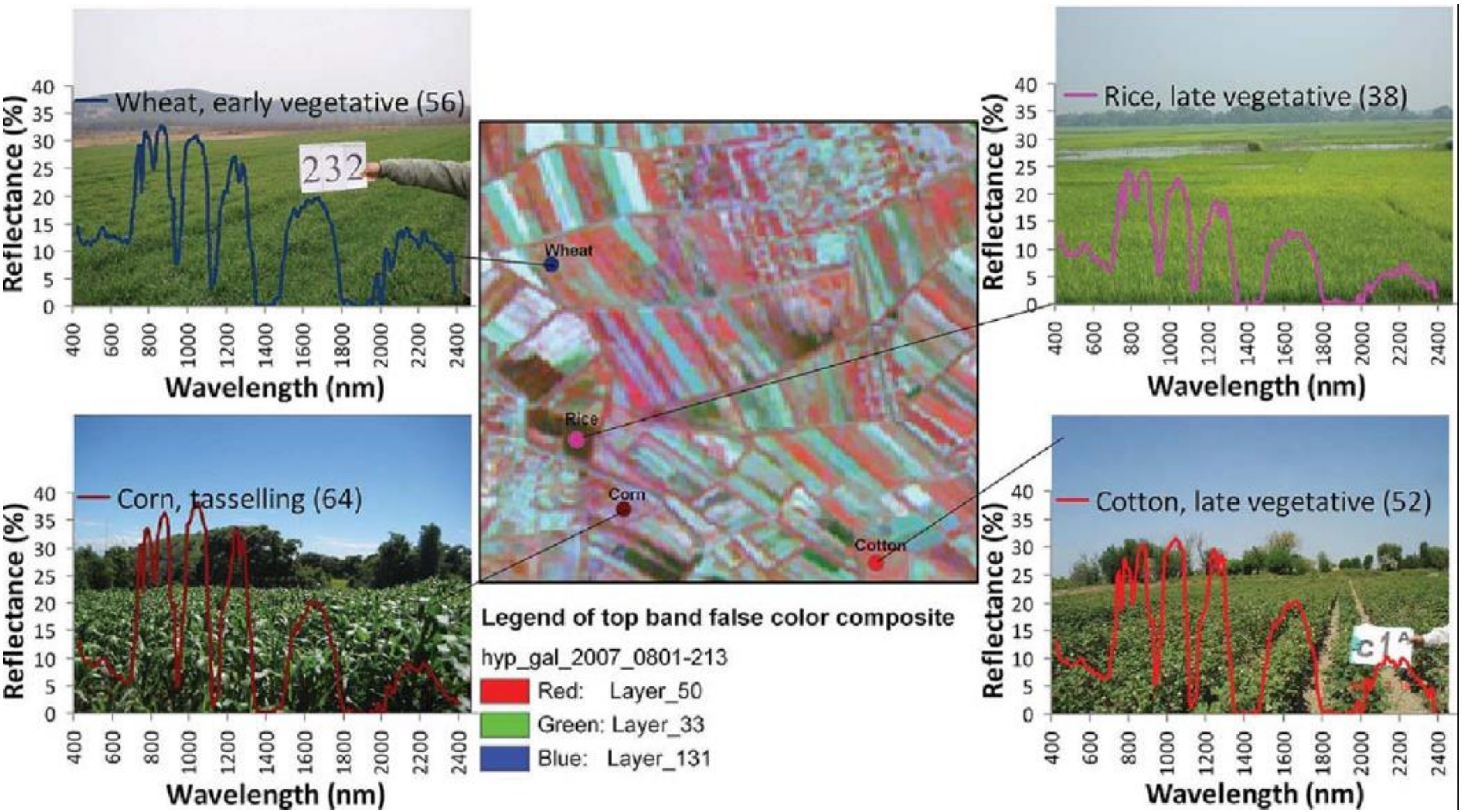


Spectral reflectance of selected species or cultivars

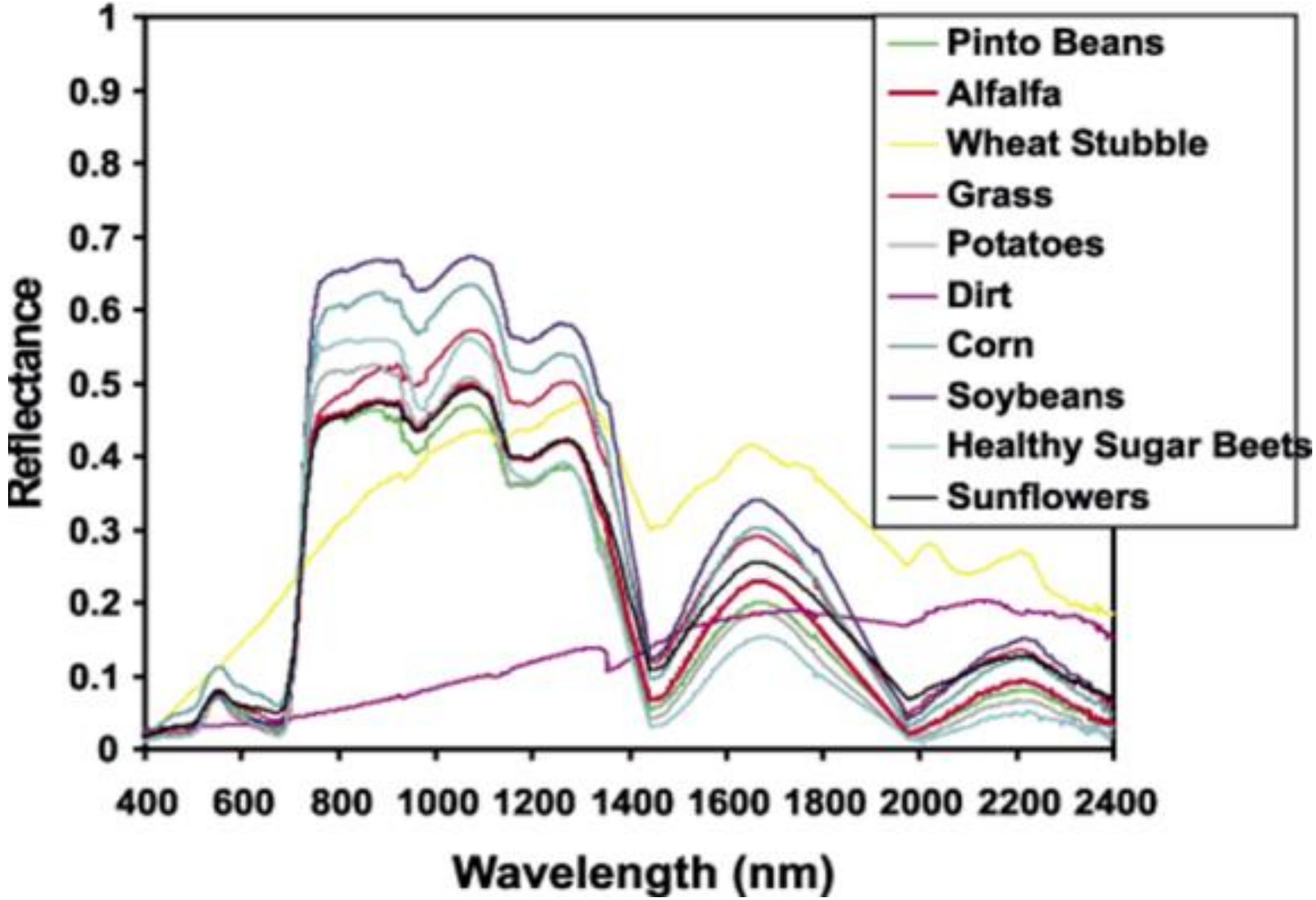
- There is different spectral reflectance curve for each of species (or cultivar), but it still retains its typical course with local max in the green spectrum and with a significant increase in reflectance in the near-IR range. Because the human eye is not sensitive to IR, vegetation appears green.

- Conversely, in black-and-white IR images, vegetation will appear much lighter compared to the visible spectrum because it reflects far more light.

Spectral reflectance of selected species



Spectral reflectance of selected species



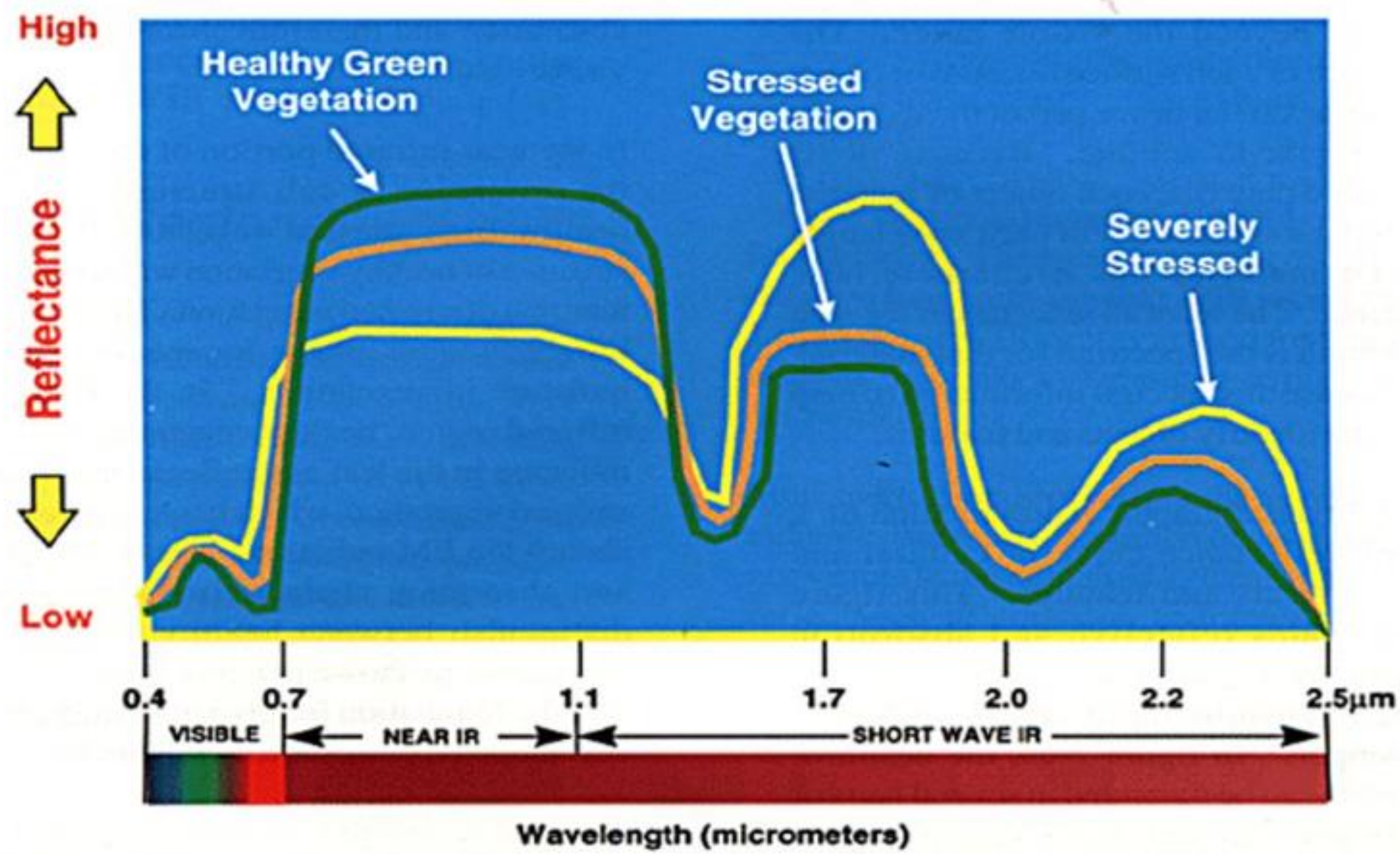
Spectral Reflectance of vegetation exposed to stress

- In vegetation exposed to some stress, its growth is impaired and chlorophyll activity decreases. The result is an increase in reflectance in the blue and red visible parts of the spectrum and a significant decrease in IR reflectivity.

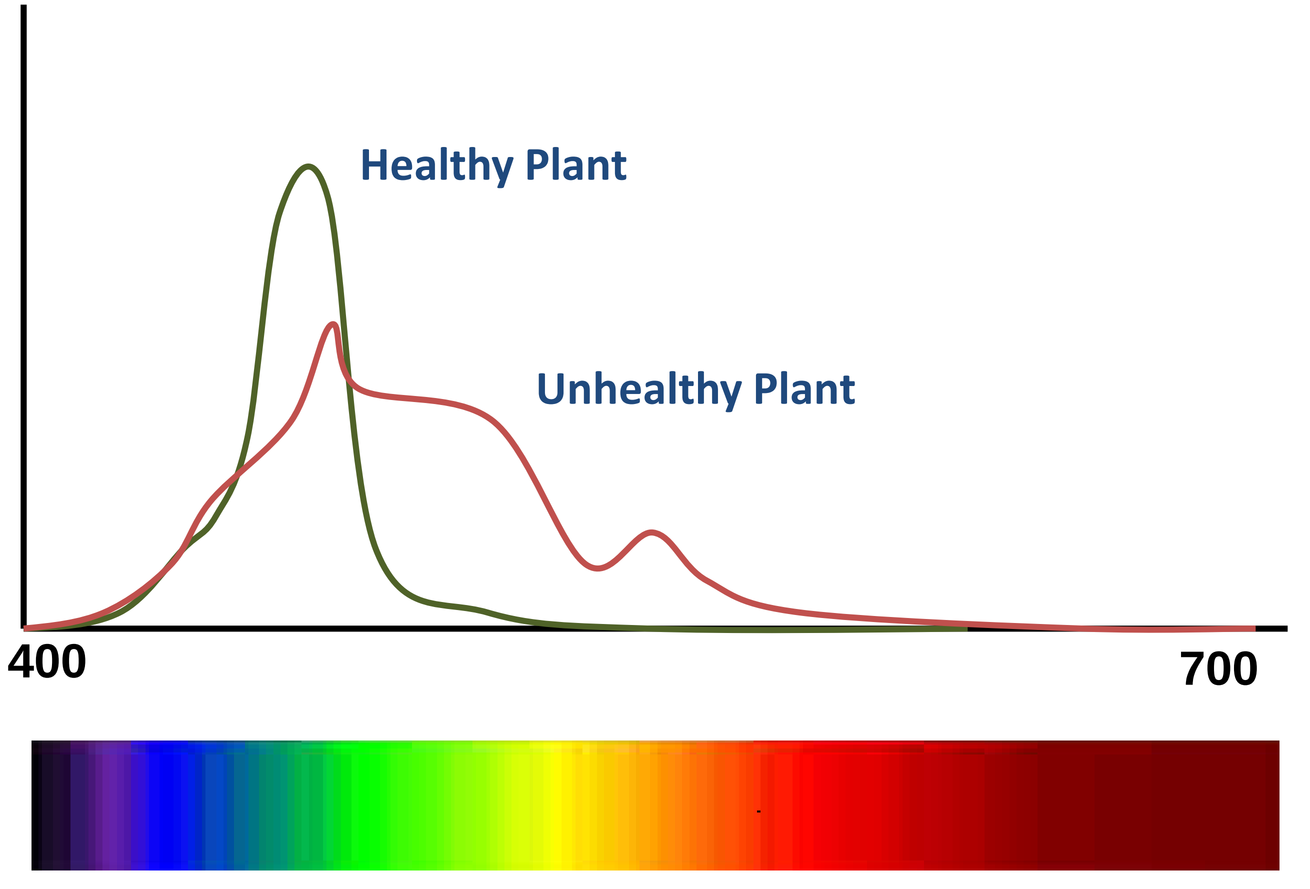
- Mapping of vegetation health status - increased reflectance in the red spectrum results in leaf yellowing (R + G = yellow)

- In some plants, for example, phenological phases of crops (tillering, stem elongation, flowering, harvesting) are projected into the spectral reflectance curve.

Spectral Reflectance of vegetation exposed to stress



How we can see the crop colors?



Practical meaning of spectral properties

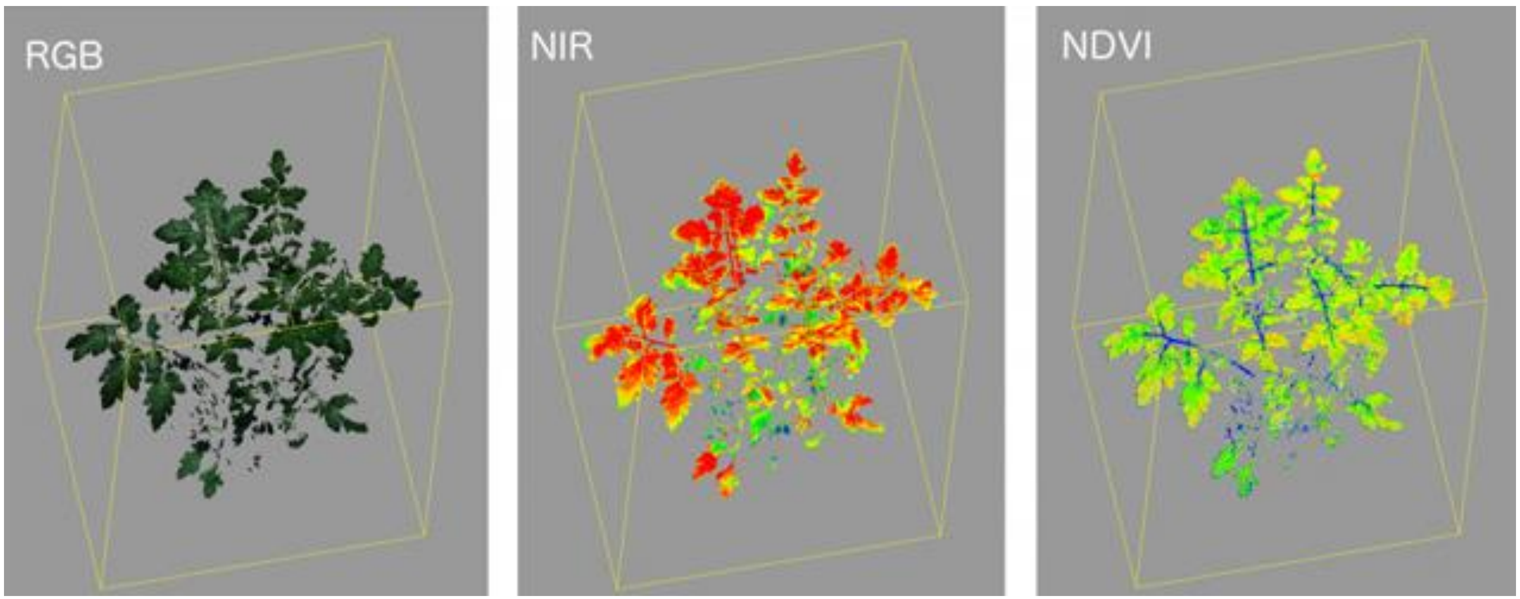
- Using the spectral reflectance curve, we can select the wavelength at which the image will appear best for identifying the surface (canopy - crop).

