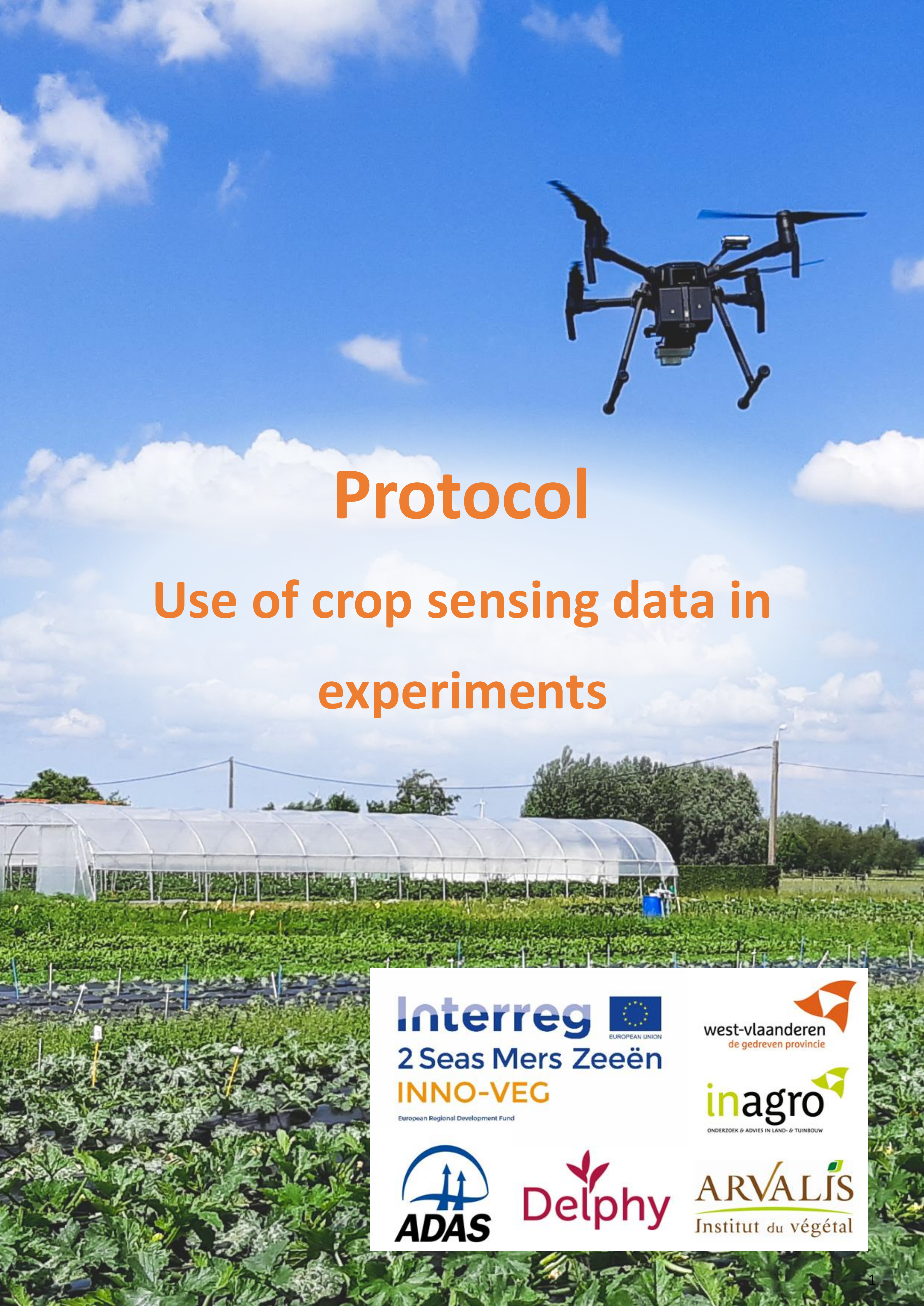


Protocol

Use of crop sensing data in experiments

Interreg
European Union
2 Seas Mers Zeeën
INNO-VEG
European Regional Development Fund

west-vlaanderen
de gedreven provincie

inagro
onderzoek & advies in land- & tuinbouw

ADAS

Delphy

ARVALIS
Institut du végétal

Authorship

ADAS

Lizzie Sagoo

Ruth Wade

Susie Roques

James Dowers

Arvalis

Jean-Pierre Cohan

Antoine Fournier

Francesca Degan

Katia Beauchene

Inagro

Eva Ampe

An Cools

Lien Deleu

Sarah Bossuyt

Gies Van Den Daele

Delphy

Cor van Oers

Hans Moggré

Elianne van Esbroeck

Funding

This Protocol has been written by researchers at ADAS in the UK, Inagro in Belgium, Delphy in the Netherlands and Arvalis in France as part of the INNO-VEG project. INNO-VEG has received funding from the Interreg 2 Seas programme 2014-2020 co-funded by the European Regional Development Fund under subsidy contract No 2S05-032.

For more information visit: https://www.inno-veg.org/

CONTENTS

Introduction

1.1 About this Protocol

This Protocol provides guidance on using crop sensing data to assess treatment differences in field experiments. The guide focusses on field vegetable and potato crops and has been produced as part of the INNO-VEG project. The Protocol is aimed at researchers, agronomists and farmers who want to use crop sensing technology to assess their crops and aims to support them to make best use of the technology.