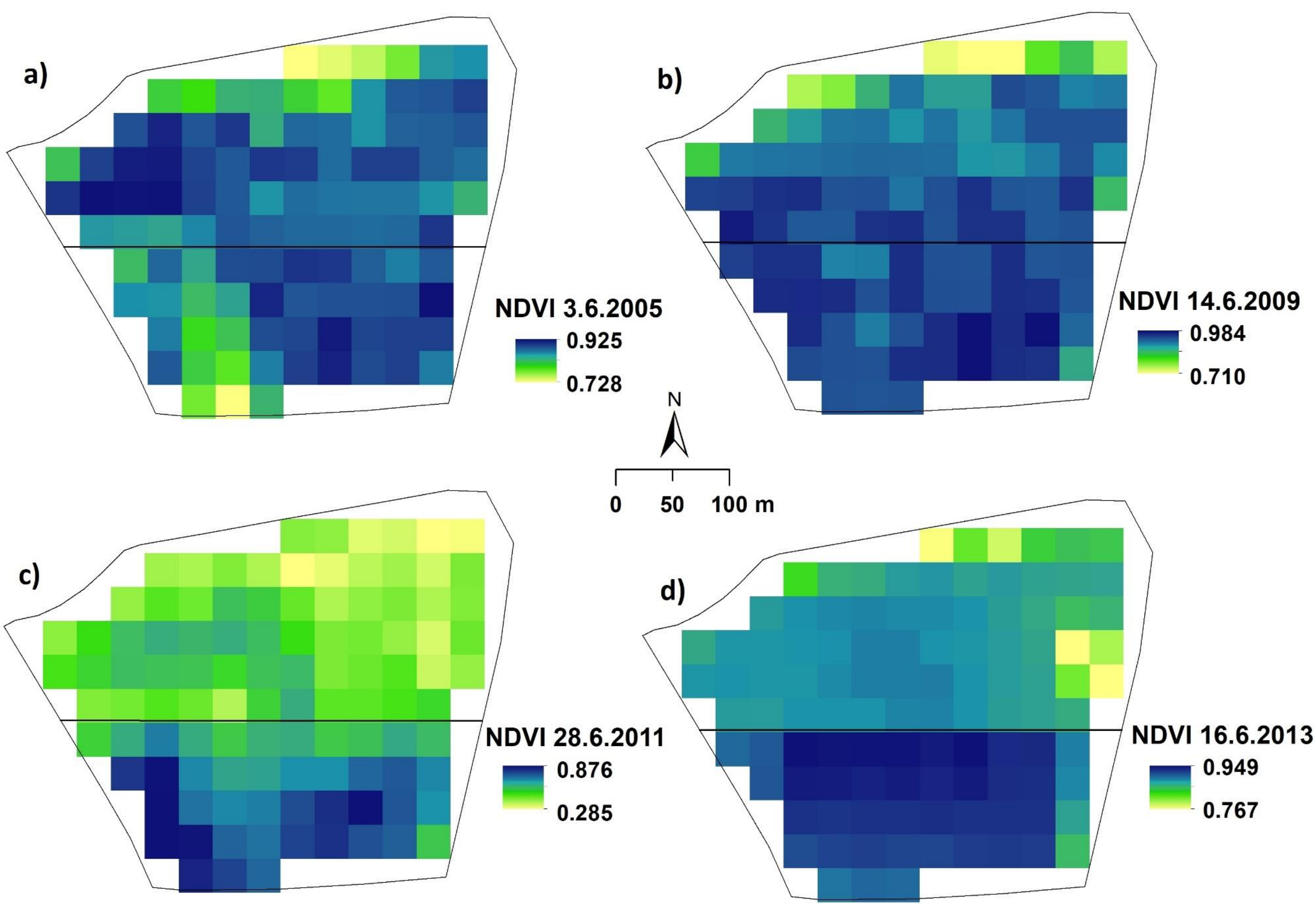
- Furthermore, multiple types of surfaces can be appropriately compared - a wavelength interval can be chosen in which it will best differ from its surroundings - from other substances.

- The knowledge of spectral properties allows to indicate processes that are noticeable later in the landscape.

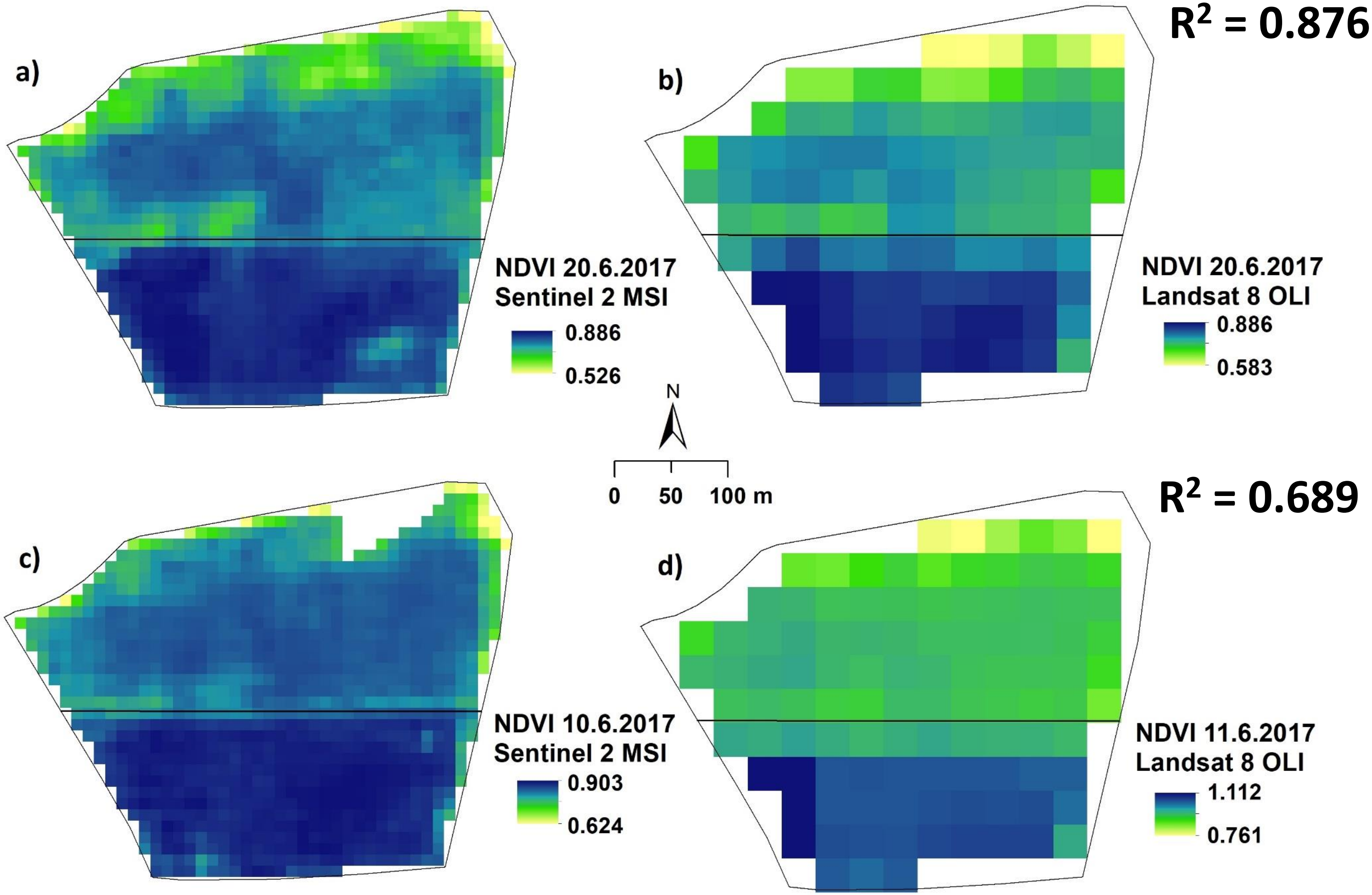
- Knowledge of spectral properties mechanisms is an essential tool for recognizing individual types of surfaces and mapping them by remote sensing.

Practical meaning of spectral properties





NDVI of winter wheat – 2005 (cultivar Ebi), 2009 (Ebi), 2011 (Baletka) and 2013 (Brilliant); LANDSAT images



NDVI of spring wheat – 2017 - two cultivars - Seance in the upper part, Astrid in the lower part

Spectral reflectance properties of vegetation

The spectral reflectance properties of the vegetation cover (canopy) are mainly formed by following factors:

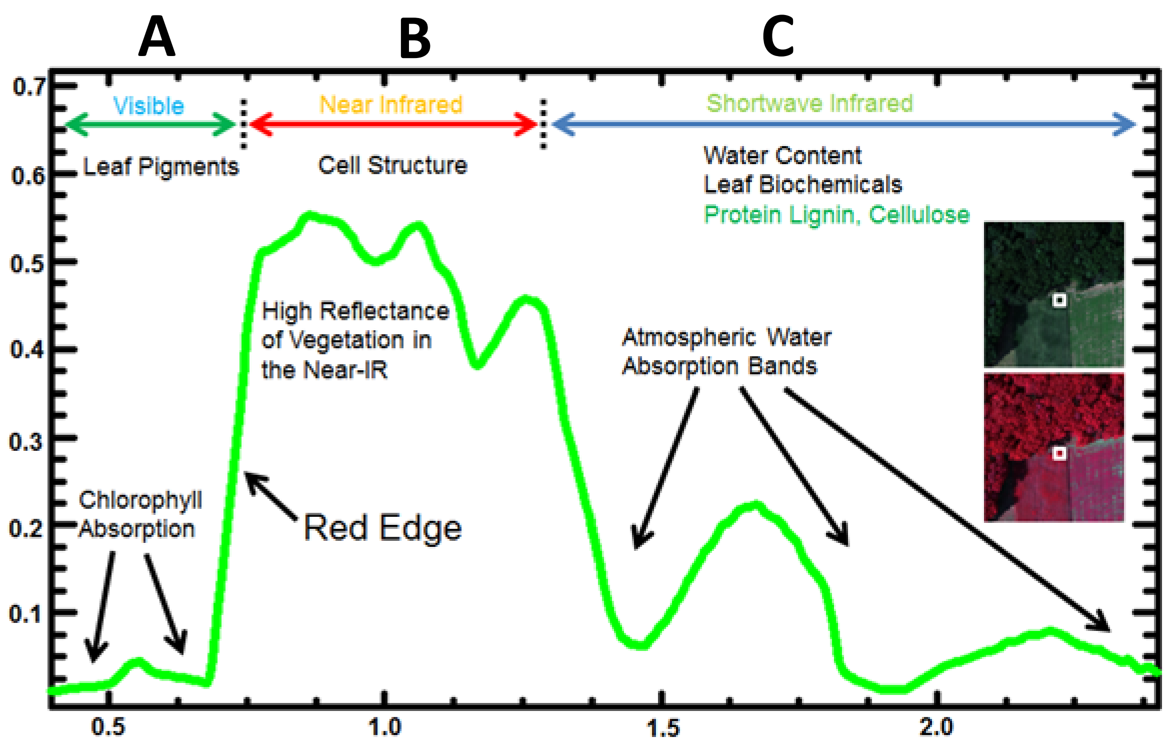
- Outer arrangement of vegetation cover
- Internal structure of individual plant parts
- Water content
- Health condition
- Properties of soil substrate

Spring barley, Vendolí, 3.5.2015
Tillering (BBCH 23)

Spring barley, Vendolí, 19.6.2015
Flowering (BBCH scale – 62)

Spectral response of the vegetation

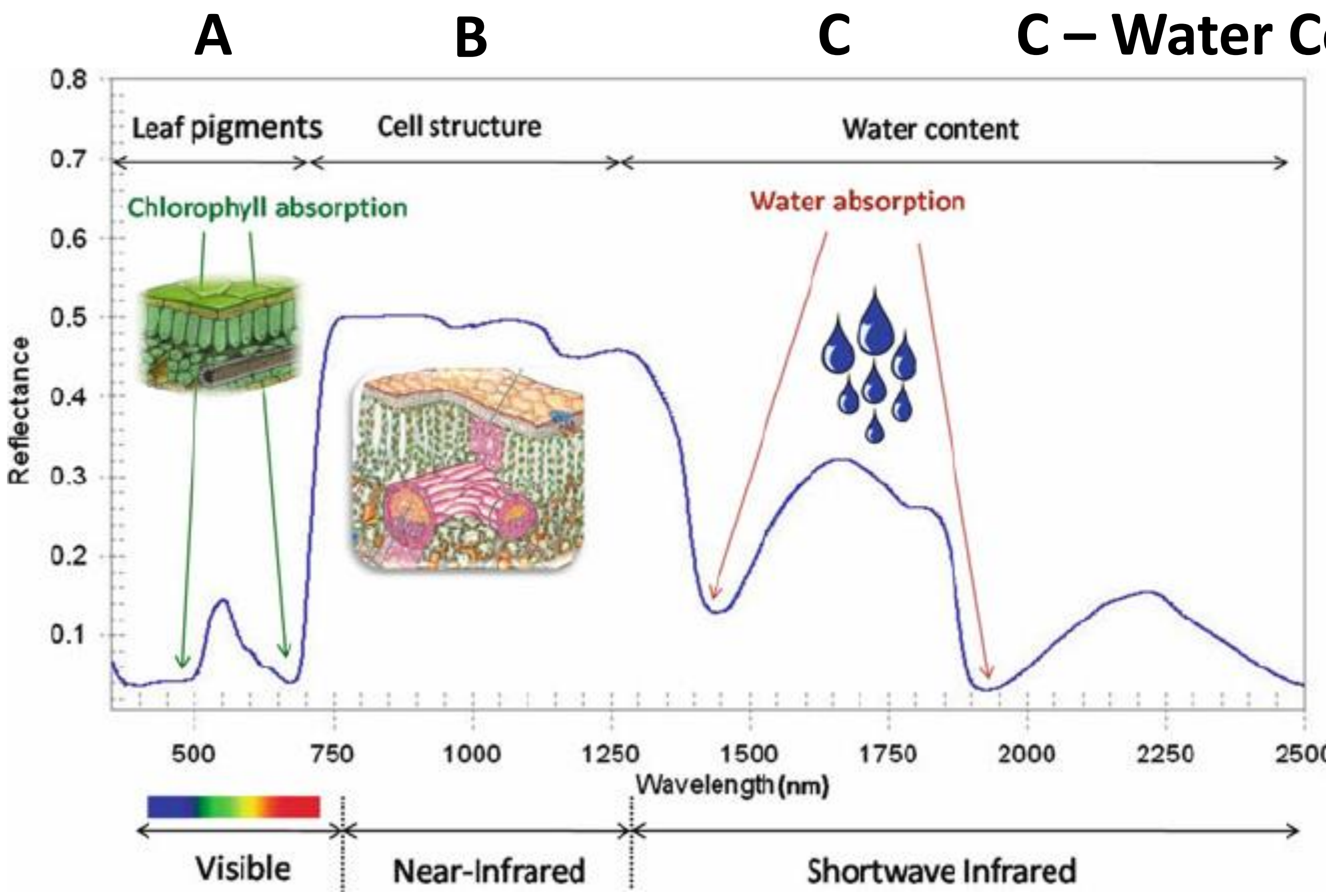
A – Leaf Pigments
B – Cell Structure
C – Water Content



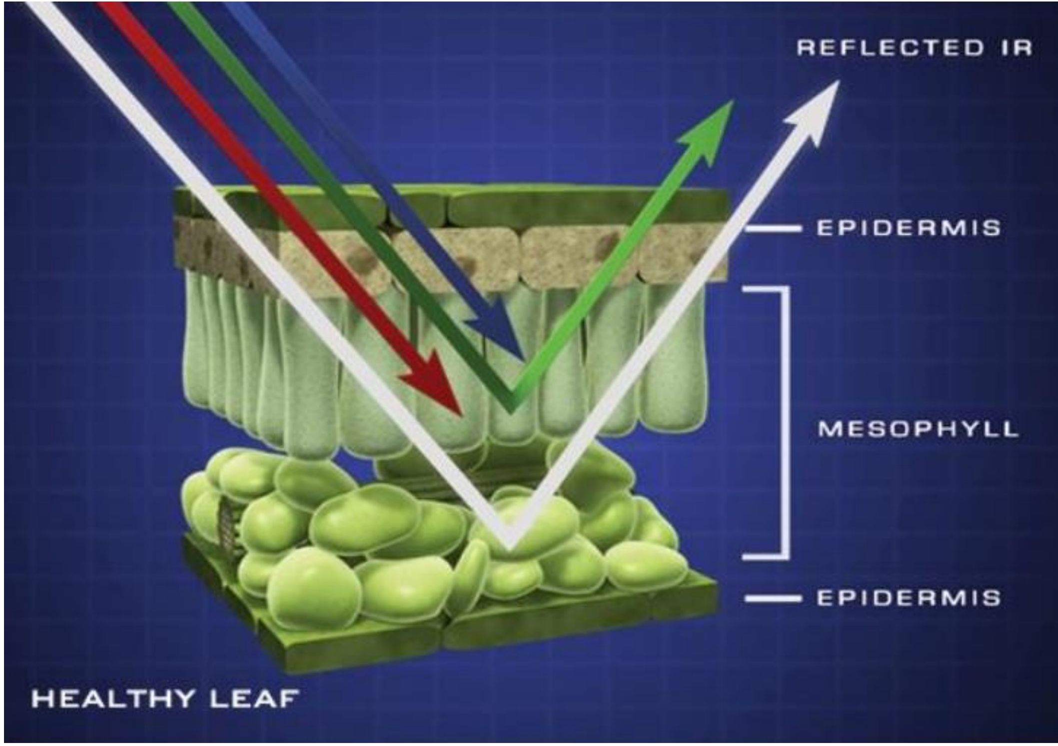
Schematic curve of the spectral properties of the "average" leaf in the visible and IR part of the EM spectrum.

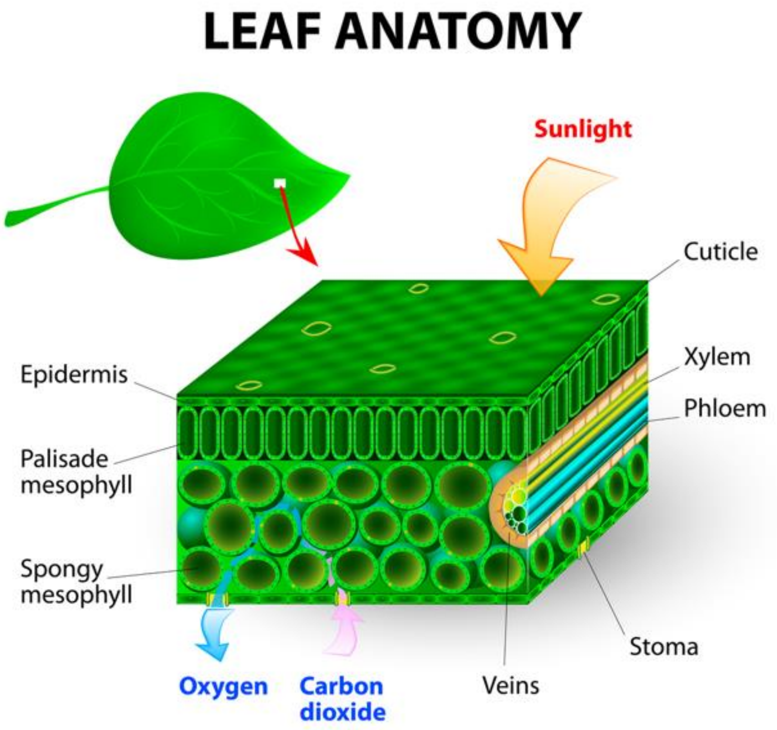
Spectral response of the vegetation

A – Leaf Pigments
B – Cell Structure
C – Water Content



Schematic curve of the spectral properties of the „typical" leaf in the visible and IR part of the EM spectrum.