The Protocol includes information on the use of crop sensing technology in the field and on the management and interpretation of the data. The information provided is based on the experience of the authors and the results of the INNO-VEG project.

1.2 INNO-VEG project

The INNO-VEG project is developing innovative methods for carrying out research into field vegetable and potato crops. Reliable research methods are crucial to underpin the evidence base needed to meet the challenges of sustainable intensification of field vegetable and potato production. Traditional crop research relies on replicated treatments in small plots and often manual hand harvesting of plots to assess crop yields and quality, which can be time consuming and expensive. Previous research and experience of the INNO-VEG project partners has demonstrated that crop sensing data can show up differences in crop performance across a field. The project was set up to see whether these crop sensing techniques can accurately assess crop performance, and if they can, whether they can be used instead of the more labour-intensive and expensive standard field assessments.

The project has focussed on field vegetable and potato crops where the measurement of yields in small plot field experiments is still mainly done by hand and where lack of yield mapping equipment on commercial harvesters limits the ability to assess treatments applied to larger field areas. A key advantage of using crop sensing data to assess treatments is the ability to upscale from small plot to field scale experiments, as crop sensing data can be relatively easily collected from larger field areas using drones or tractor mounted sensors.

The guidance in this Protocol has been based on the results of more than 60 field experiments carried out in 2019 and 2020 across the UK, France, Belgium and the Netherlands where traditional field measurements (i.e. hand harvest or experimental harvest machine assessments of yield and crop quality) were compared with crop sensing data.

These experiments covered a number of horticultural crop groups (including potatoes,

brassicas, alliums, leafy salads, carrots, vining peas and cucurbits) and research priority areas (e.g. soil management, crop nutrition, cultivar evaluation and crop protection) in order to generate data to evaluate the suitability of crop sensing data to assess treatment differences in field experiments.

The experiments were set up to address the key questions relating to the use of crop sensing in field experiments including applicability across different crop types with different growth patterns (e.g root crops compared to leafy salads), use of different crop sensors and vegetation indices, timing of measurements and any additional requirements for 'ground truthing' to 'calibrate' the spatial crop data.

In addition to this Protocol, the INNO-VEG project will publish a 'Framework for farmer led research' for the use of crop sensing data to assess field scale experiments. The framework will provide farmers with the information they require to set up and run field scale experiments including experimental design, application of treatments and sourcing crop sensing data. The Framework will be available to download from the INNO-VEG website in mid-2021.

1.3 INNO-VEG network

In addition to the field experiments, the INNO-VEG project has set up a cross-border (the UK, France, Belgium and the Netherlands) network to facilitate innovation between the precision farming and sensor technology industries, research organisations and the field vegetable and potato crop sectors through:

- Sharing results and information from the INNO-VEG project
- Hosting networking meetings and
- Providing an online discussion platform where members can post comments and ask questions.

The network was launched in October 2019 and is free to join. For more information and to register with the network, visit the website www.inno-veg.org

SECTION 2: CROP SENSING

2.1 Introduction – what is crop sensing?

Crop sensing is simply the process of using sensors to collect information about a growing crop. This document focusses on the most common commercially used form of crop sensing – **crop reflectance measurements**[1], where optical sensors are used to measure the amount of light radiation reflected from the crop at different wavelengths.

A growing crop will absorb, transmit and reflect incoming radiation (Figure 1). The proportion of radiation absorbed, transmitted or reflected will vary across the electromagnetic spectrum (at different wavelengths) depending on crop characteristics. Most crop reflectance sensors measure reflectance in the visible (about 400-700 nm) and near infrared portion (about 700-2500 nm) of the electromagnetic spectrum.

The variation in reflectance at different wavelengths is called the crops **spectral signature** (Box 1). A healthy well-developed crop will have a different spectral signature to a less well developed or unhealthy crop. In this way, we can use crop reflectance measurements to provide information on crop growth and vigour.