Chlorophyll absorbs 70% to 90% of incident radiation in the blue and red parts of the EM spectrum.

A - pigmentation absorption (leaf pigments) part (0,4 – 0,7 μm)

- For the spectral properties of the leaves in the visible part of the spectrum, the most important are the pigment substances, and especially the chlorophyll and carotenes.
- Chlorophyll absorbs 70% to 90% of the incident radiation in the blue and red parts of the EM spectrum.
- Between these absorption bands there is a local maximum reflectance in the green part of EM spectrum.

$\Rightarrow$ This is the reason of the green color of the plants during the growing season.

B – Cell Structure part (0,7 – 1,4 µm)

- Significant increase in reflectance at wavelengths of around 0.7 µm is typical for vegetation.
- Reflection in this part of the EM spectrum affects the morphological formation of the leaf, which is very variable in the individual plant species.
- Therefore, image materials acquired in this part of the EM spectrum are more suitable for distinguishing areas covered by vegetation from other areas. Furthermore, they are suitable for distinguishing individual plant species, which may be very similar in terms of their reflectance properties in the visible spectrum.

C – Water Content part (1,3 – 3 µm)

- The reflectance is formed by water absorption bands with centres at 1.4 wavelengths; 1.9 and 2.7 µm.
- Local reflectance peaks occur at 1.6 and 2.2 µm wavelengths.
- In this part of the spectrum, the reflectance is approximately inversely proportional to the water content of the sheet.
- Changes in water content - for example, water stress in plants will manifest itself most at these wavelengths.

Spectral properties of vegetation and soil substrate

- Spectral reflectance of vegetation is formed by soil composition, nutrient content, presence of some minerals.

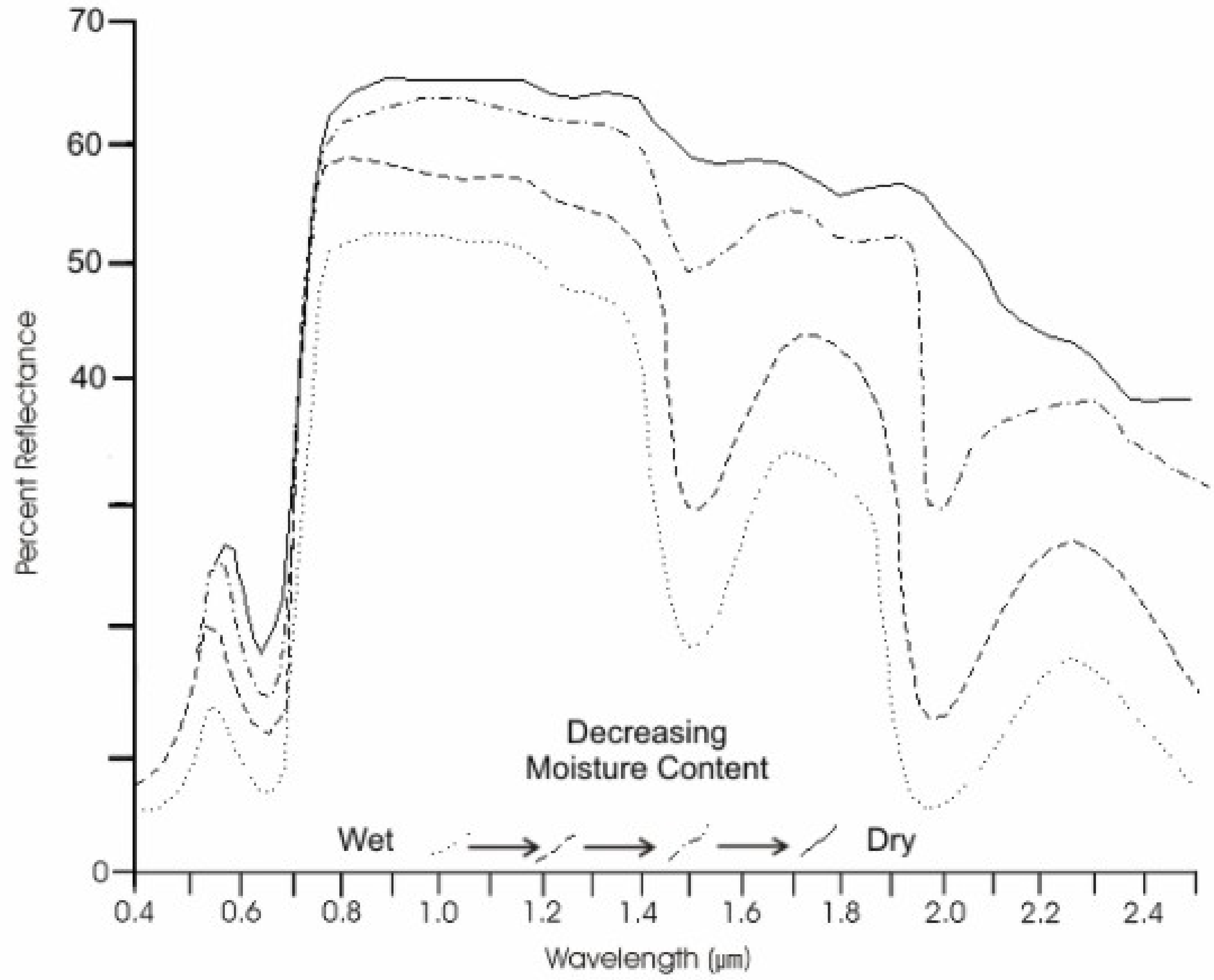
- Fe or Mg deficiency results in a reduced chlorophyll content and thus leads to a change in spectral properties (leaf yellowing).

- Spectral response of plants can be partially used to detect the presence of some minerals.

Spectral properties of water

In terms of reflectance properties, the following are particularly important for water:

- Compared to other minerals or surfaces, the substance is relatively homogeneous.
- It may appear in images in different states whose reflectance properties differ.
- In the IR part of the EM spectrum, the water behaves almost like an absolutely black body - intensely absorbing radiation and appearing the darkest in the images.
- Its reflection properties are different from other conventional surfaces.
- It modifies the spectral properties of all substances in which it is present, for example vegetation or soil.



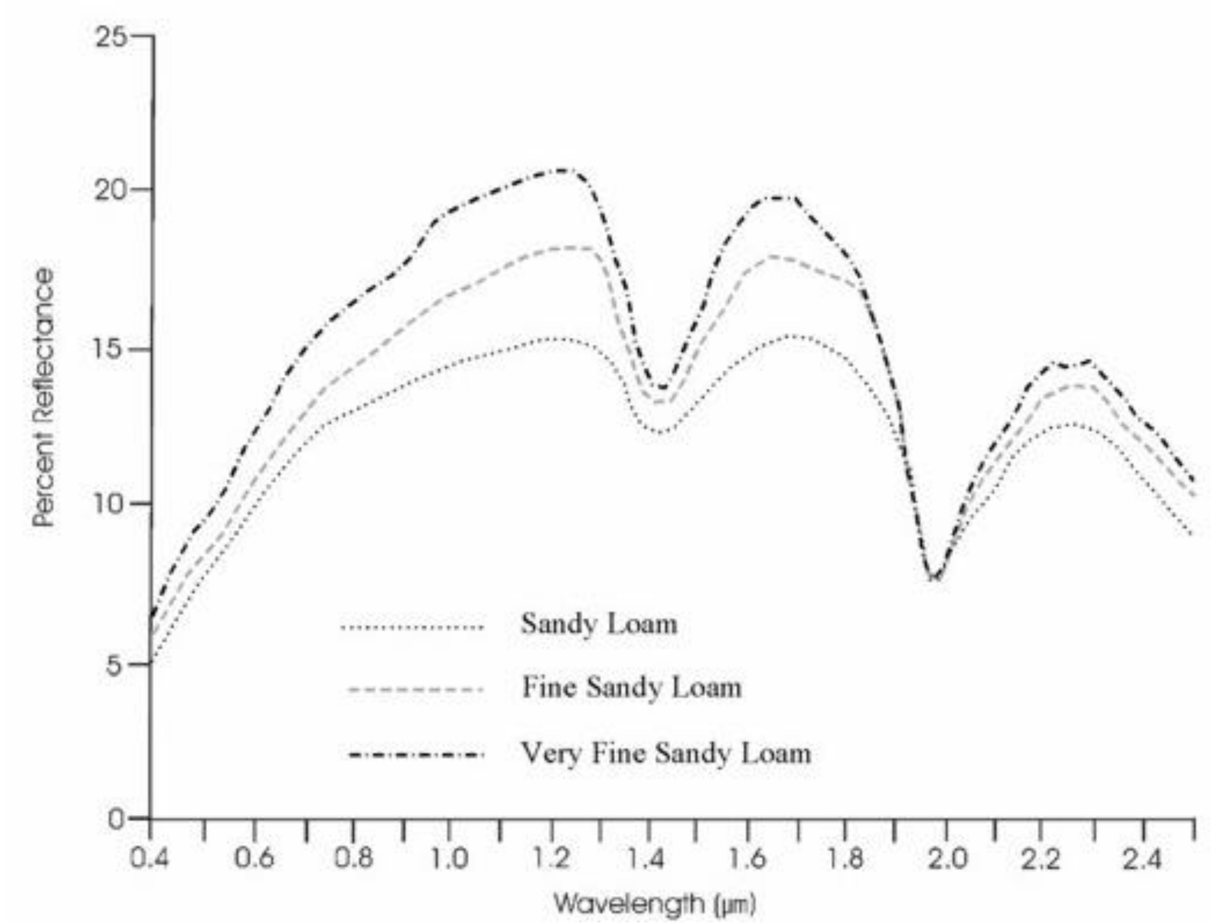
Water cause decreasing of the spectral response.

Spectral properties of soil

In particular, the following factors shape the soil's spectral properties:

- Mineral composition
- Soil moisture
- Organic matter content
- Texture (roughness) of soil substrate

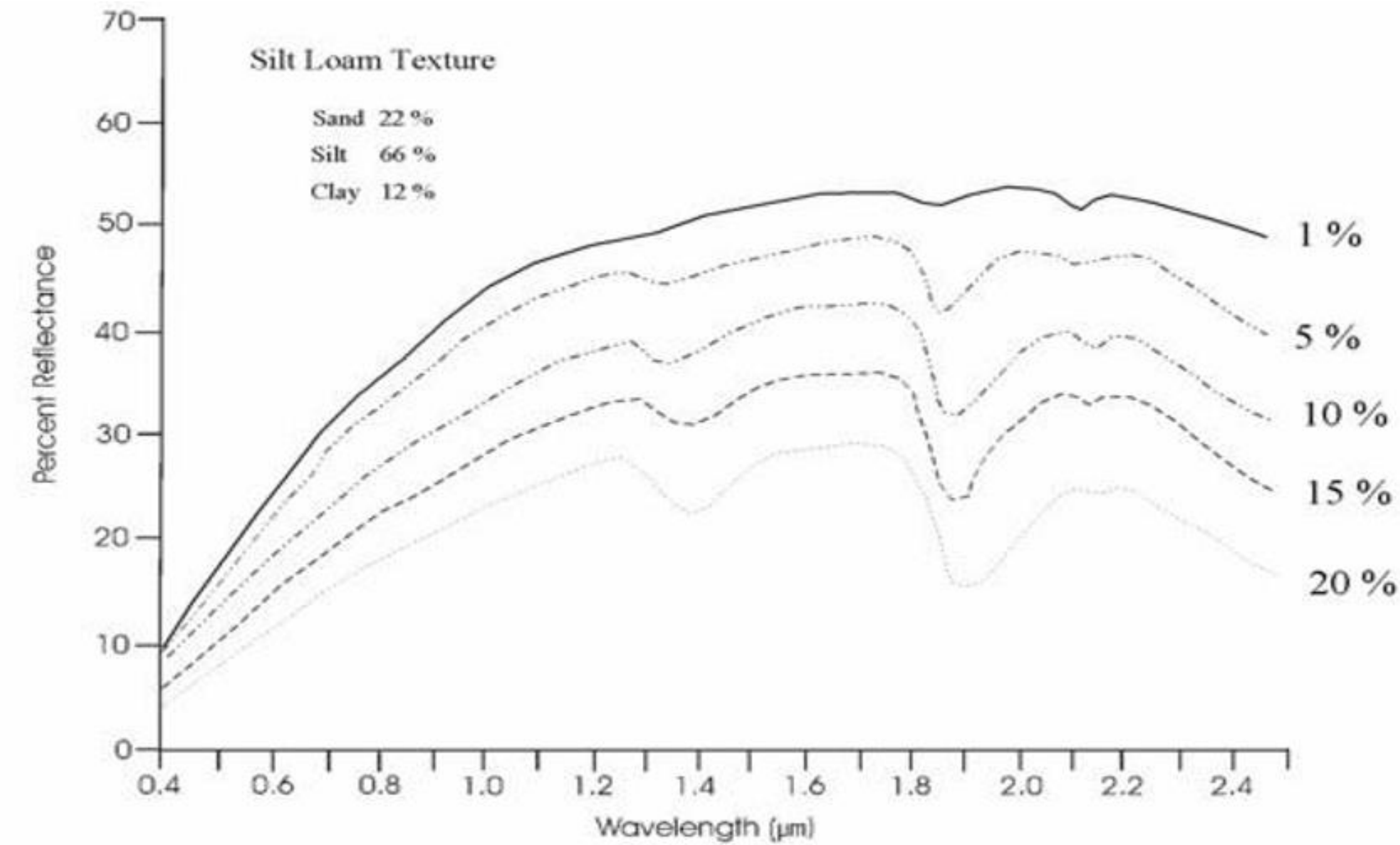
The soil is highly heterogeneous in terms of spectral properties.



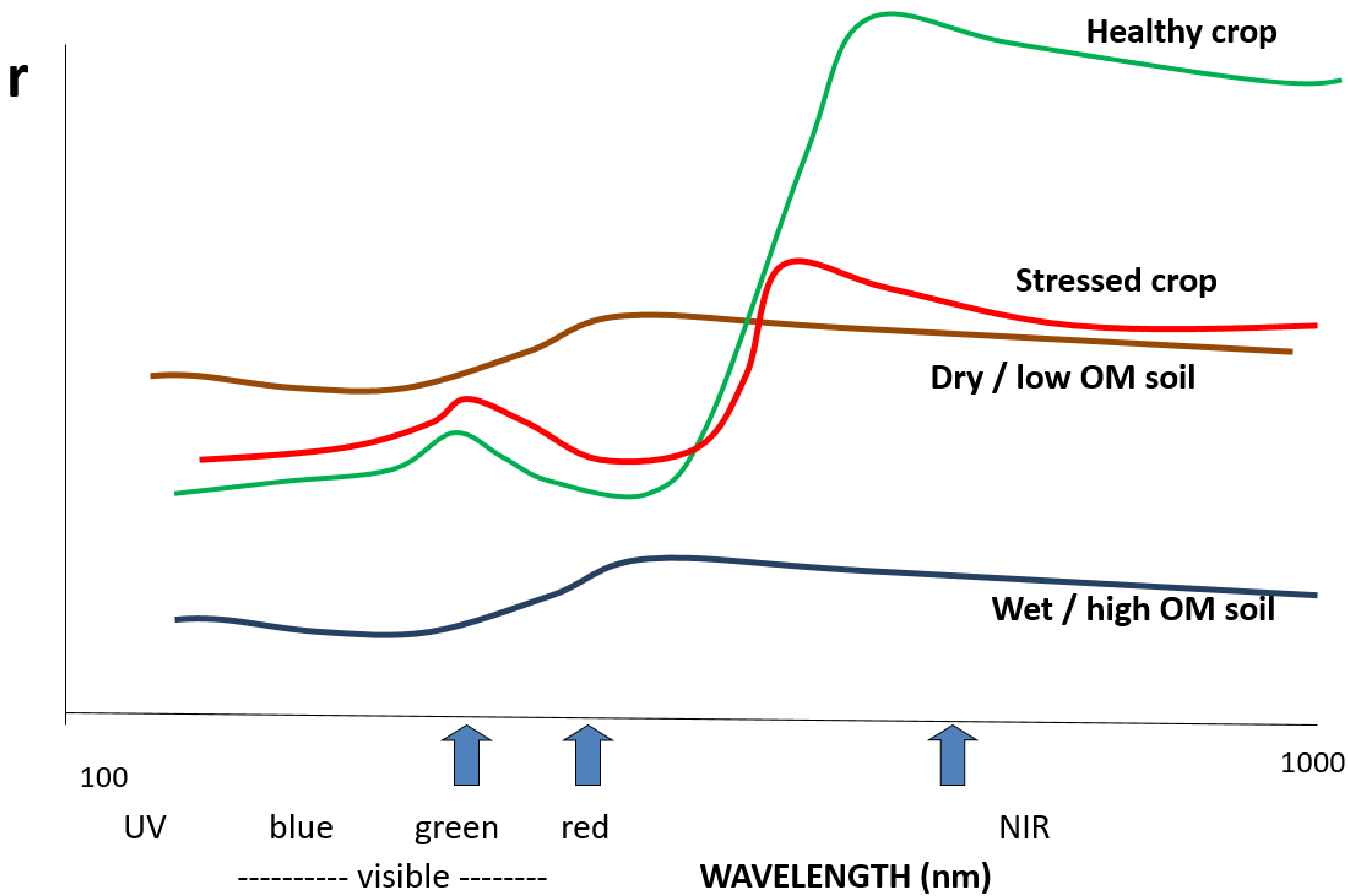
The soil is highly heterogeneous in terms of spectral properties.

Spectral properties of soil

- Higher soil moisture causes reduced reflectance.
- Soil moisture content often strongly correlates with soil texture.
- Coarse sandy soil with low soil moisture content has higher reflectance.
- Poorly drained soils with a fine-grained structure will generally have lower reflectance.
- The mineral composition manifests itself in the characteristic color of the soil.
- In the field of microwaves, the amount of reflected or emitted longwave radiation is mainly influenced by moisture and surface roughness.



Variation in the spectral reflectance characteristics of soil according moisture content.


r
Healthy crop
Stressed crop
Dry / low OM soil
Wet / high OM soil
100
1000
UV
blue
green
red
NIR
---------- visible --------
WAVELENGTH (nm)

3.4.2015 after rain

28.3.2015

The vegetation status can be monitored using

Color Synthesis

or

Vegetation Indices

Vegetation indices are indicative of, for example, the presence of green matter, the health status and structure of vegetation, the amount of water contained in plants, the amount of chlorophyll, nitrogen, etc.

Leaf Area Index

- Leaf Area Index = **LAI** - Indicates the density (volume) of the vegetation cover (measured by handheld sensor or remote sensing technologies).

- A dimensionless number that indicates how many times the area of all the leaves is larger than the unit area of the column in which the leaves are located.

- Near-infrared reflectivity is used.

- Multiple layers of the sheet cause repeated reflection of the radiation in the infrared part of the spectrum, the reflectance is then maximal at 6-8 layers of leaves.

Color synthesis of spectral bands

The applicability of individual spectral bands is closely related to the purpose of their use.

Spectral band	**Use**
Blue	Differentiation of vegetation from bare soil
Green	Characteristics of green vegetation, local maximum reflectance
Red	Differentiation of areas with vegetation from bare soil, absorption zone
Vegetation Red Edge	Increase of reflectance in vegetation, health condition of vegetation
NIR	Crop identification, health status and biomass content, soil moisture
SWIR1	Water content in plants, water stress
SWIR2	Water content in plants, water stress

Color synthesis and their use

- Color syntheses, or combinations of spectral bands, allow a view of the image in other spectral bands than the human eye allows.
- Many syntheses can "pull" information from the image that is not visible in true colors.
- The following list of color syntheses does not contain all possible combinations, only their selection.

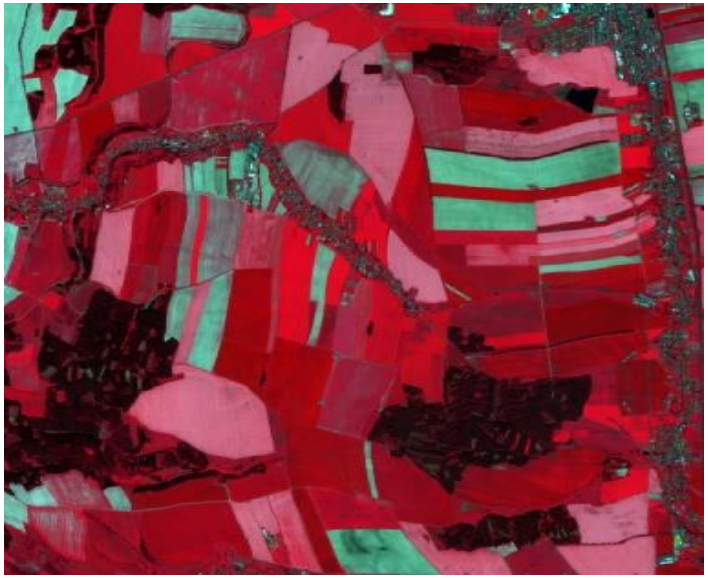
Red-Green-Blue

It is a synthesis in true colors as the human eye sees the world. Vegetation appears here as a green, bare soil in shades of brown. The combination of these bands sometimes makes it difficult to distinguish objects. It is especially suitable for a quick view of the status, including the size of the object.

True Color Synthesis (RGB). The image is taken from the Sentinel-2 satellite on 23 May 2016.

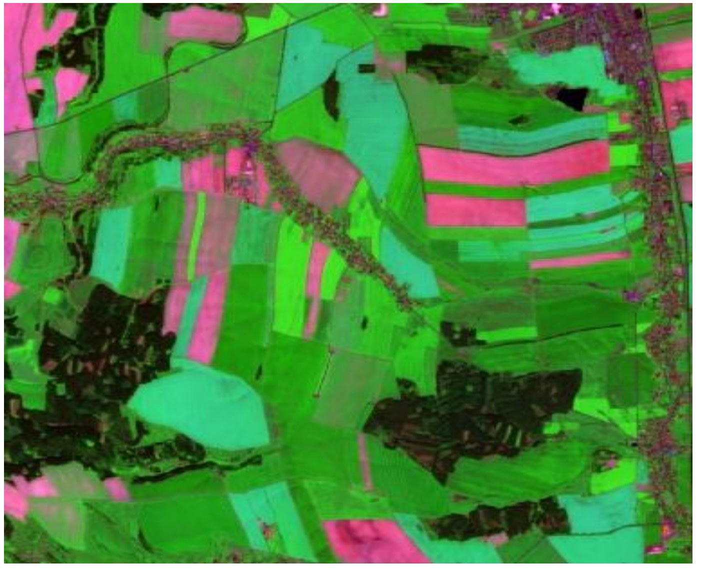
NIR-Red-Green

It is a classic synthesis in false colors. Vegetation appears in shades of red. Bare soil in shades of brown-green. It is particularly suitable for the determination of vegetation status, whether for health or for the determination of phenological phases, including the size of crops grown.



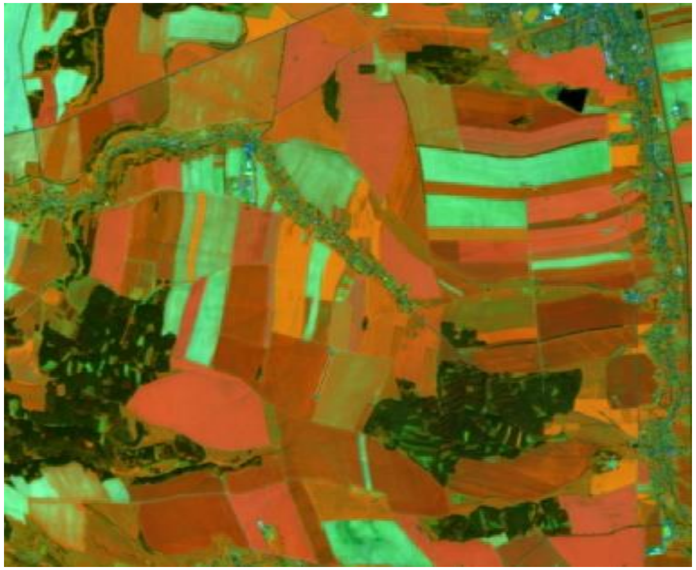
SWIR2-NIR-Green

It is a visualization that is not very influenced by the admixture of the atmosphere. The picture here appears to be "pure". Vegetation is displayed in shades of green. Bare soil in shades of pink. It is suitable for distinguishing individual areas with vegetation. Built-up areas and bare soil can coincide.



NIR-SWIR1-Blue

It is a visualization that is suitable for wide use in agriculture (differentiation of different types of vegetation, determination of phenological phases or health condition of the stand). Vegetation appears in shades of red, orange, brown and yellow. Bare soil is in shades of green.



NIR-SWIR1-Red

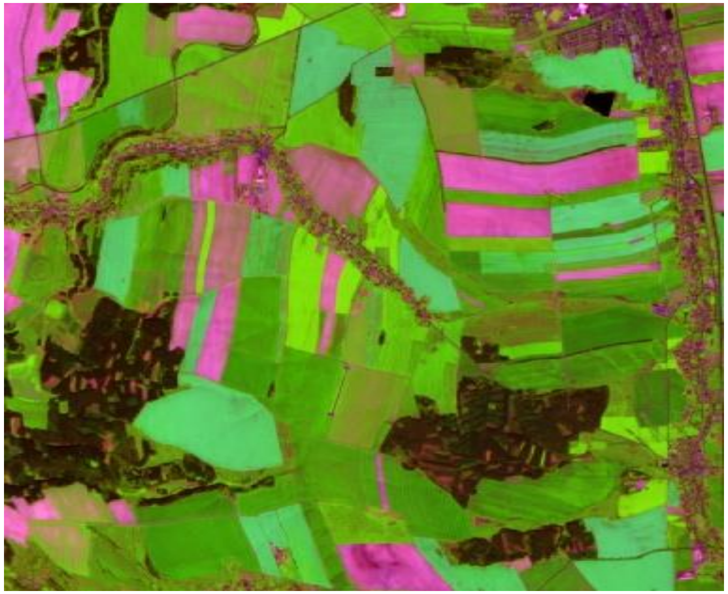
It is a visualization where a wide range of spectrum is used, so it has a large amount of information. Vegetation appears in shades of brown, green and orange). The darker the tint, the wetter the surface of the object.

SWIR2-SWIR1-Red

It is a visualization that is "cleaned" from the effects of the atmosphere. The vegetation appears in shades of green, the soil in a wide variety of colors. The combination is used to estimate the phenological phase of the stand and its uniformity.

SWIR1-NIR-Red

It is a visualization that is very similar in its use to the combination of NIR-SWIR1-Blue and SWIR1-NIR-Blue, ie. it is widely used in agriculture (crop differentiation, crop involvement (uniformity), phenological phase, soil moisture, etc.).



Purpose of monitoring	Red-Green-Blue	NIR-Red-Green	SWIR2-NIR-Green	NIR SWIR1-Blue	NIR SWIR1-Red	SWIR2-SWIR1-Red	SWIR1-NIR-Red
Types of vegetation	3	2	2	1	1	2	1
Health condition of vegetation	3	1	2	2	2	3	1
Border of fields	3	1	2	1	1	2	2
Soil condition	1	1	2	2	2	2	2
Water content	3	3	2	2	2	2	2

Suitability of selected color syntheses in the RGB system for agricultural monitoring purposes: 1 = most appropriate; 2 = moderate; 3 = inappropriate.

Vegetation indices

They can be divided

- according to the number and range of bands entering the process
- their purpose of use – according to www.harrisgeospatial.com

In this way, the indices are merged into seven basic categories:

Broadband Greeness
Narrowband Greeness
Light Use Efficiency
Canopy Nitrogen
Dry or Senescent Carbon
Leaf Pigments
Canopy Water Content

Broadband Greeness

- The broadband greenness VIs are among the simplest measures of the general quantity and vigor of green vegetation.

- They are combinations of reflectance measurements that are sensitive to the combined effects of foliage chlorophyll concentration, canopy leaf area, foliage clumping, and canopy architecture.

- These VIs are designed to provide a measure of the overall amount and quality of photosynthetic material in vegetation, which is essential for understanding the state of vegetation for any purpose.

- Many of the broadband greenness indices can work effectively, even with image data collected from broadband multispectral sensors.

- Applications include vegetation phenology (growth) studies, land-use and climatological impact assessments, and vegetation productivity modeling.

Overview of indices:

- Difference Vegetation Index (DVI)
- Enhanced Vegetation Index (EVI)
- Global Environmental Monitoring Index (GEMI)
- Green Atmospherically Resistant Index (GARI)
- Green Chlorophyll Index (GCI)
- Green Difference Vegetation Index (GDVI)
- Green Leaf Index (GLI)
- Green Normalized Difference Vegetation Index (GNDVI)
- Green Optimized Soil Adjusted Vegetation Index (GOSAVI)
- Green Ratio Vegetation Index (GRVI)
- Green Soil Adjusted Vegetation Index (GSAVI)
- Green Vegetation Index (GVI)
- Infrared Percentage Vegetation Index (IPVI)
- Leaf Area Index (LAI)

- Modified Non-Linear Index (MNLI)
- Modified Simple Ratio (MSR)
- Modified Soil Adjusted Vegetation Index 2 (MSAVI2)
- Non-Linear Index (NLI)
- Normalized Difference Vegetation Index (NDVI)
- Optimized Soil Adjusted Vegetation Index (OSAVI)
- Renormalized Difference Vegetation Index (RDVI)
- Soil Adjusted Vegetation Index (SAVI)
- Simple Ratio (SR)
- Sum Green Index (SGI)
- Transformed Difference Vegetation Index (TDVI)
- Triangular Greenness Index (TGI)
- Visible Atmospherically Resistant Index (VARI)
- Wide Dynamic Range Vegetation Index (WDRVI)
- WorldView Improved Vegetation Index (WV-VI)

Narrowband Greeness

- Narrowband greenness VIs are combinations of reflectance measurements sensitive to the combined effects of foliage chlorophyll concentration, canopy leaf area, foliage clumping, and canopy architecture.
- Similar to the broadband greenness VIs, narrowband greenness VIs are designed to provide a measure of the overall amount and quality of photosynthetic material in vegetation, which is essential for understanding the state of vegetation.
- Narrowband greenness VIs are intended for use with imaging spectrometers.
- One area where narrowband greenness VIs are useful is precision agriculture. This is an information- and technology-based agricultural management system to identify, analyze, and manage site-soil spatial and temporal variability.

Overview of indices:

- Atmospherically Resistant Vegetation Index (ARVI)
- Modified Chlorophyll Absorption Ratio Index (MCARI)
- Modified Chlorophyll Absorption Ratio Index - Improved (MCARI2)
- Modified Red Edge Normalized Difference Vegetation Index (MRENDVI)
- Modified Red Edge Simple Ratio (MRESR)
- Modified Triangular Vegetation Index (MTVI)
- Modified Triangular Vegetation Index - Improved (MTVI2)
- Red Edge Normalized Difference Vegetation Index (RENDVI)
- Red Edge Position Index (REPI)
- Transformed Chlorophyll Absorption Reflectance Index (TCARI)
- Triangular Vegetation Index (TVI)
- Vogelmann Red Edge Index 1 (VREI1)
- Vogelmann Red Edge Index 2 (VREI2)

Light Use Efficiency

- The light use efficiency VIs provide a measure of the efficiency with which vegetation can use incident light for photosynthesis. Light use efficiency is highly related to carbon uptake efficiency and vegetative growth rates, and is somewhat related to fractional absorption of photosynthetically active radiation (fAPAR).
- These VIs help to estimate growth rate and production, which is useful in precision agriculture. These VIs use reflectance measurements in the visible spectrum to take advantage of relationships between different pigment types to assess the overall light use efficiency of the vegetation.

- Photochemical Reflectance Index
- Structure Insensitive Pigment Index
- Red Green Ratio Index

Canopy Nitrogen

- Canopy Nitrogen VIs provide a measure of nitrogen concentration of remotely sensed foliage.
- Nitrogen is an important component of chlorophyll and is generally present in high concentration in vegetation that is growing quickly.
- This VI uses reflectance measurements in the shortwave infrared range to measure relative amounts of nitrogen contained in vegetation canopies.

- Normalized Difference Nitrogen Index

Dry or Senescent Carbon

- The dry or senescent carbon VIs provide an estimate of the amount of carbon in dry states of lignin and cellulose.
- Lignin is a carbon-based molecule used by plants for structural components; cellulose is primarily used in the construction of cell walls in plant tissues. Dry carbon molecules are present in large amounts in woody materials and senescent, dead, or dormant vegetation. These materials are highly flammable when dry. Increases in these materials can indicate when vegetation is undergoing senescence.
- It is possible to use these VIs for fire fuel analysis and detection of surface litter.
- These indices provide suspect results in wet environments, or when the dry materials are obscured by a green canopy.

Overview:

- Cellulose Absorption Index
- Lignin Cellulose Absorption Index
- Normalized Difference Lignin Index
- Plant Senescence Reflectance Index

Leaf Pigments

- The leaf pigment VIs provide a measure of stress-related pigments, which are present in higher concentrations in weakened vegetation.

- These VIs do not measure chlorophyll, which is measured using the greenness indices.

- Anthocyanin Reflectance Index 1 (ARI1)
- Anthocyanin Reflectance Index 2 (ARI2)
- Carotenoid Reflectance Index 1 (CRI1)
- Carotenoid Reflectance Index 2 (CRI2)

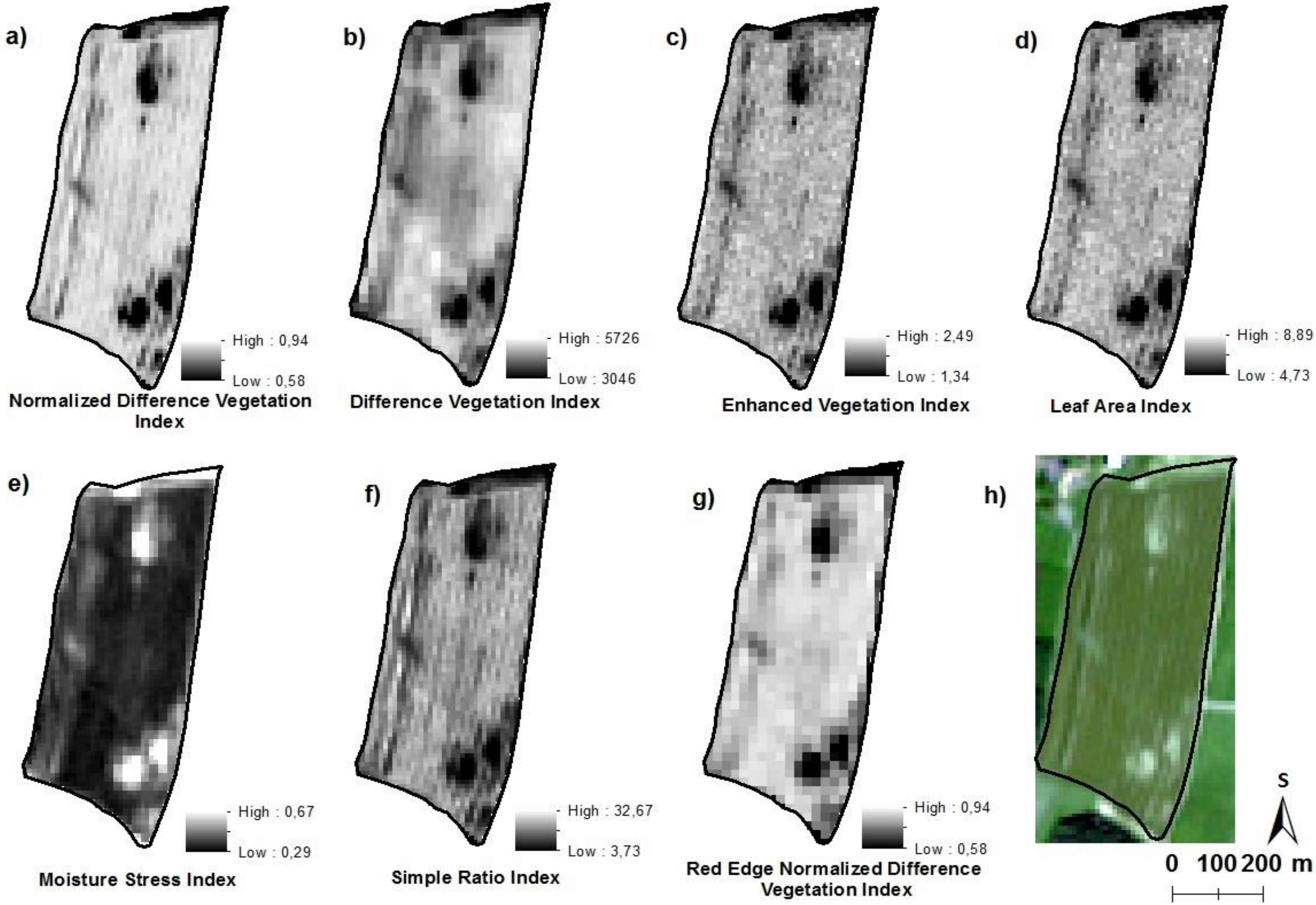
Canopy Water Content

- The canopy water content VIs provide a measure of the amount of water contained in the foliage canopy.
- Water content is an important quantity of vegetation because higher water content indicates healthier vegetation that is likely to grow faster and be more fire-resistant.
- Canopy water content VIs use reflectance measurements in the near-infrared and shortwave infrared regions to take advantage of known absorption features of water and the penetration depth of light in the near-infrared region to make integrated measurements of total column water content.

- Moisture Stress Index
- Normalized Difference Infrared Index
- Normalized Difference Water Index
- Normalized Multi-band Drought Index
- Water Band Index

Interpretation – an example

- In the figure - see below, there is an example of the use of spectral indices to assess the canopy of winter wheat. The Sentinel 2 image is taken on May 28, 2017, which corresponds to the growth stage of BBCH 34 on the selected stand. Spectral indices were chosen to illustratively show how the canopy can be interpreted in this growth phase.
- Experimental field has a total area of about 24 hectares. Its surface is slightly wavy with an average slope of 6%. The range of altitudes is between 543-571 m above sea level. The main soil is modal cambisol on the base of calcareous sandstones. Some parts of the land are heavily eroded, especially in the sloping parts of the area. The average rainfall here is 700 millimeters. The average temperature is between 6 and 7 ° C.