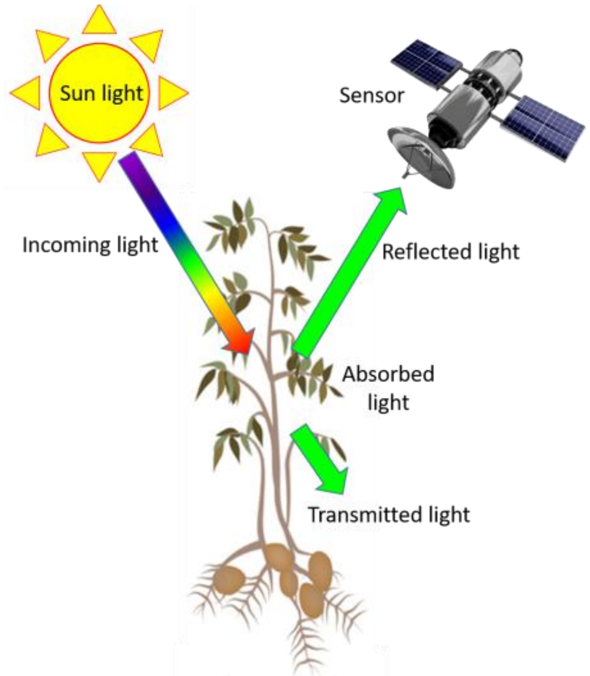
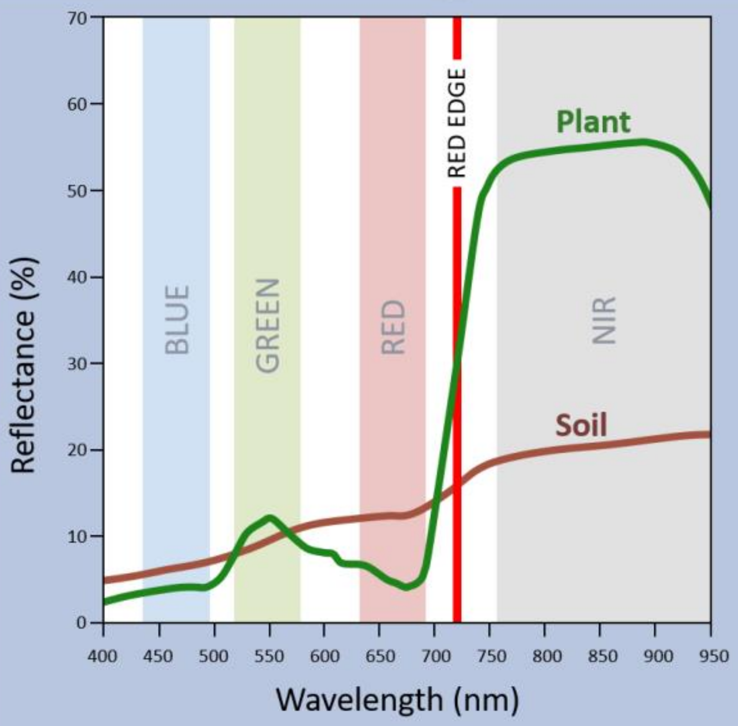


Figure 1. Incoming radiation is reflected, transmitted and absorbed by the crop canopy

Differences in reflectance at specific wavelengths can be expressed as a **Vegetation Index** (VI)– these can be calculated in many ways, but the most well-known is the Normalised Difference Vegetation Index (NDVI). Since reflectance from the crop is determined by the size and vigour of its canopy, vegetation indices have been shown to correlate well with crop characteristics such as above ground biomass and crop vigour.

Box 1. Crop reflectance

Plant tissue absorbs most of the visible radiation for photosynthesis. However, there are differences in absorption within the visible region. Absorption is higher in the red and blue, than green region, which causes the green colour of growing crops. In contrast, plant tissue reflects most radiation in the near infrared (NIR) region. The amount of radiation reflected increases sharply between the visible and near infrared bands in what is known as the red-edge transition zone. A thick healthy crop will typically reflect less radiation in the visible and more in the near infrared regions than a thinner or stressed crop.



1. Other sensor technologies exist, like Lidar (Laser) or microwave measurements. These are less frequently commercially used in agriculture and are not addressed in this Protocol document

2.2 Types of crop sensors

Optical crop sensors can be categorised according to the reflectance measurements recorded, the light source used and the platform/vector that the sensor is mounted on. Below we consider the main types of crop sensors

2.2.1 Sensor type (according to reflectance measurements made)

RGB cameras can be used to take an image in the visible (RGB = Red, Green, Blue) light spectrum, which recreates almost exactly what our eyes see. RGB images can be analysed at the pixel scale to identify objects (e.g. crop counting), to calculate the relative surface of an object of a given colour (e.g. % crop green colour) or to calculate a limited number of Vegetation Indies which use reflectance from the RGB wavebands. The main limitation of these sensors is that they do not provide crop reflectance from the near infrared waveband, which is needed to calculate some of the most useful Vegetation Indices.

Multispectral cameras measure light from several wavebands simultaneously. By definition, a RBG camera is a form of multispectral camera, however the term 'multispectral camera' is normally used for a camera which measures from both the visible and near infrared wavebands. Inclusion of the near infrared waveband allows calculation of Vegetation Indices which provide a better representation of crop growth and vigour. Multispectral cameras generally measure between 4 and 12 wavebands; inclusion of the green, red, red-edge and near infrared wavebands allows calculation of many Vegetation Indices related to crop biomass and vigour.

Hyperspectral cameras measure light in narrower (typically 5-10 nm) and more numerous bands than multispectral cameras. Hyperspectral cameras provide crop reflectance data across a *continuous* range of wavebands and therefore have a greater potential to detect differences in crop growth than multispectral cameras. However, hyperspectral cameras are more expensive and generate very large quantities of data to process.

Spectroradiometers measures reflectance from a limited area. Spectroradiometers can be multi- or hyper- spectral, however unlike cameras, a spectroradiometer provides measurements for the whole area measured and not in an image format able to be decomposed in individual pixels. Spectroradiometers are relatively quick and easy to use and are well suited to measurements from small areas.