Selection of indices for winter wheat growth from May 28, 2017, ie BBCH 34 growth phase. Image is taken from Sentinel-2A satellite. Selected spectral indices a) to g); True Color Image h).

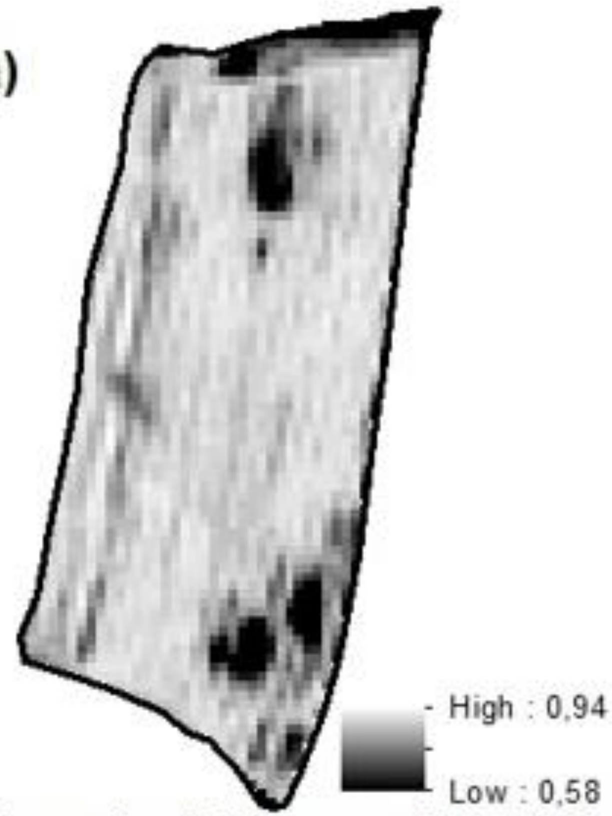
Normalized Difference Vegetation Index (NDVI)

- This index is a measure of healthy, green vegetation. The combination of its normalized difference formulation and use of the highest absorption and reflectance regions of chlorophyll make it robust over a wide range of conditions. It can, however, saturate in dense vegetation conditions when LAI becomes high. The value of this index ranges from -1 to 1. The common range for green vegetation is 0.2 to 0.8.
- The increasing value of NDVI points to higher density of the vegetation cover (higher LAI). Values approaching 1 indicate good growth in the later growth phase. NDVI values outside the range <0.2; 1> indicate that they are not vegetation and when defining vegetation it is necessary to remove "defective" pixels, eg a billboard standing on a field, road, pole etc.

Interpretation:

- Most of the winter wheat crop area is dense with higher LAI. The index value indicates that the growth is beneficial. Lower values at noticeably limited locations indicate shining ground due to problems on headlands (technogenic compaction) or long-term erosion processes on land. Low values of this index on the South-East part of the plot detect a stable waterlogged problem when surface runoff accumulates.

a)



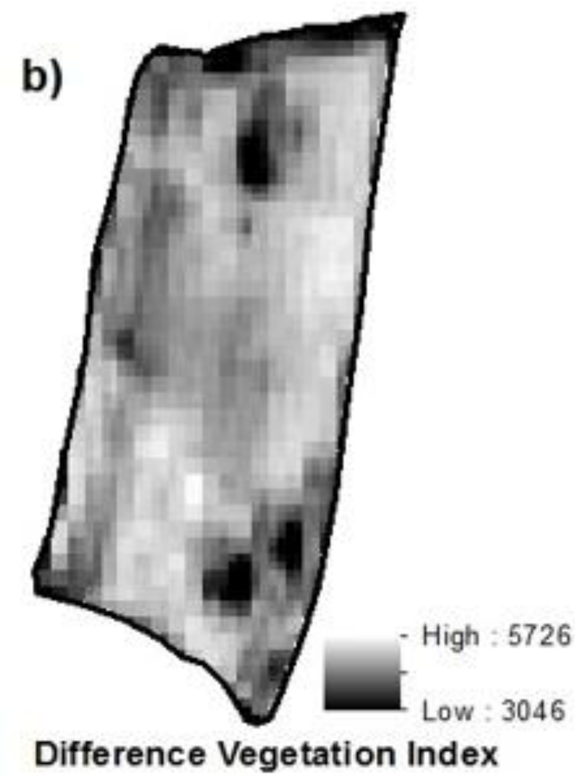
Normalized Difference Vegetation Index

Difference Vegetation Index (DVI)

- This index distinguishes between soil and vegetation, but it does not account for the difference between reflectance and radiance caused by atmospheric effects or shadows.

Interpretation:

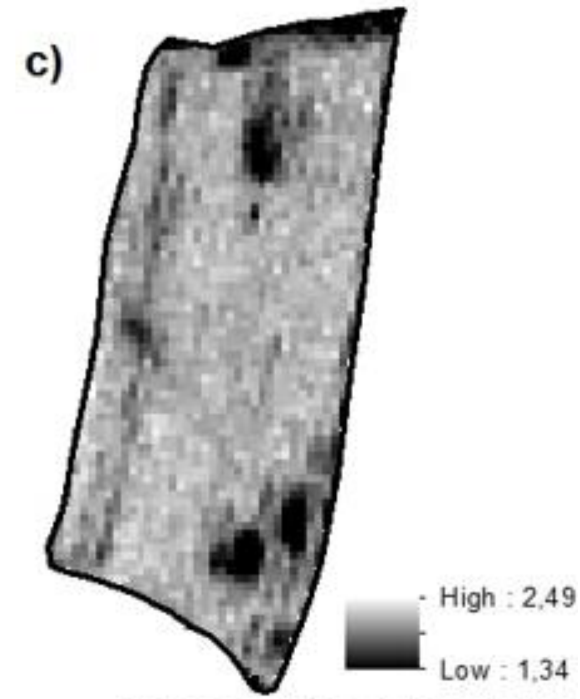
The crop stand status captured by this index copies the previous index (NDVI). There is a clearer distinction between places where soil is more visible from places where the vegetation is more dense (higher volume). Unlike NDVI, it is thus more suitable for the detection of leaves covering, ie for the earlier vegetation phase.



Enhanced Vegetation Index (EVI)

- This index was originally developed for use with MODIS data as an improvement over NDVI by optimizing the vegetation signal in areas of high leaf area index (LAI).
- It is most useful in high LAI regions where NDVI may saturate.
- It uses the blue reflectance region to correct for soil background signals and to reduce atmospheric influences, including aerosol scattering. EVI values should range from 0 to 1 for vegetation pixels.

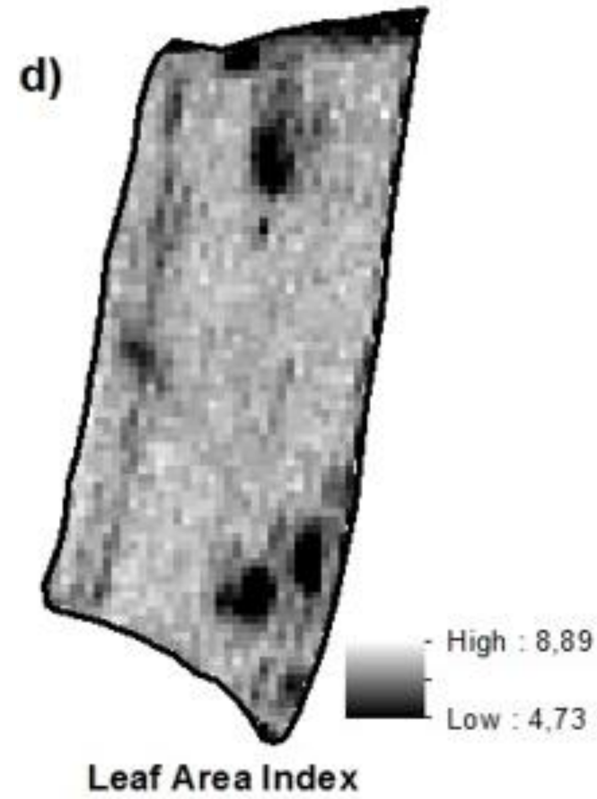
- The index better emphasizes the state already detected by NDVI.



Enhanced Vegetation Index

Leaf Area Index (LAI)

- This index is used to estimate foliage cover and to forecast crop growth and yield. High LAI values typically range from approximately 0 to 3.5. However, when the scene contains clouds and other bright features that produce saturated pixels, the LAI values can exceed 3.5.



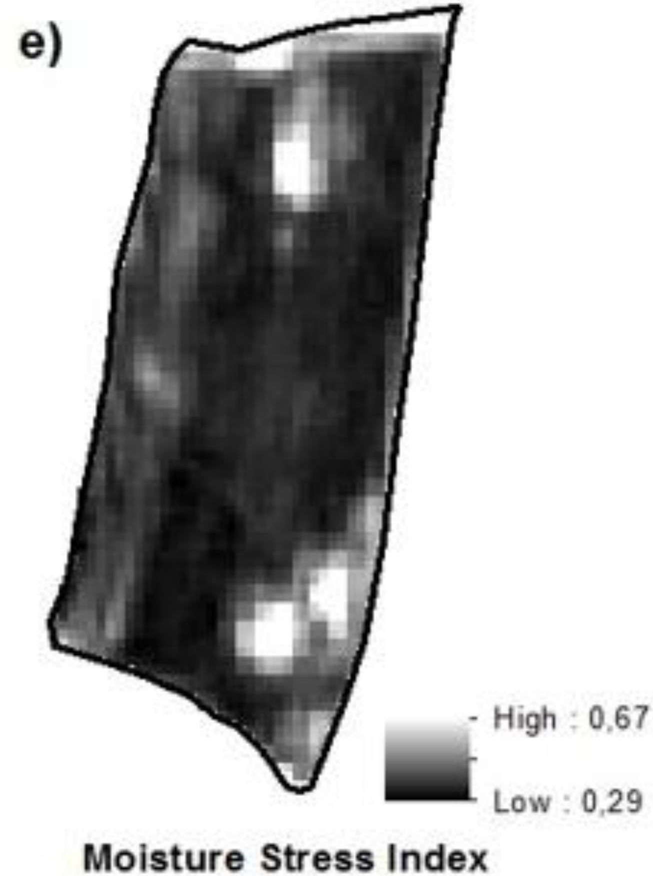
<u>Interpretation:</u>
Index The index almost copies the EVI index as it is computationally based on it. Again, it better emphasizes the condition found by NDVI.

Moisture Stress Index (MSI)

- This index is a reflectance measurement that is sensitive to increasing leaf water content.
- As the water content of leaves in vegetation canopies increases, the strength of the absorption around 1599 nm increases. Absorption at 819 nm is nearly unaffected by changing water content, so it is used as the reference.
- Applications include canopy stress analysis, productivity prediction and modeling, fire hazard condition analysis, and studies of ecosystem physiology.
- The MSI is inverted relative to the other water VIs; higher values indicate greater water stress and less water content. The value of this index ranges from 0 to more than 3. The common range for green vegetation is 0.4 to 2.

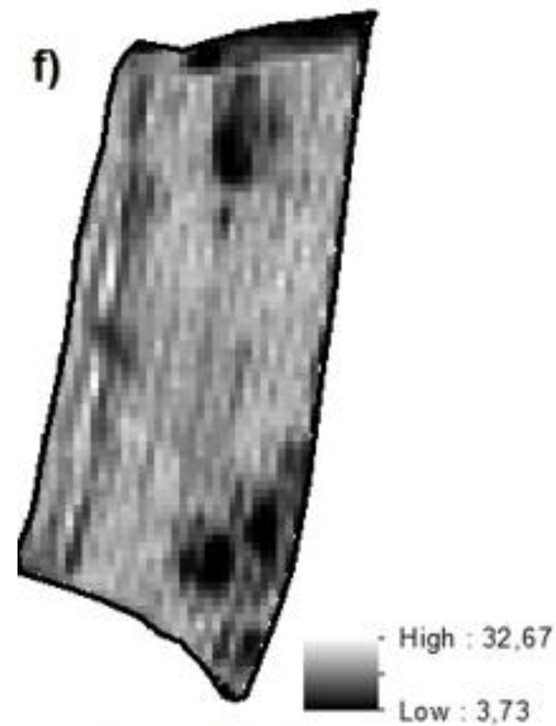
Interpretation:

Again, the index copies the crop stand state found by NDVI, but is inverse to it. Significant water stress is detected in areas with sparse vegetation, ie on headlands and at erosion-endangered sites. It is also suitable for detecting the effects of drought.



Simple Ratio Index (SR)

- This index is a ratio of (1) the wavelength with highest reflectance for vegetation and (2) the wavelength of the deepest chlorophyll absorption. The simple equation is easy to understand and is effective over a wide range of conditions. As with the NDVI, it can saturate in dense vegetation when LAI becomes very high.

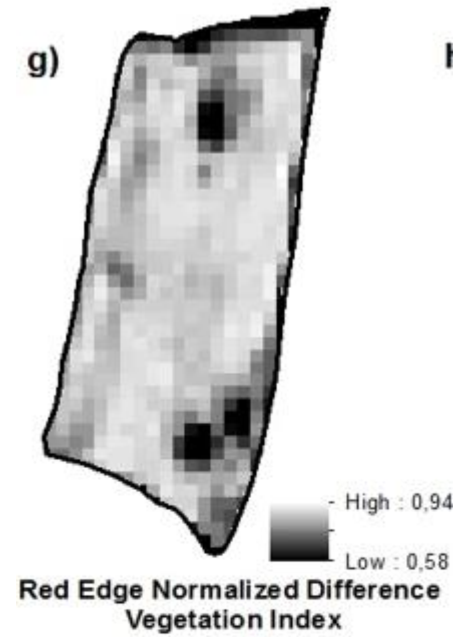


Simple Ratio Index

<u>Interpretation:</u>
This index again copies the crop stand state already found by NDVI, but unlike NDVI, it better illustrates how the canopy is dense.

Red Edge Normalized Difference Vegetation Index (RENDVI)

- This index is a modification of the traditional broadband NDVI.
- Applications include precision agriculture, forest monitoring, and vegetation stress detection.
- This VI differs from the NDVI by using bands along the red edge, instead of the main absorption and reflectance peaks. It capitalizes on the sensitivity of the vegetation red edge to small changes in canopy foliage content, gap fraction, and senescence.
- The value of this index ranges from -1 to 1. The common range for green vegetation is 0.2 to 0.9.



Interpretation:

This index better illustrates minor spatial changes in vegetation status.

Summary

- NDVI is one of the most used indices and can be used for the initial view of the crop stand status.

- Since other indices work with similar characteristics, their resulting state is very similar to NDVI. As a rule, they differ only in detail in the state of the crop stand.

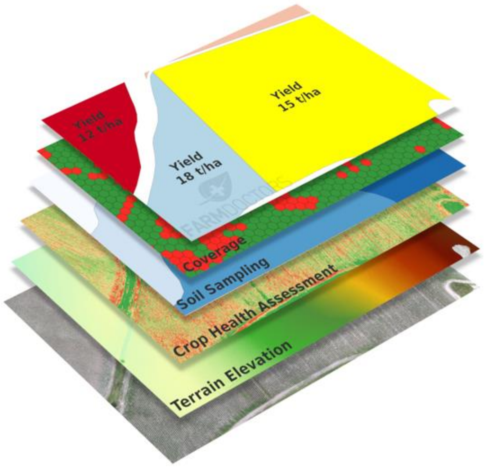
- Only a few indices, eg NDVI, have a clearly defined range of values for the detection of vegetation status.

- Most indices then work with values for which an experimental estimate is needed based on crop stand status and clearly defined indices.

- Some indices, such as MSI, are inverse to the NDVI index. This index has a very recent use in drought stress mapping. As a general rule, the value found for a particular stand does not necessarily correspond to that of another variety and other habitat.

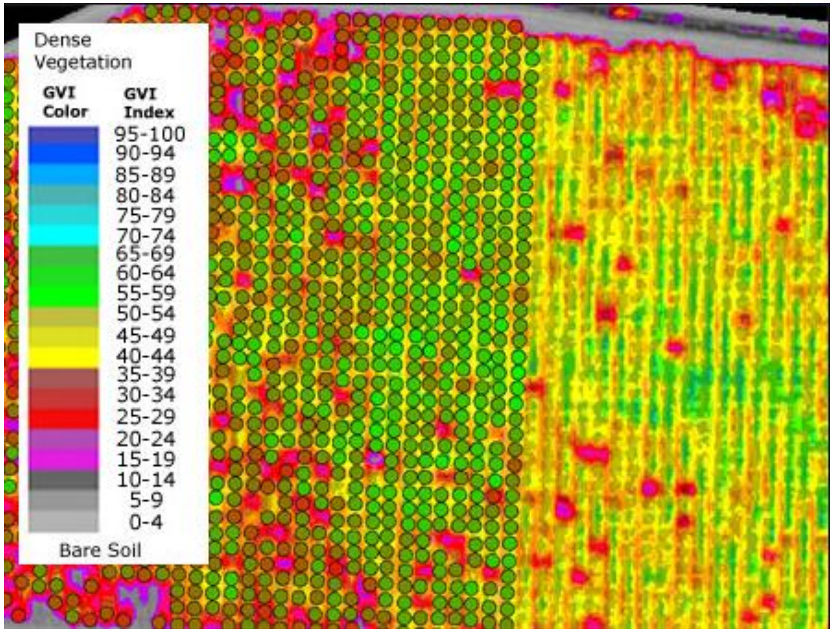
- For this reason, it is very important to work with the history of the development of the crop stands on specific plots.

- The maps of vegetation indices can be used as application maps.



- Among the most widely used spectral indices in plant production are NDVI, EVI, RENDVI (or NDRE) GNDVI, MSI (or NDWI) and LAI.

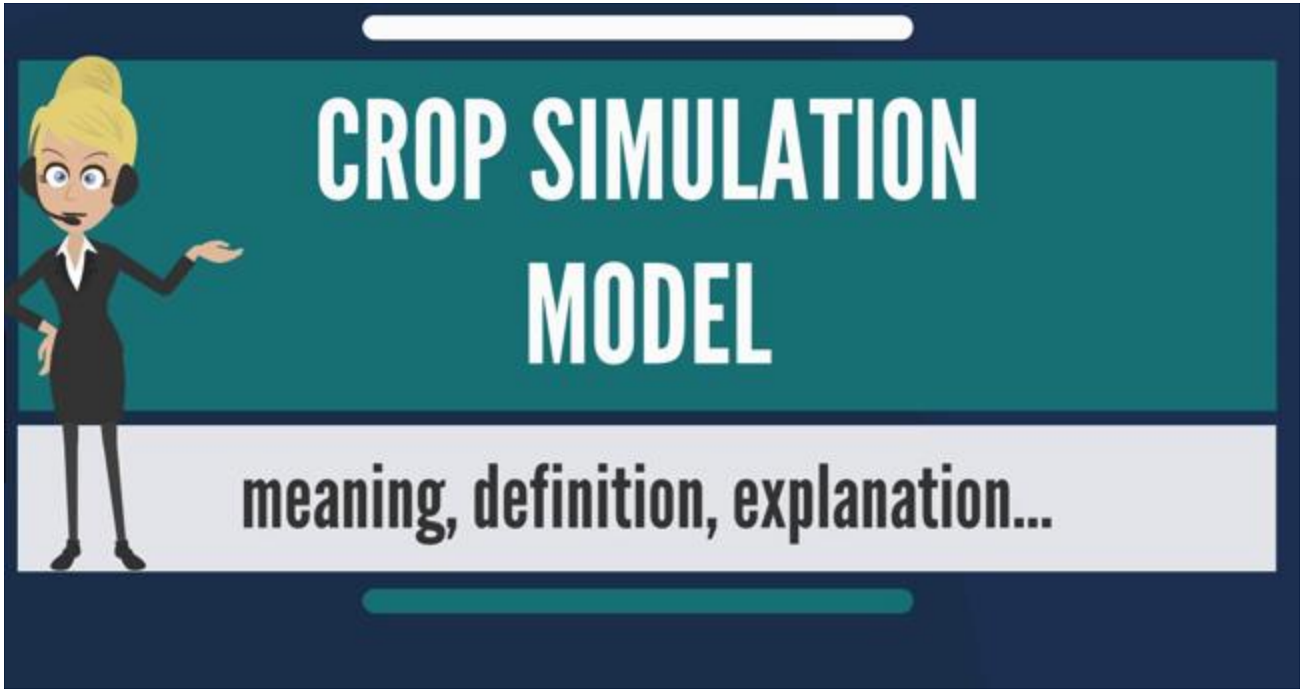
- Areas of use that correspond to the use of selected spectral indices include, in particular, the assessment of the health status and structure of the crop stand, the chlorophyll content, the detection of water stress, the estimate of the leaf area to predict crop growth and yield.



- In the case of assessing water stress, increasing values of the MSI spectral index mean increasing water stress of plants.

- It is also always necessary to realize which agricultural crops we evaluate. E.g. The Brassicaceae family (eg oilseed rape) will have a different spectral curve for the development of spectral index values than the Poaceae family depending on other characteristics corresponding to those of these families.

CROP MODELS

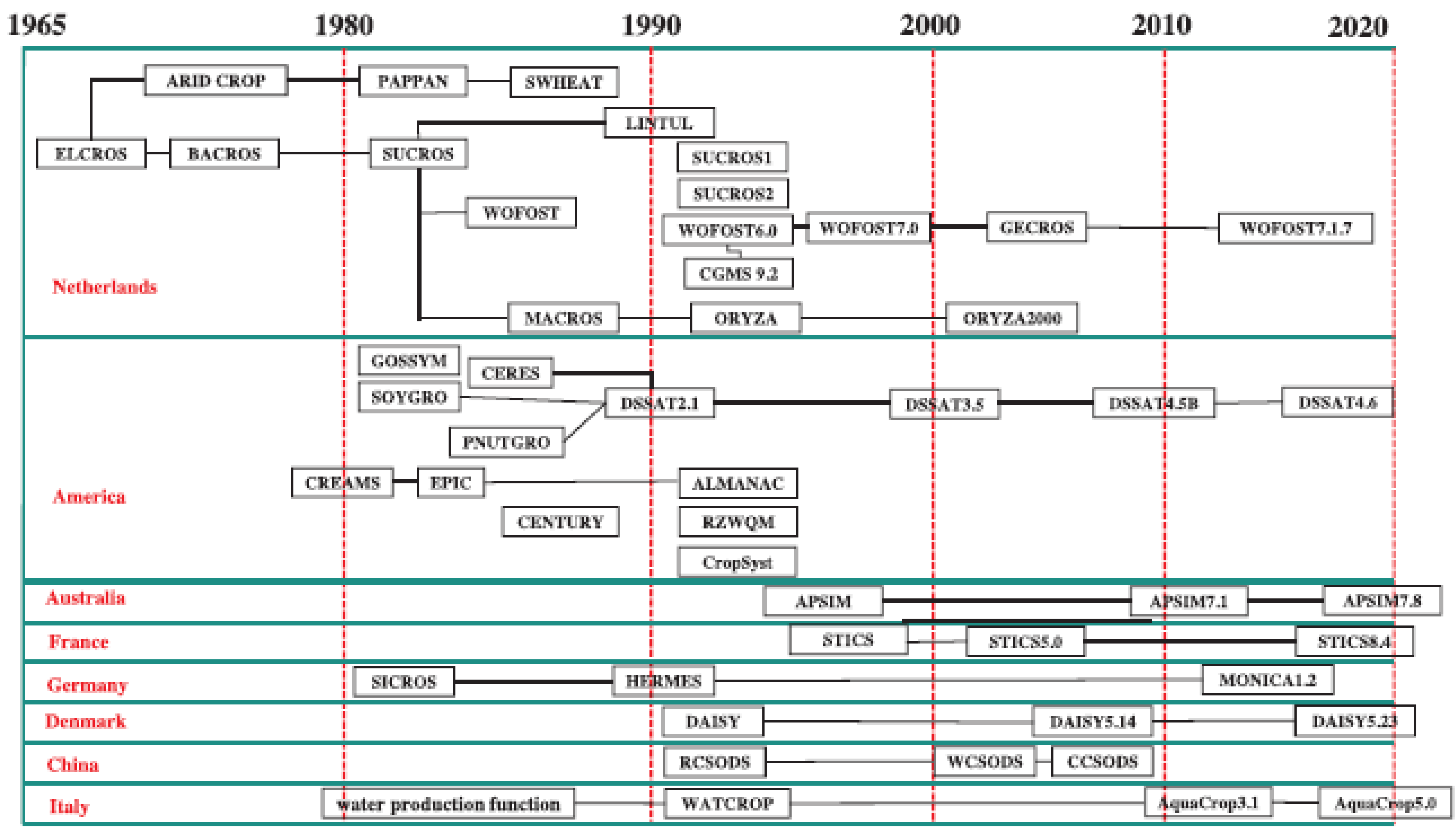


CROP MODELS

- After nearly 40 years of development, crop models have advanced from the initial qualitative simulation of crop growth to quantitative simulation of crop growth and from simulation of single physiological and ecological growth processes to simulation of the whole growth process. Through the combination of crop models and a multidisciplinary approach, considerable progress has been attained.

- Further development of crop models will provide better opportunities to analyze the response of crops to changes in the field management practices and environmental conditions worldwide.

X. Jin et al. 2018

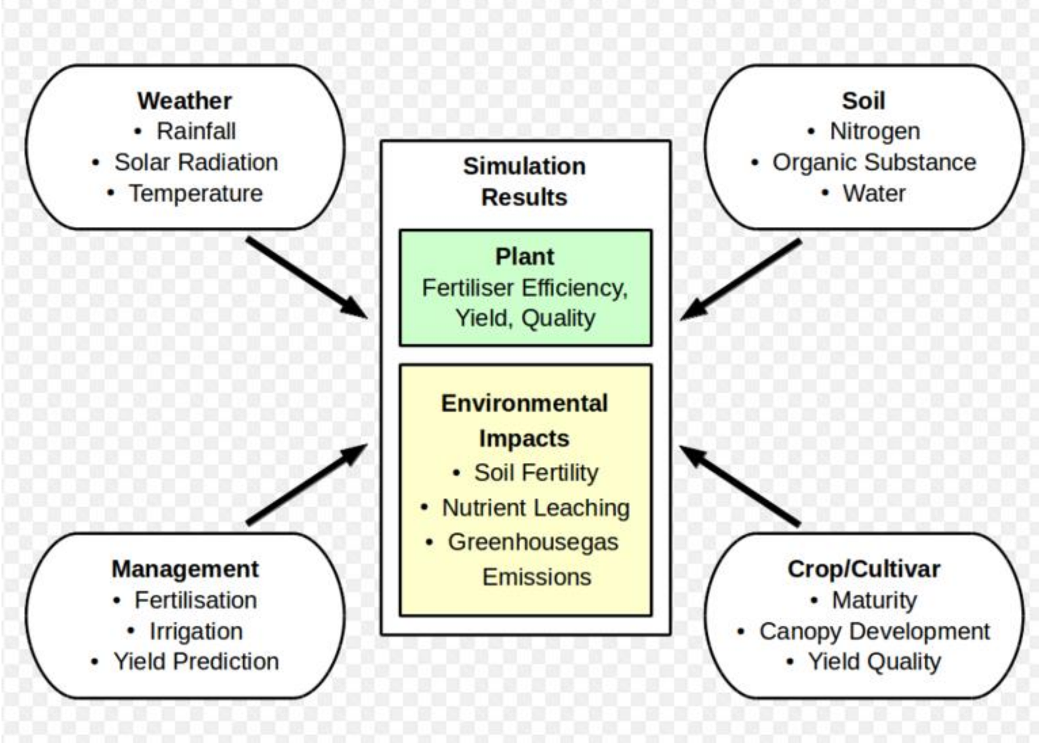


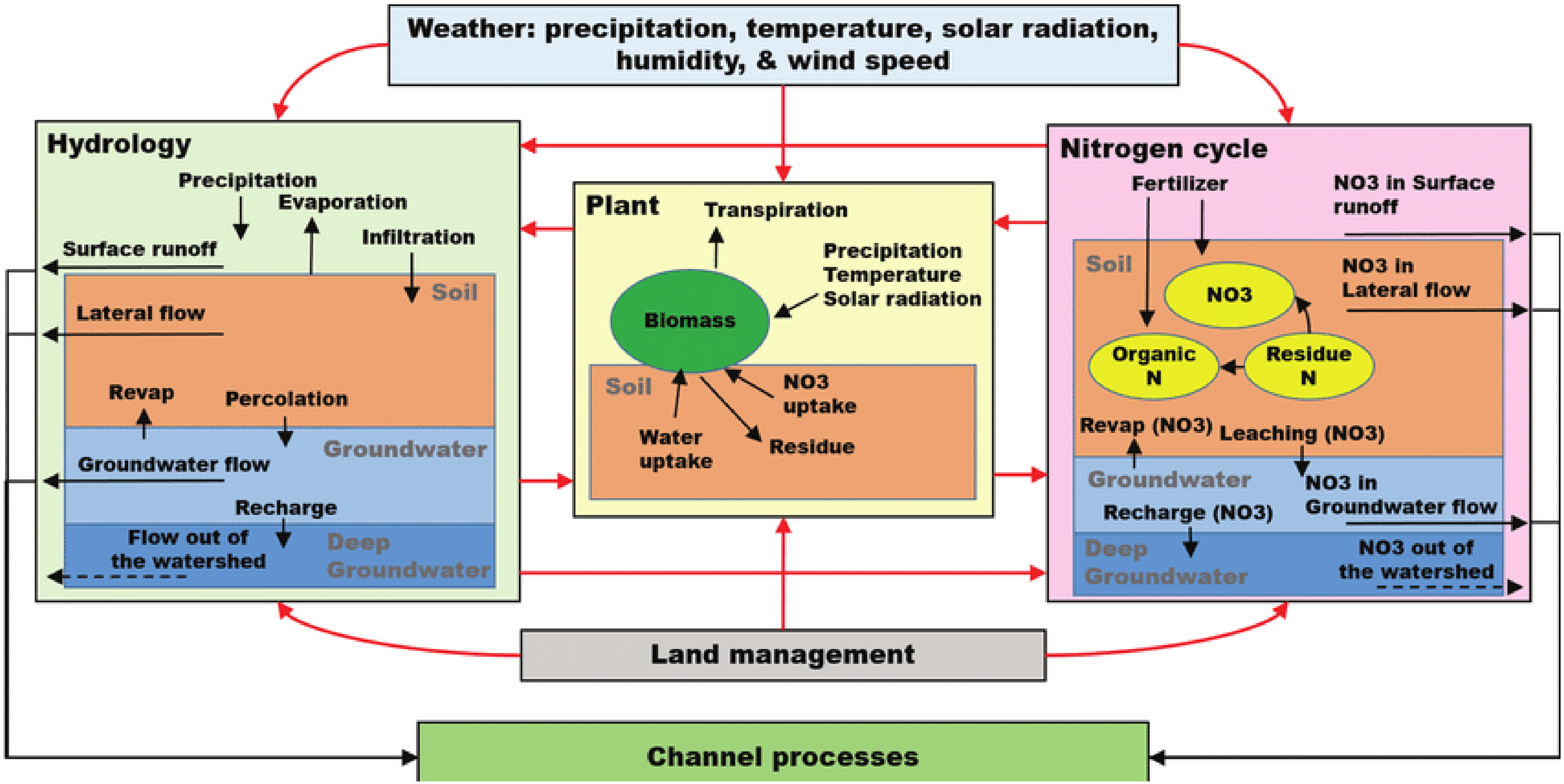
A timeline on the development of the main **crop models**.

Crop models have been refined and updated to better simulate crop growth status and crop yield.

Disadvantages

- Crop models need to account for spatial variation when crop yields are estimated over large regions.
- However, the spatial distribution of soil properties (soil moisture), canopy state variables (LAI, biomass, nitrogen content, etc.), and meteorological data are often uncertain.
- These uncertainties mainly affect crop model physiological growth simulation processes, leading to larger errors in crop yield estimation when crop models are used.

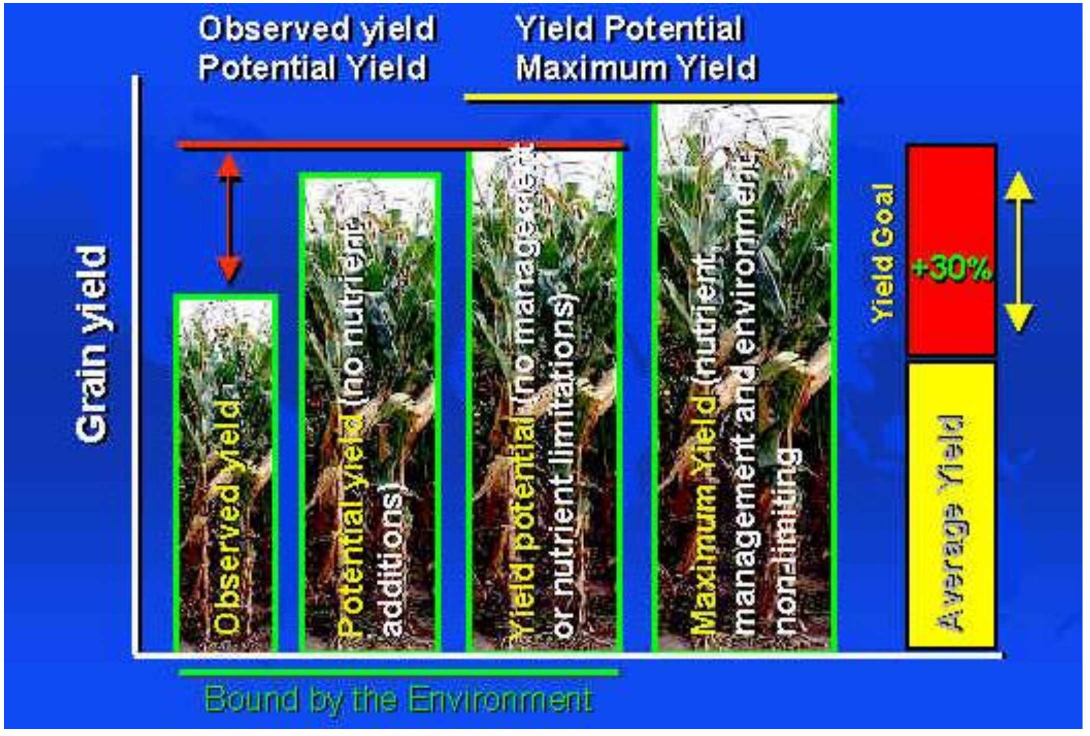




Weather: precipitation, temperature, solar radiation, humidity, & wind speed
Hydrology
Precipitation
Evaporation
Infiltration
Surface runoff
Soil
Lateral flow
Revap
Percolation
Groundwater
Groundwater flow
Recharge
Flow out of the watershed
Deep Groundwater
Plant
Transpiration
Precipitation
Temperature
Solar radiation
Biomass
Soil
NO3 uptake
Water uptake
Residue
Nitrogen cycle
Fertilizer
NO3 in Surface runoff
Soil
NO3
NO3 in Lateral flow
Organic N
Residue N
Revap (NO3)
Leaching (NO3)
Groundwater
NO3 in Groundwater flow
Recharge (NO3)
Deep Groundwater
NO3 out of the watershed
Land management
Channel processes

- The rapid development of remote sensing technology offers more potential for accurate and reliable quantitative estimates of soil properties and canopy state variables at regional scales.
- Remote sensing is very important tool for estimation of crop canopy state variables or soil properties over large areas, such as the fraction of absorbed photosynthetically active radiation (FAPAR) LAI, canopy cover, biomass, leaf nitrogen accumulation, evapotranspiration and soil properties.
- These canopy state variables and soil property variables need to be integrated with crop models since they are important parameters at crop canopy growth stages.
- Crop models have been used in the past to simulate these canopy state variables. Canopy cover and LAI were used to drive crop biomass accumulation in different crop models while remote sensing methods were used to estimate these canopy state variables and soil properties for input into crop models and drive crop phenology information.

- The use of satellite images or a combination of satellite images and, for example, yield data can be a simpler variant (or substitute) of very complicated crop models.
- Based on various input parameters, the yield potential or yield frequency map can be derived.



Yield potential (Yp) is defined as the yield of an adapted crop cultivar as determined by solar radiation, temperature, carbon dioxide, and genetic traits that govern length of growing period, light interception by the crop canopy and its conversion to biomass, and partition of biomass to the harvestable organs.

Water-limited yield potential (Yw) is determined by these previous factors and also by water supply amount and distribution during the crop growth period and field and soil properties that affect soil water availability such as slope, plant-available soil water holding capacity, and depth of the root zone.

For a specific location and year, the cropyield gap (Yg) is defined as the difference between **Yp (irrigated systems) or Yw (rainfed) and average actual farm yield (Ya).**

Normalised yield frequency map - a multi-year yield map. Normalisation converts the absolute yield values to relative yield values and this should be repeated for each year’s data and crop type.

Practical Example:

- Study area
  - Experimental field
    - 24.7 ha
    - Elevation ranges from 543 m to 571 m a.s.l.
    - 6 % slope
    - Strongly eroded
    - 700 mm per year precipitation
    - Average temperatures 6- 7 °C
    - Crop rotation: winter wheat (2014), spring barley (2015), winter rape (2016), winter wheat (2017), spring barley (2018)

- Yield and remote sensing data
  - Combine harvester New Holland CR9080 – EGNOS correction (2014, 2015, 2016, 2018)
  - Satellite imagery: Landsat 8 (2014), SPOT 7 (2015), Sentinel 2A (2016, 2017, 2018)
  - Normalised difference Vegetation Index (NDVI(
  - ArcGIS 10.4.1 SW, Statistica 8.0 SW

Methods:

The crop yield (**FIGURE 1**) was measured by a combine harvester New Holland CR9080 equipped with yield monitor and DGPS receiver with EGNOS correction. The accuracy of this system is ± 0.1-0.3 m in horizontal and ± 0.2-0.6 m in vertical direction. The yield data are saved every 1 second with coordinates to the external memory. The yield data were process by basic statistical method in order to eliminate the errors of yield measurement system. The yield data sets were then interpolated to kriging maps using experimental variograms.