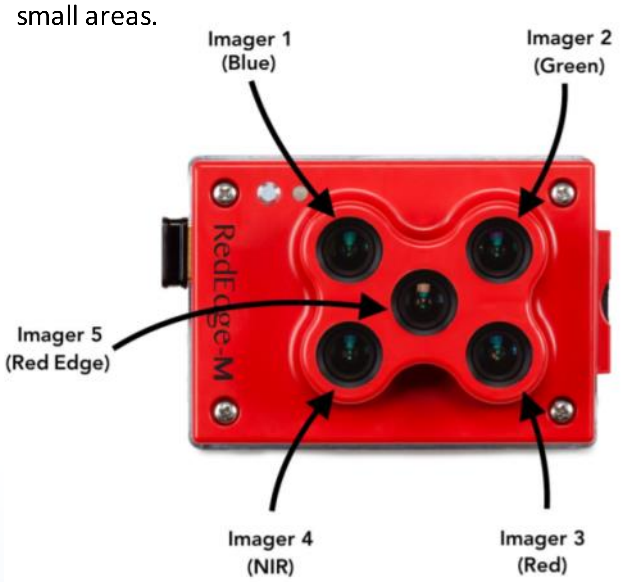


Figure 2. The MicaSense RedEdge camera has five sensors which measure reflectance from the Blue, Green, Red, Red-Edge and Near Infrared wavebands

2.2.2 Passive and active sensors

Sensors can be classified as passive or active sensors depending on the light source used. Passive sensors use the sun as their light source and measure the amount of reflected sunlight. Because passive sensors rely on sunlight, reflectance measurements are affected by the angle of the sun and cloud cover and it is generally recommended to take measurements close to solar noon when the sun is highest the sky and when cloud cover is minimal. Some passive sensors try to minimise the impact of varying light conditions by also measuring incident light above the crop canopy to enable to correction for varying light levels and/or frequent calibration of the sensor using a white reference panel.

Active sensors emit their own light source and measure the amount of light reflected to the sensor. Active sensors use a modified light source which allows them to distinguish the reflectance from the background sunlight. This means that measurements are independent of changing background light levels and active sensors can be used at any time of day and without disturbance by passing cloud cover.

2.2.3 Sensor platform

Sensors can be mounted on different platforms or vectors to collect the data. Measuring using satellite or drone mounted sensors is called remote sensing, whereas measuring using ground based hand-held, or tractor mounted sensors is often referred to as proximal sensing as the sensor is closer to the object.

Handheld sensors provide a relatively quick and easy way of measuring reflectance from a limited number of points within a field. Some handheld sensors include a display which shows crop reflectance measured in real time. Handheld sensors are well suited to small plot experimental work or where there are a limited number of comparisons/a small area to measure from. The main disadvantage is that handheld sensors have a limited field of view, meaning that they only measure from a small area of crop. It is not possible to provide crop reflectance information from larger areas using handheld sensors.

Rolling vectors can be used to mount sensors and collect crop reflectance data as the vector moves through the field. These include **tractors** and other moving **frame or gantry systems**. Commercially available tractor mounted sensors are typically mounted on the cab or at the front of the vehicle and provide the flexibility to collect crop reflectance data during routine field management operations. Frame or gantry systems are most commonly used to collect data from trials and may be custom built to fit trial layouts. The resolution of the data collected will depend on the width between paths that the vector moves down. Tractor mounted sensors typically record crop reflectance data from an area either side of the field tramlines and will not cover the whole field area. The software available with most commercially available tractor mounted sensors then uses data interpolation methods to provide a complete crop reflectance map of the field.

Unmanned Aerial Vehicles (UAVs), also commonly known as drones, can be used to collect high resolution imagery from whole field areas. The flight path of the UAV is controlled either by pre-programmed onboard computer or by the remote control of a pilot on the ground.

Figure 3. The handheld FieldSpec spectroradiometer has a field of view equal to half the measurement height; at a 1 m measurement height the sensor measures from a circular area 50 cm diameter

Figure 4. The Fritzmeier ISARIA multispectral sensor is mounted on the front of the tractor

The UAV captures multiple overlapping images of the areas of interest which are then combined or ‘stitched’ together into a single orthomosaic map for each waveband measured using photogrammetry software. The use of UAVs is strictly controlled in Europe. Therefore, most farmers and researchers using UAV imagery will use a specialist UAV operator to collect the data and stitch the images together. The spatial resolution or Ground Sampling Distance (GSD) is the distance between two consecutive pixel centres measured on the ground. The GSD depends on the sensor model and flight height but is typically around 4 cm GSD at 60 m flight height and 8 cm GSD at 120 m flight height. It will typically take around 30 minutes to collect data from a 10-ha field using a drone flown at 120 m with 75% image overlap. Whilst the high spatial resolution available from UAV sensors is an advantage of this platform, UAV surveys can produce large amounts of data that can be time consuming to download and process. Multispectral (5-band) imagery from a UAV survey at 120 m flight height for a 10-ha field will typically be 150-200 MB when stitched together into a single image for each waveband. Most UAV mounted sensors are multispectral; hyperspectral sensors are available, but they significantly increase the volume of data to process.

Manned aircraft can also be used to collect crop reflectance data with the same sensors that are used on UAVs. Manned aircraft will usually be more expensive than UAV surveys at the individual field level but may be more cost effective if the area to be surveyed is large. Manned aircraft will normally fly at a higher level than UAVs so the spatial resolution may be lower, but unlike UAVs they are not limited by the weight (payload) that they can carry, and this may be an advantage if there is a requirement for specific heavier sensor models.

Figure 5. UAV mounted sensors can provide high resolution crop imagery

Satellite imagery is collected remotely and is relatively cheap and easy to access compared to other methods of crop sensing. The main limitations of satellite sensors are lower image resolution, frequency of measurements and the influence cloud cover. The majority of satellite sensors are passive sensors which cannot penetrate cloud cover, which means there will be no usable data for areas of the image covered by cloud. Free satellite imagery is available at medium resolution (10–30m) from ESA’s Sentinel 2 and NASA’s Landsat 8. Higher resolution data (5m–50cm) is commercially available for purchase. Satellite imagery can be useful to identify differences in crop performance across a field. As the resolution and frequency of data acquisition increases, it will become increasing attractive to use to evaluate larger field scale trials. However, because of the lower resolution available, it is not currently suitable to assess small plot experiments and was not considered as part of the INNO-VEG project.

2.3 Vegetation indices

A Vegetation Index (VI) is a numerical value calculated as a mathematical combination of reflectance values measured at two or more wavelengths, which can be related to crop characteristics such as above ground biomass and crop vigour. A large number of vegetation indices have been developed and are described in the scientific literature. Different VIs have been developed to be sensitive to specific plant characteristics such as biomass, nitrogen content or crop moisture status. The Index Database website provides one of the most comprehensive databases of remote sensing indices.

The Normalised Difference Vegetation Index (NDVI) is perhaps the most commonly used and well-known vegetation index. It is calculated as a ratio between reflectance in the red and near infrared wavebands. The NDVI formula will provide a value between -1.0 and +1.0; water has a negative value due to its strong absorption of near infrared radiation, soil surfaces typically have a value from 0.1 to 0.2 and cropped land from 0.2 to 1.0, with higher values for thicker crop covers. NDVI provides a good correlation with vegetation cover until the crop canopy closes and the Leaf Area Index (LAI) increases above about 3.0; above this point the response of NDVI to increases vegetation flattens out or 'saturates'. This saturation effect is well known, and other Vegetation Indices have been developed to try and provide a better measure of crop biomass at higher LAIs.

Several vegetation indices have been developed to be sensitive to leaf chlorophyll status, including MCARI2, MTCI and CI Green (Table 1). Leaf chlorophyll content provides an indicator of photosynthetic activity and therefore potential yield as well as a measure of the crop nitrogen status. Other indices have been developed using the red-edge reflectance band, such as CI Red Edge, NDRE, REIP, and have been shown to be more sensitive to biomass at higher LAIs.

The INNO-VEG project focussed on seven Vegetation Indices (Table 1). These Vegetation Indices were selected to provide a limited number of contrasting vegetation indices which have already been shown to be correlated to key crop variables such as biomass and nitrogen content. This list should not be considered a recommendation; there are a number of other Vegetation Indices which have been shown in the scientific literature to provide equally good correlations with these crop variables. However, it should also be noted that many of the hundreds of published vegetation indices are highly correlated with each other and there may be little to be gained by calculating large numbers of similar vegetation indices.