Relative yield values were calculated for each yield data set with the aim to standardize the yield data (the actual yield value to average yield value of the plot converted to percentages). The relative yield maps were then converted to rasters, resampled to equal spatial resolution (10 m according to Sentinel 2 spatial resolution) and recalculated to yield frequency maps (Maphanyane et al., 2018) with help of Cell Statistics tool in ArcGIS 10.4.1 SW (ESRI, Redlands, CA, USA). The maximum values of the input's yield data were used for yield frequency maps calculation.

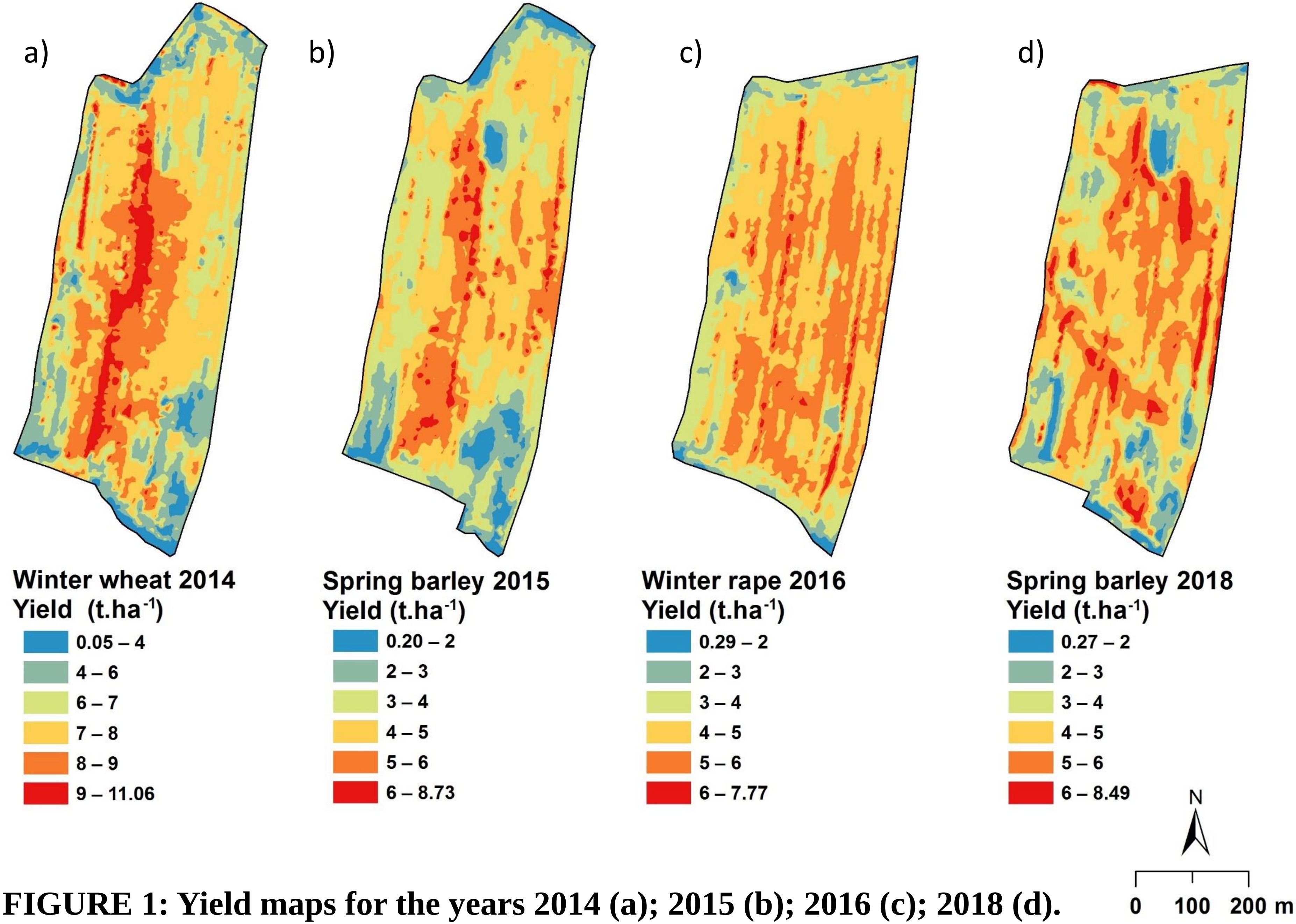


FIGURE 1: Yield maps for the years 2014 (a); 2015 (b); 2016 (c); 2018 (d).

Normalized Difference Vegetation Index (FIGURE 2) was calculated from each image.

The yield frequency maps - FIGURE 3 (a-b) - were derived from the all measured years and from cereals only (except winter rape yield).

NDVI frequency maps - FIGURE 3(c-f) - with the help of Cell Statistics tool were created in four variations, where maximum values of the input data were used. The NDVI frequency maps were derived on the base of – all NDVI images, NDVI images for cereals only (without 2016 – winter rape), all NDVI images except 2014 (with 30 m spatial resolution/Landsat image) and NDVI for cereals (except 2014 and 2016).

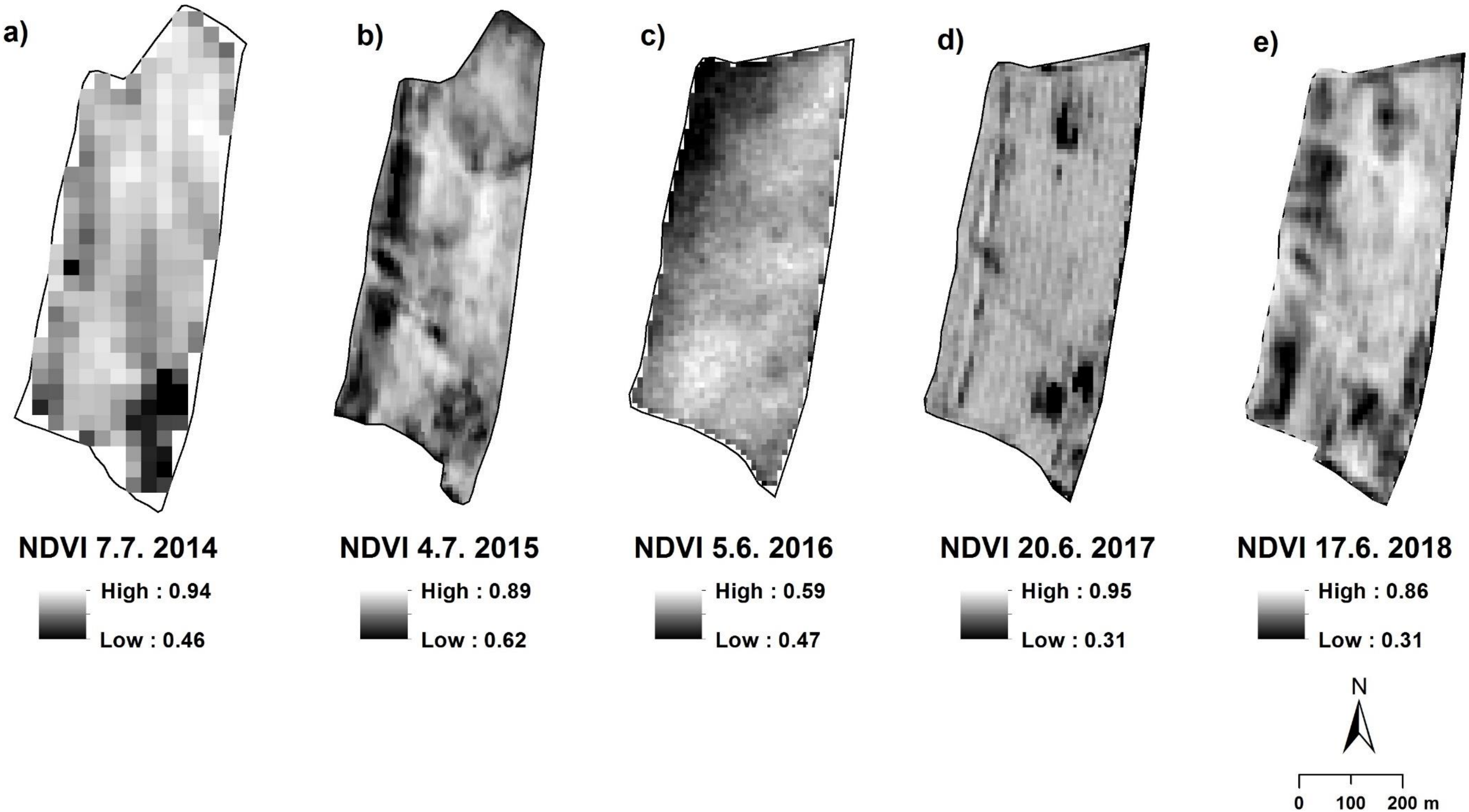


FIGURE 2: NDVI for the years 2014 (a); 2015 (b); 2016 (c); 2017 (e); 2018 (f).

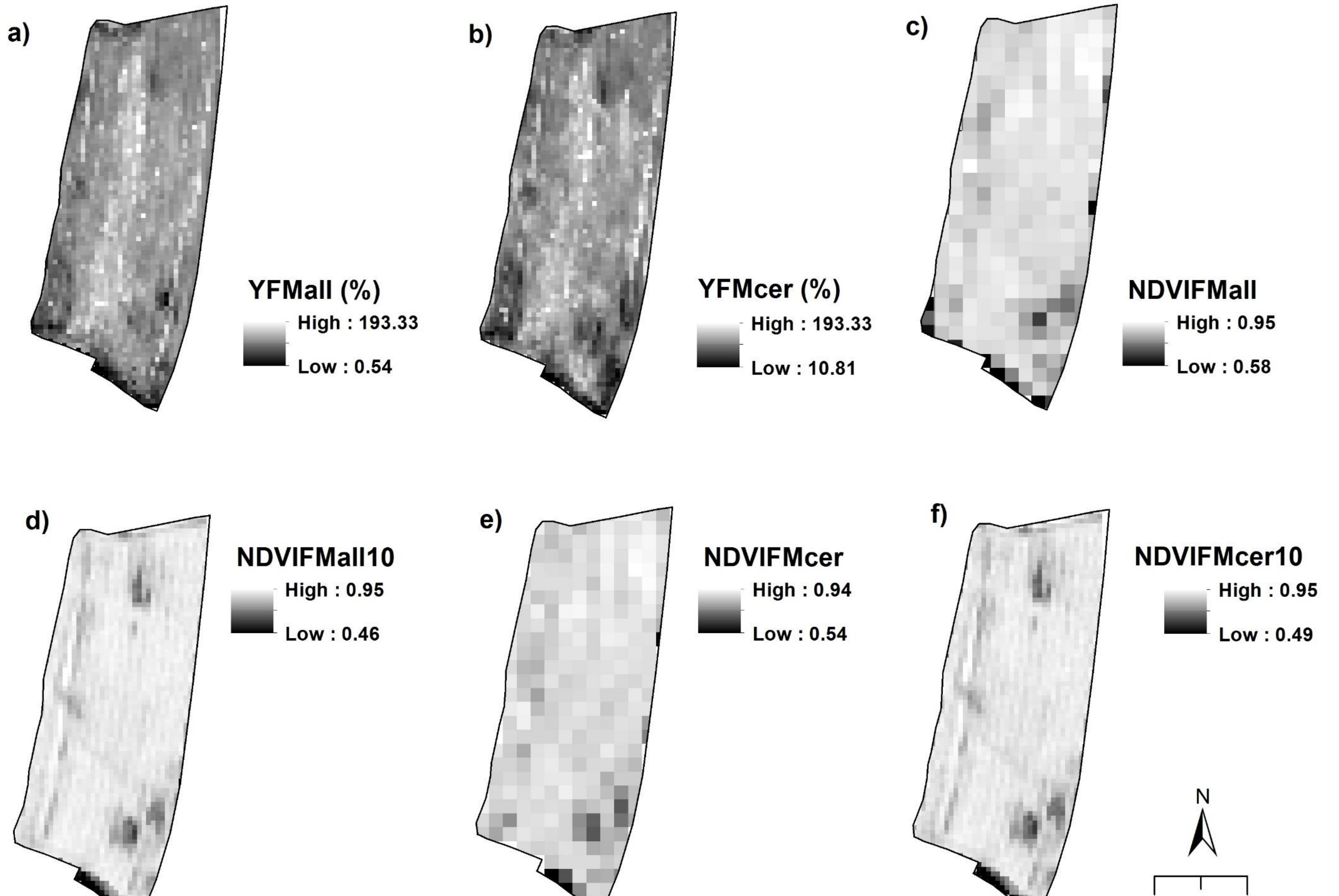

a)
YFMall (%)
High : 193.33
Low : 0.54
b)
YFMcer (%)
High : 193.33
Low : 10.81
c)
NDVIFMall
High : 0.95
Low : 0.58
d)
NDVIFMall10
High : 0.95
Low : 0.46
e)
NDVIFMcer
High : 0.94
Low : 0.54
f)
NDVIFMcer10
High : 0.95
Low : 0.49
N
0 100 200 m

FIGURE 3

Explanation:

NDVI = Normalised Difference Vegetation Index for selected terms; YFMcer = yield frequency map for cereals only;

YFMall = for all yield maps;

NDVIFMcer = NDVI frequency map for cereals;

NDVIFMcer10 = NDVI frequency map for cereals without Landsat image/2014;

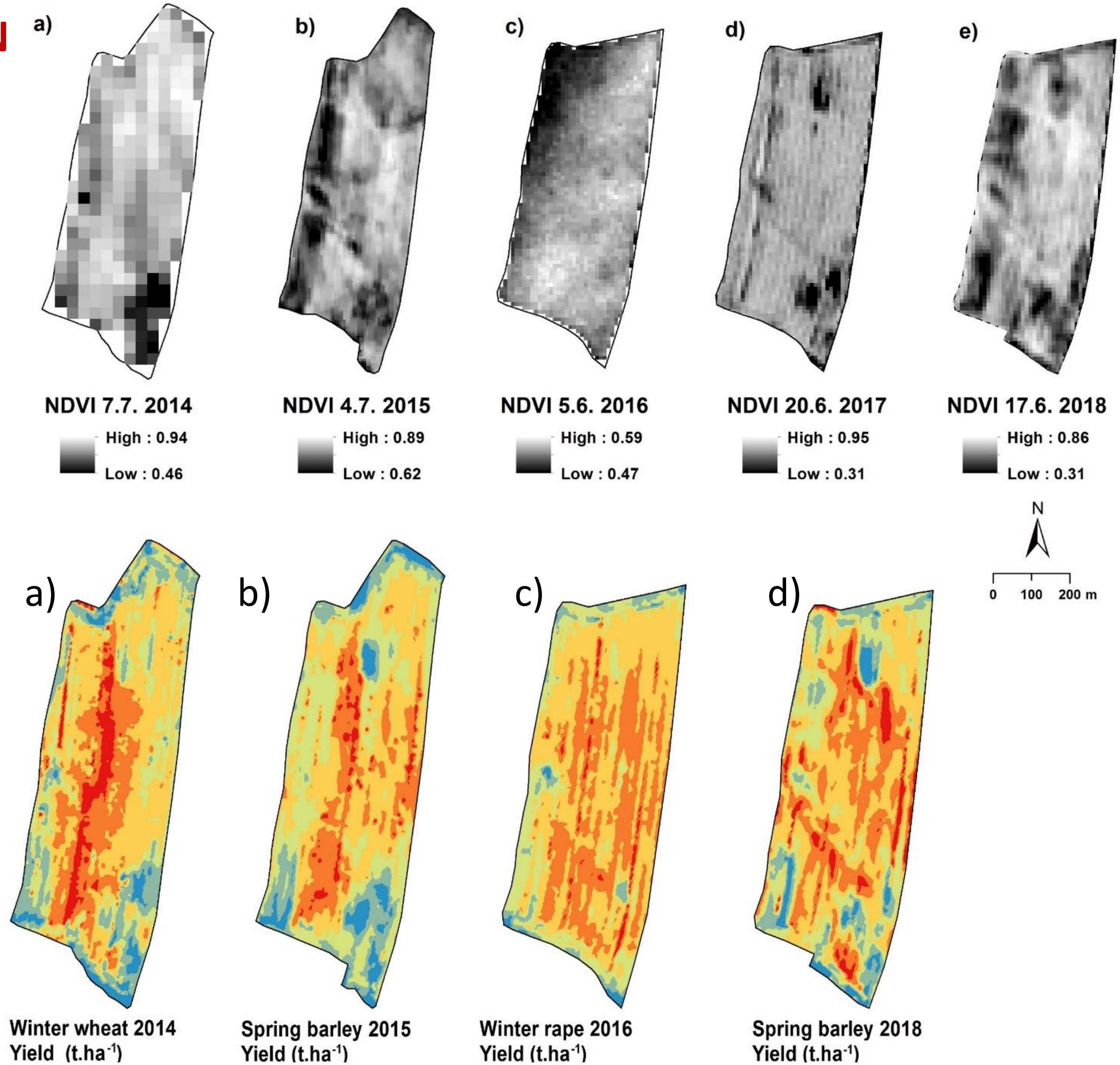
NDVIFMall = NDVIFM for all years;