Table 1. Vegetation Indices used in the INNO-VEG project

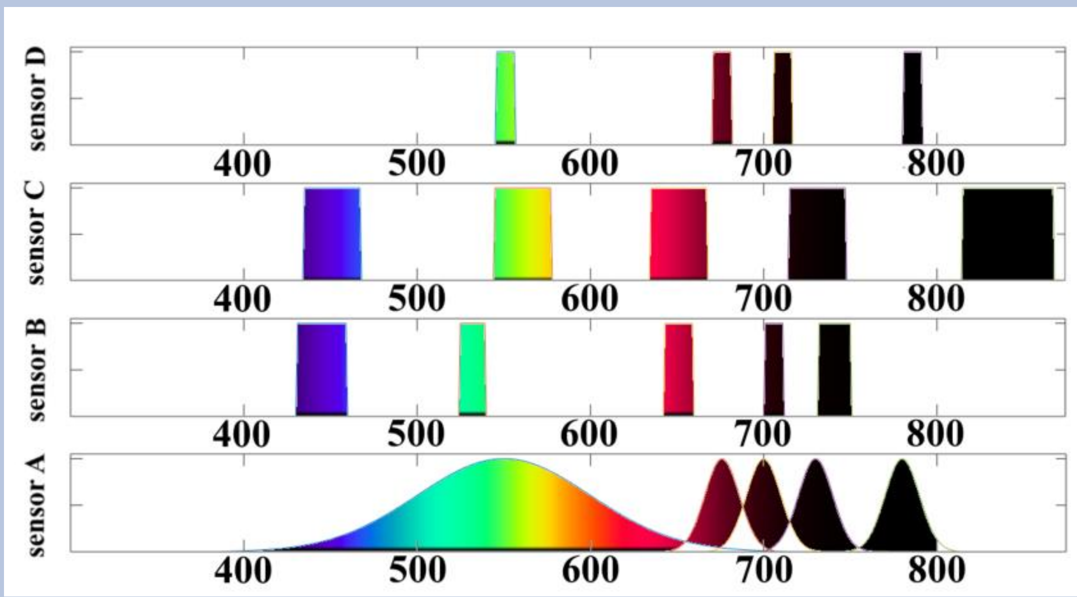
Vegetation Index (VI)	Acronym	Comments	Equation[1]	Wavebands used (λ)[2]	Reference
Normalised Difference Vegetation Index	NDVI	Most well-known and commonly used index. Provides good discrimination between vegetation and soil and sensitive to biomass up to a LAI about 3.	$\frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$	λRED = 670 nm λNIR = 800 nm	Rouse et al. (1974)
Modified Chlorophyll Absorption in Reflectance Index 2	MCARI2	Sensitive to leaf chlorophyll concentrations. Care should be taken with the complex algebraic calculation.	$1.5A\left(\frac{2.5 \times (\rho_{NIR} - \rho_{RED}) - 1.3 \times (\rho_{NIR} - \rho_{GREEN})}{\sqrt{(2 \times \rho_{NIR} + 1)^2 - \left(6 \times \rho_{NIR} - 5 \times \sqrt{\rho_{RED}}\right) - 0.5}}\right)$	λGREEN = 550 nm λRED = 670 nm λNIR = 800 nm	Haboudane et al. (2004)
Meris Terrestrial Chlorophyll Index	MTCI	Developed to estimate chlorophyll content using the MERIS satellite bands.	$\frac{\rho_3 - \rho_2}{\rho_2 - \rho_1}$	λ1 = 681 nm λ2 = 708 nm λ3= 753 nm	Dash and Curran (2004)
Chlorophyll Index Green	CIgreen	Sensitive to leaf chlorophyll concentrations using NIR and Green bands.	$\frac{\rho_{NIR}}{\rho_{GREEN}} - 1$	λGREEN = 550 nm λNIR = 800 nm	Gitelson et al. (2005)
Chlorophyll index Red Edge	CIrededge	Sensitive to leaf chlorophyll concentrations using NIR and Rededge bands.	$\frac{\rho_{NIR}}{\rho_{RedEdge}} - 1$	λRedEdge = 710 nm λNIR = 800 nm	Gitelson et al. (2005)
Normalized Difference Red Edge	NDRE	Substitutes Rededge for red band in NDVI equation. Provides better sensitivity to biomass at higher LAI than NDVI.	$\frac{\rho_{NIR} - \rho_{RedEdge}}{\rho_{NIR} + \rho_{RedEdge}}$	λRedEdge = 720 nm λNIR = 790 nm	Barnes et al. (2000)
Red Edge Inflection Point	REIP	Estimates the position of the Red Edge Infection Point from 4 bands. Sensitive to leaf chlorophyll content & biomass. Not all multispectral sensors will provide the required bands to calculate this index.	$700 + 40 \times \left(\frac{\left(\frac{\rho_{RED} + \rho_{NIR}}{2}\right) - \rho_1}{\rho_2 - \rho_1}\right)$	λRED = 670 nm λNIR = 780 nm λ1 = 700 nm λ2 = 740 nm	Herrmann et al. (2011)

[1]ρ = reflectance recorded in the specified wavebands (λ). [2]. Where the equation for the Vegetation Index provides a range for the wavebands used (i.e. Green, Red, Red edge or NIR), we have suggested precise wavebands based on the most common values found in the literature for these Vegetation Indices.

Box 2. Impact of spectral bandwidth and position on the calculation of Vegetation Indices

If using a hyperspectral sensor, which provides crop reflectance data across a continuous range of wavebands, the user can select the precise wavebands required to calculate the chosen Vegetation Indices. If using a multispectral sensor, the user is limited to the wavebands provided by the sensor. Multispectral sensors which measure reflectance in the Green, Red, Red edge and NIR bands enable allows calculation of many Vegetation Indices related to crop biomass and vigour. However, the bandwidth and position within the Green, Red, Red edge and NIR regions will vary from sensor to sensor, and this may impact on the calculated Vegetation Indices.

This is illustrated in the figure below which shows the spectral specification of four commercially available multispectral sensors. The main differences are in position of central waveband, band width measured and filtering method. Most sensors either use a 'gated' filtering method which calculates an average of reflectance measured within the specified band, or a 'gaussian' type filter where reflectance measurements near the central waveband are weighted more than those at either end of the band width. For example, sensor A measure red at 675 nm +/- 5nm using a gated filtering method, sensor B measures red at 650 nm +/- 16 nm using a gated filtering method, sensor B measures red at 668 nm +/- 5 nm using a gated filtering method and sensor C measures red at 670 nm +/- 5nm using a gaussian filtering method.



The INNO-VEG project used data from two hyperspectral sensors to simulate the effect of the position of central waveband, band width measured, and filtering method used by sensors A-D on the Vegetation Indices shown in Table 1. This showed that Vegetation Indices which used the Green, Red and NIR bands only were the least sensitive to sensor characteristics, while the vegetation indices which used the Red edge band were the most sensitive to sensor characterises.

The amount of radiation reflected increases sharply in the Red-edge region and therefore a small difference in band width/position can have a notable impact on Vegetation Indices calculated. Sensor characteristics had the greatest impact on MTCI and CI-Red edge, both of which use the red edge band; 23% of comparisons had a difference of >5% and 9% of comparison had a difference of >10%.