NDVIFMall10 = NDVIFM for all years without Landsat image/2014

COMPARISON

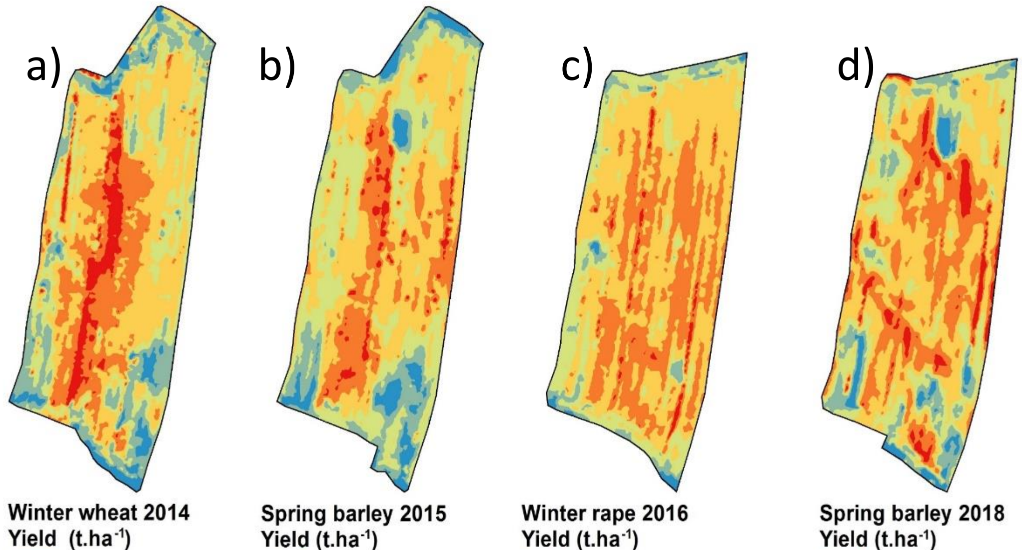
NDVI

YIELD

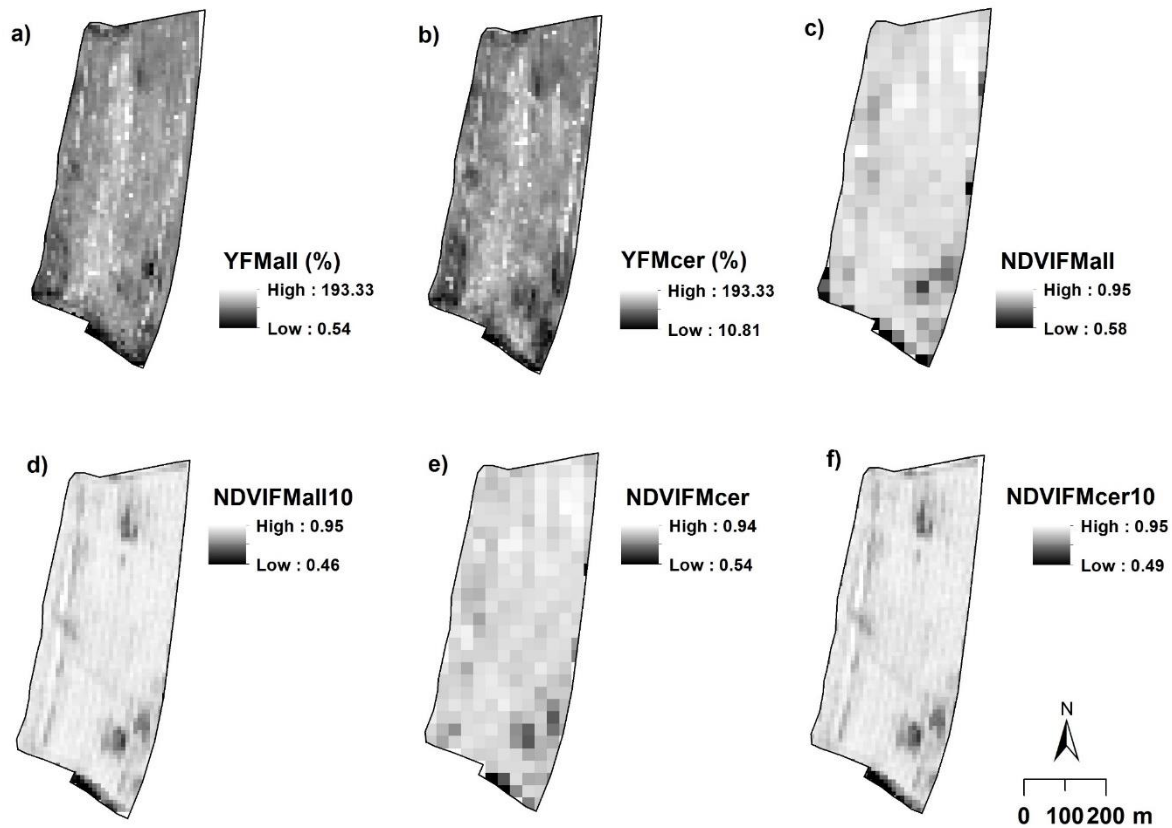


COMPARISON

YIELD



MODELS



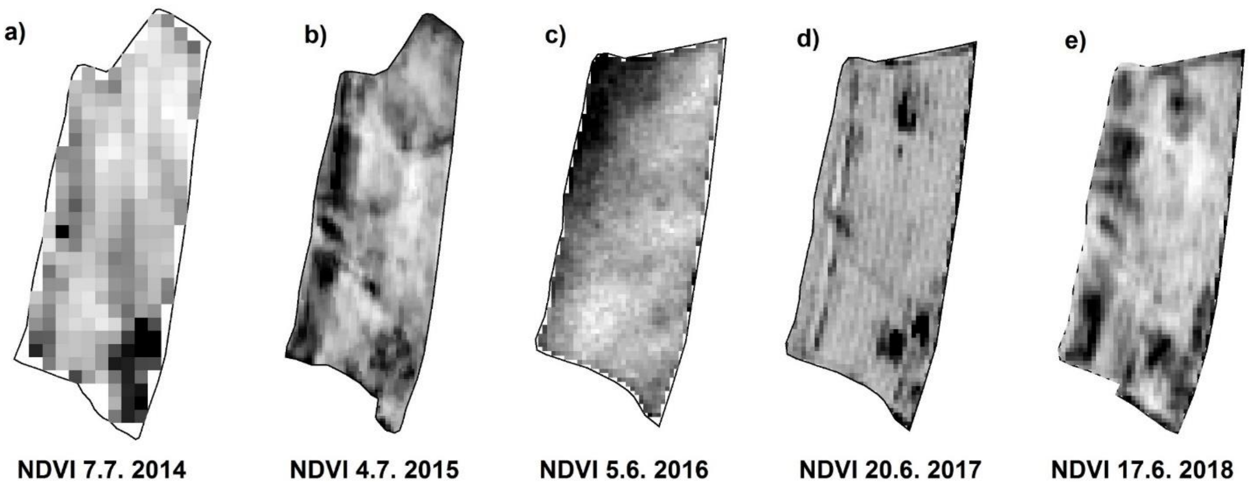
Coefficients of determination between yield from selected years and Yield/NDVI frequency maps and NDVI (at 5% significance level).

Models	Yield 18	Yield 16	Yield 15	Yield 14
YFMcer	0.56	0.15	0.59	0.45
YFMall	0.24	0.16	0.46	0.44
NDVIFMcer	0.12	0.01	0.22	0.14
NDVIFMcer10	0.24	0.03	0.24	0.13
NDVIFMall	0.10	0.31	0.07	0.07
NDVIFMall10	0.30	0.08	0.36	0.16
NDVI180617	0.52	0.10	0.36	0.16
NDVI170620	0.27	0.08	0.34	0.16
NDVI160605	0.05	0.13	0.05	0.03
NDVI150704	0.18	0.09	0.27	0.08
NDVI140707	0.06	0.05	0.26	0.19

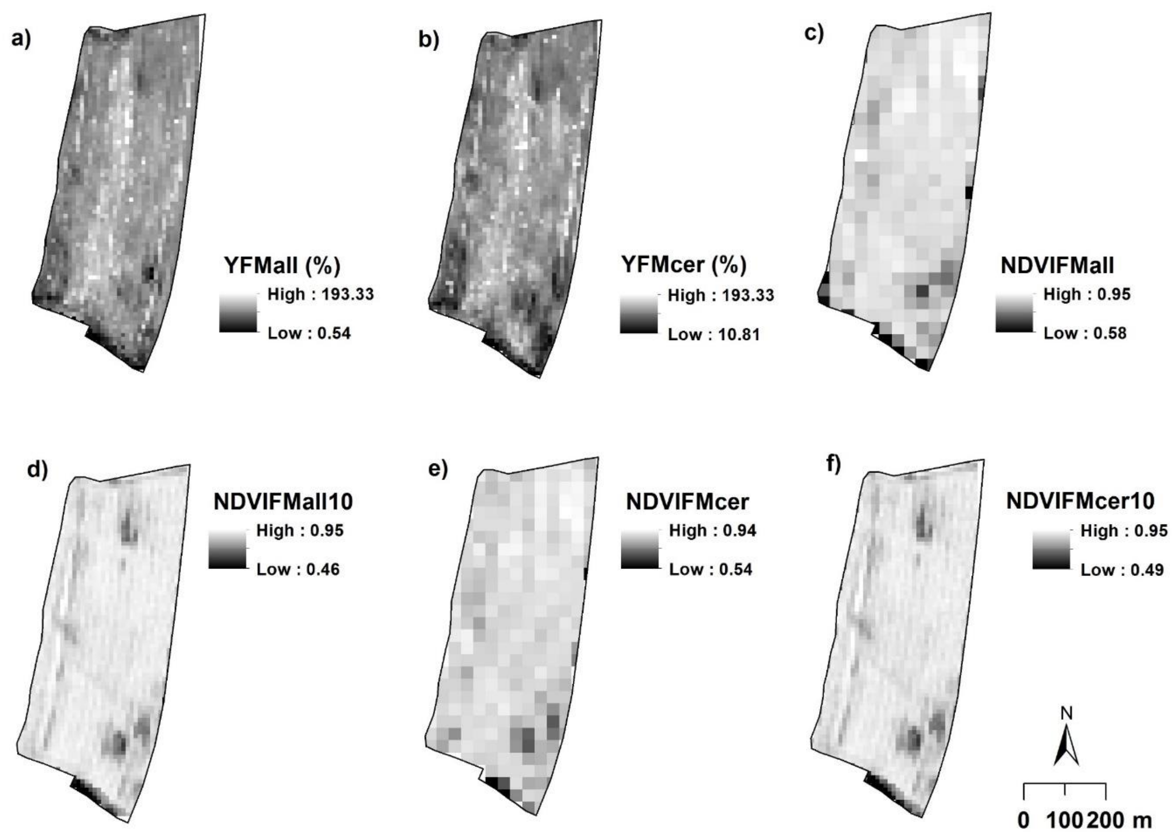
The results of the measurment prove, that yield prediction of winter rape (2016), which is based on yield frequency maps, has lower usability than the yield prediction of cereals.

COMPARISON

NDVI



MODELS



Coefficients of determination between NDVI from selected terms and Yield/NDVI frequency maps (at 5% significance level).

	NDVI180617	NDVI170620	NDVI160605	NDVI150704	NDVI140707
YFMcer	0.38	0.24	0.04	0.17	0.14
YFMall	0.18	0.16	0.08	0.12	0.14
NDVIFMcer	0.20	0.31	0.006	0.12	0.35
NDVIFMcer10	0.18	0.38	0.008	0.07	0.14
NDVIFMall	0.06	0.03	0.14	0.06	0.05
NDVIFMall10	0.26	0.96	0.02	0.12	0.18

This table shows the coefficients of determination between NDVI from selected terms and Yield / NDVI models. The models have the best explanation for the yield variability in 2017 and 2018. It might have been caused by the weather, because there was more precipitation and higher temperatures in the key time period (BBCH 20-29).

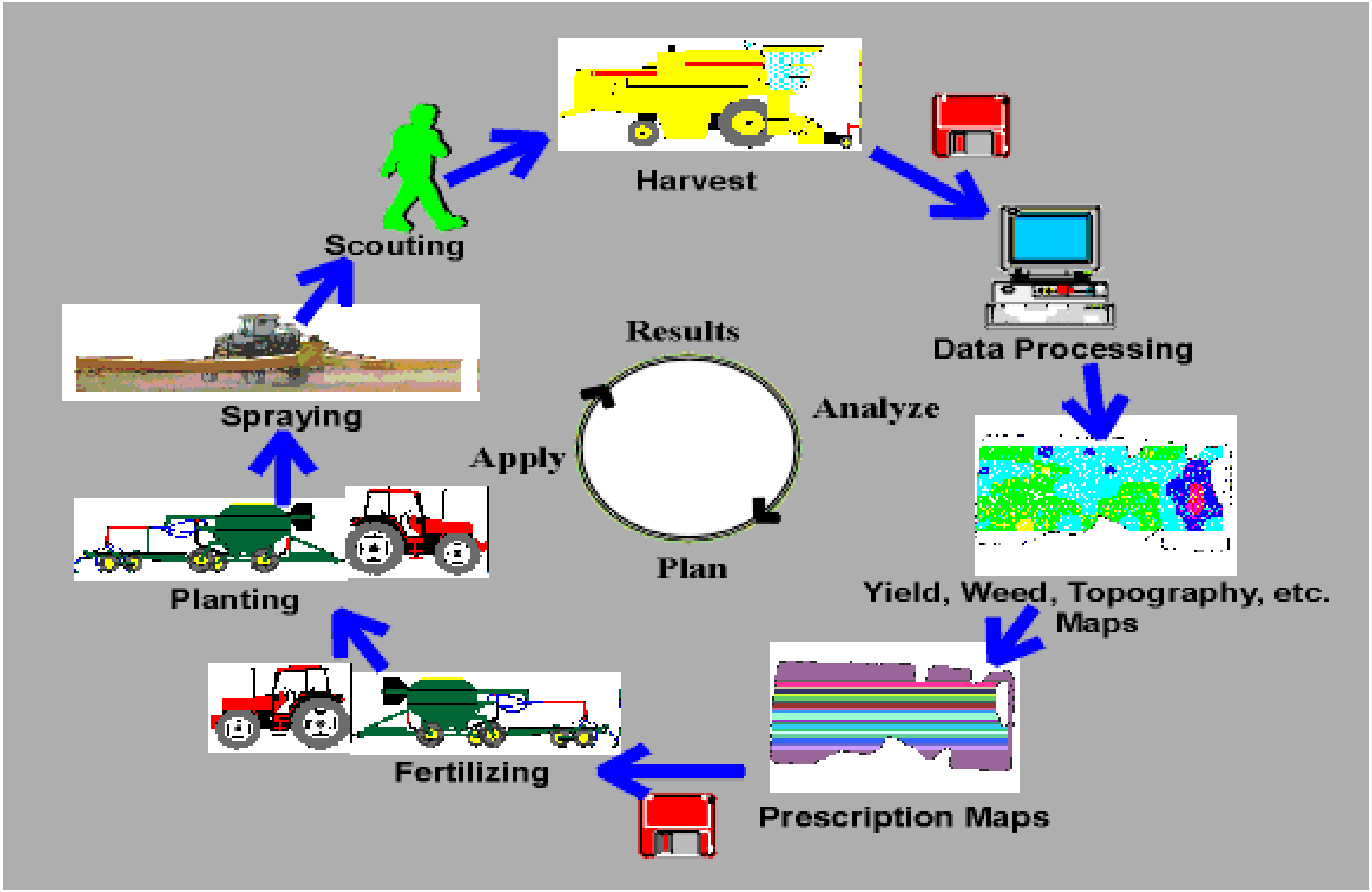
Results and recommendations:

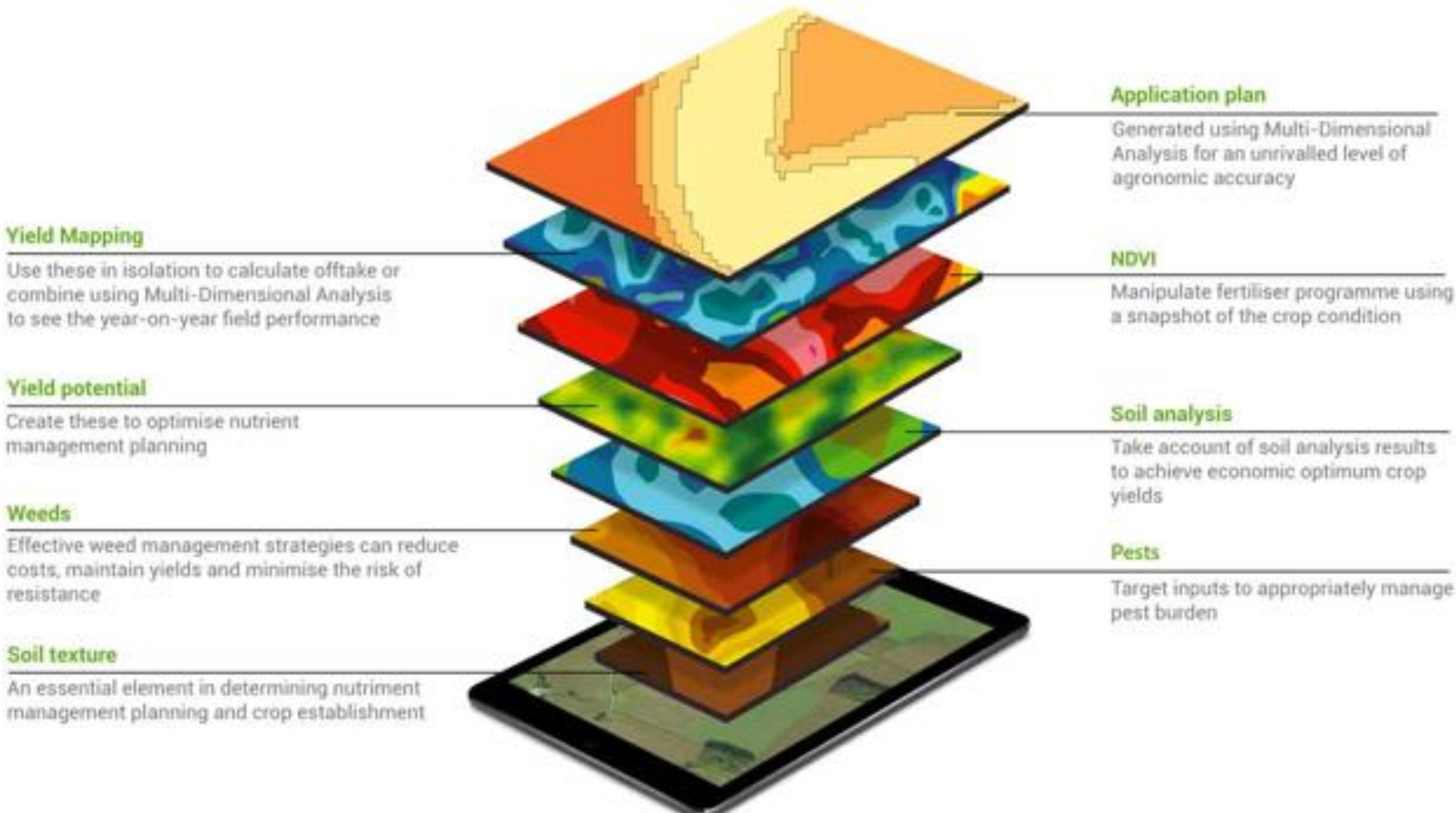
- The study proves that the best model for crop yield estimation is in this case the yield frequency map for cereals. This model explains the yield variability from 44% in average for all selected years.

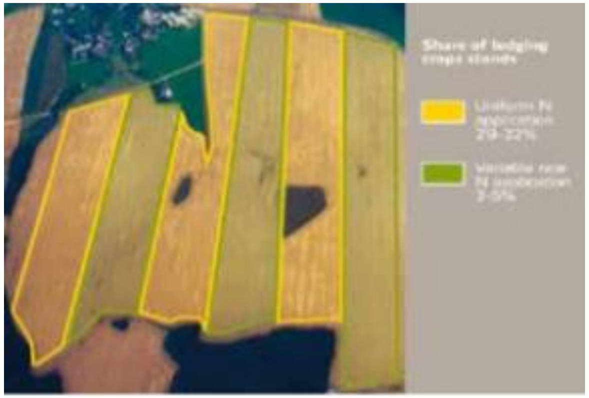
- For crop condition, the best model seems to be the NDVI frequency map. This model explains winter wheat crop structure from 96% (in 2017) and from 31% in average for all selected NDVI images.

- In general, the models were more significant for cereals and in drier and warmer years.

- **Application maps**




Application plan
Generated using Multi-Dimensional Analysis for an unrivalled level of agronomic accuracy
Yield Mapping
Use these in isolation to calculate offtake or combine using Multi-Dimensional Analysis to see the year-on-year field performance
NDVI
Manipulate fertiliser programme using a snapshot of the crop condition
Yield potential
Create these to optimise nutrient management planning
Soil analysis
Take account of soil analysis results to achieve economic optimum crop yields
Weeds
Effective weed management strategies can reduce costs, maintain yields and minimise the risk of resistance
Pests
Target inputs to appropriately manage pest burden
Soil texture
An essential element in determining nutriment management planning and crop establishment



Thanks for your attention!