We recommend using the same sensor for measurements from an experiment and being cautious when comparing absolute vegetation index values calculated from different sensors, particularly if these vegetation indices use the Red-edge band. Although vegetation indices measured using two different sensors may show a similar correlation with a measured crop parameter, the characteristic of that relationship may be different between the sensors making it difficult to use a vegetation index value calculated using sensor A to estimate a crop parameter based on an equation developed using sensor B.

Designing the field trial

Field experiments enable researchers, industry and farmers to test the effect of different crop or soil management practices, such as the impact of different soil cultivation, fertiliser products or fertiliser rates on crop yields, and are essential to provide farmers with the evidence base to support sustainable profitable crop production.

When designing a field experiment which will use crop sensing as part of the assessments, the same principles apply as when designing 'conventional' field experiments.

Treatments: decide on the treatment(s) and include an untreated control. The selected treatment should be the only factor that is varied across the experiment; all other factors should be consistent across the experiment area.

Select the experiment area: most fields have some level of natural underlying soil variability and it is important to try and position the experiment in an area that is as even as possible. If available, look at soil electrical conductivity (EC) maps, yield maps from previous crops, or freely available satellite NDVI maps to help select an area where soil/crop variability is minimised.

Decide on plot size: larger plots are generally better, however it is important to consider how the treatments will be applied. If applying treatments by hand, plot sizes will generally be smaller than if applying by machinery.

Replication and randomisation: replicating treatments increases the power to detect treatment differences. Ideally include 2-4 replicates of each treatment and randomly allocate each treatment to the plots. Randomisation helps to minimise the effect of any underlying variation across the experimental area and to make fair comparisons between treatments.

Measure the impact of the treatment: the guide focusses on the use of crop reflectance data to assess the impact of treatments in crop assessments. Most crop sensors can be used to measure crop reflectance from plots without any need to adjust the experiment design or layout. The only exception is for tractor or rolling vector mounted sensors, where it is important to consider the position of the sensor when the tractor/vector travels along the tramlines to ensure the sensor can measure from the plot area.

Further information: INNO-VEG project partner ADAS have produced a Guide to Farmers' crop trials which provides guidance on setting up field experiments. The INNO-VEG project will publish a Framework for Farmer led research focussing on field vegetable and potatoes at the end of 2021.

Best practice when collecting crop sensing data

4.1 Introduction

When collecting crop reflectance data, it is important to plan data collection in advance and to follow best practices in the field to minimise the effects of measurement errors associated with solar angle, weather conditions, geolocation and sensor calibration, which can all affect the quality of the crop reflectance data collected. Here we provide guidance on factors to consider when planning your data collection and provide best practice guidance on how to minimise measurement errors.

This guidance is applicable to most sensors and focusses on operation in the field. In addition, it is important to operate the sensor according to the manufacturer's instructions.

4.2 Radiometric calibration

A radiometric calibration is used to convert radiance measured by the sensor (in the form of a digital number – DN) into absolute reflectance values. This is done using a calibrated refence panel with known reflectance values across the electromagnetic spectrum. Measurements from a calibrated reference panel are used by the sensor or processing software to convert the sensor measurements to absolute reflectance values by reference to the values given by the calibration target. A radiometric calibration should be done at the time of sensor measurements to account for current ambient light conditions.

Most sensor manufacturers recommend taking measurements from a calibrated reference panel before and after field measurements. Additional measurements may be taken during field measurements and this can be useful to help account for changes to ambient light conditions (see section 4.3). If using a handheld or tractor mounted sensor it is relatively easy to take additional measurements from the calibrated reference panel during field measurements if light conditions change. If using a drone mounted sensors, calibration targets can be placed in the field to be used during the flight, but these must be large enough to be seen from the air, and most drone operators only use pre and post flight calibration images.

The sensor should be held above the calibrated reference panel, making sure neither the sensor or operator are shading the reference panel and that light is not reflected onto the panel from any surrounding objects including the operator. Dark clothing helps to minimise light reflected from the operator. The reference panel must be kept clean and if it does get dirty it should be cleaned according to manufactures instructions.

4.3 Time of day and ambient light conditions (passive sensors)

As passive sensors use the sun as their light source, crop reflectance measurements will be affected by both the angle of the sun and ambient light conditions. It is recommended to collect crop reflectance data within 2-3 hours of solar noon when the sun is highest in the sky to minimise the effects of shadowing (solar noon = 12:00 GMT).

The best conditions for data collection are clear sunny days; if this is not possible aim for light overcast days when the variation in ambient light conditions is minimal. Try to avoid collecting data on partially cloudy days when passing clouds can cause large variations in light levels. If collecting data under partially cloudy conditions is unavoidable, try to wait for a large enough gap in the clouds before collecting measurements and/or

Figure 6. Frequent changes in light levels on partially cloudy days like this will affect crop reflectance measurements

take additional calibration measurements as light conditions change. Although many vegetation indices partially compensate for variations in ambient light conditions by calculating a ratio of crop reflectance between two or more wavebands, large variations in ambient light will still influence the results. In a recent paper, Assmann *et al*. (2018) estimated that cloud cover accounted for a 0.02 error in mean NDVI.

4.4 Geolocation

Geolocation or georeferencing is the process of attaching geographic positional data to the crop reflectance imagery. Georeferencing may not be required for data collected from hand held sensors from small plots, where it may only be necessary to record the plot identifier alongside the image or scan number. However, most drone and tractor mounted sensor imagery will need be geolocated.

Accurate geolocation is essential if that data is part of a time series or is to be compared or combined with other sources of geo-referenced data as it allows the different data layers to be precisely overlaid. Geolocation is also essential to identify plot or treatment areas if these are identified using GPS data.

Most drone mounted sensors will be linked to a GPS device on the drone which will record the co-ordinates of the sensor as each image is taken. However, most drone GPS systems have an accuracy of around +/- 2-3m, which is not sufficient to accurate overlay multiple data layers. An RTK-GPS drone will increase the accuracy of geolocation to within a couple of centimetres and will overcome this problem, however RTK-GPS drones are expensive. A common alternative is to use Ground Control Points (GCPs) in combination with standard drone GPS.

Ground Control Points are targets on the ground which can be seen in the image. The co-ordinates of the GCPs can be recorded using a handheld RTK-GPS device and combined with the drone GPS data to increase the geolocation accuracy from a couple of meters to a couple of centimetres. Generally, it is recommended to position 5 GCPs across the field of interest – one in each corner, but usually at least 20m from the field edge, and one in the middle of the field. However, more GCPs may be useful for larger fields or fields with varying topography. Note that if using QGIS software to process the imagery a minimum of 6 GCP points is required for geolocation.

An ideal GCP marker is a black and white checkerboard pattern which is easily visible in the image due to the contrasting reflectance from the black and white colours (Fig 8). These GCPs can be made easily using tiles and either black and white paint or vinyl stickers.

4.5 When to collect the data

The strength of the relationship between Vegetation Indices and crop yield or other crop parameter of interest often depends on crop growth stage. Therefore, it is important to consider when during the season or at what crop growth stage to collect crop reflectance data so that the data collected provides the best measure of crop yield/performance. This is discussed in more detail for each crop type included in the INNO-VEG project in part two of this guide.

Figure 7. Black and white checker board GCP in onion crop

As discussed in section 2.3, Vegetation Indices provide a measure of the above ground biomass, and therefore we usually provide the best measure of crop yield when above ground biomass is best correlated with yield. For most crops, the relationship with yield improves from establishment through to peak above ground biomass. For crops that are harvested before they sensence (i.e., vegetable brassicas, leafy salads) the best relationship with final crop yield may be close to harvest. For crops that senesce before they are harvested (i.e., potatoes, onions), the best relationship may be just prior to senescence. This was seen most clearly in onions, where the. Vegetation Indices and yield increased until the start of crop senescence and then fell significantly once the crop started sensing. However, crop reflectance data can also provide a good measure of crop senescence and can be useful if we want to measure crop senescence characteristics. This is discussed in more detail for potatoes in section 3 of this guide.

4.6 Other considerations

The following factors should also be considered when collecting crop reflectance data:

- The presence of weeds will affect the reflectance data. Ideally try and avoid measuring from areas with high weed cover as this may affect the results.
- Some vegetable crops are covered with plastic, fleece or netting to protect them from adverse weather or from pests. It is not possible to measure crop reflectance through these covers and they should be removed prior to measurement.
- Avoid taking crop reflectance measurements during or soon after irrigation as the water droplets will affect reflectance measurements and may affect background soil reflectance due to areas of wet/dry soil. Soil moisture content would not normally be an issue following rainfall, however irrigation can create an uneven pattern of wet and dry soil across the field which may affect reflectance measurements in some wavebands.
- If using a proximal handheld or tractor/vector mounted sensor make sure the 'field of view' of the sensor is targeted at the crop and that measurements do not include an unequal amount of soil and crop. Many vegetable crops are planted in rows or beds and measurements should be targeted to the centre of the beds/ rows to avoid the bare interrow strips. If this is not possible, you should make sure the proportion of crop and soil area in the field of view remains consistent during the measurements.

4.7 Ground truthing

Ground truthing is the process of checking or validating crop reflectance or Vegetation Index data with direct measurement of the crop in the field.

If a specific Vegetation Index has already been shown be well correlated to yield for a particular crop type, then it may not be necessary to ground truth the data and instead be sufficient to measure the impact of a treatment on the Vegetation Index as a proxy or indicator of yield.

However, if you want to quantify crop yield, then you will need to collect ground truth data from the field to provide a calibration (relationship) between Vegetation Index values and yield. Ideally you should collect yield data from a minimum of 5 GPS located points in the field to correlate to the Vegetation Index data and provide a calibration which can be used to estimate yield from the Vegetation Index data.

Box 3. Commissioning a drone survey

The use of UAVs is strictly controlled in Europe. Therefore, most farmers and researchers using UAV imagery will use a specialist UAV operator to collect the data. When commissioning a UAV survey it is important to provide clear information on the requirements for the survey. You should consider:

UAV provider: Use an established UAV company with experience of carrying out crop surveys.

Sensor used: Consider which Vegetation Indices you want to calculate before you commission the survey as this will determine which wavebands you need. Specify the sensor or the wavebands you require. If you are comparing data between surveys, make sure the same sensor is used for each.

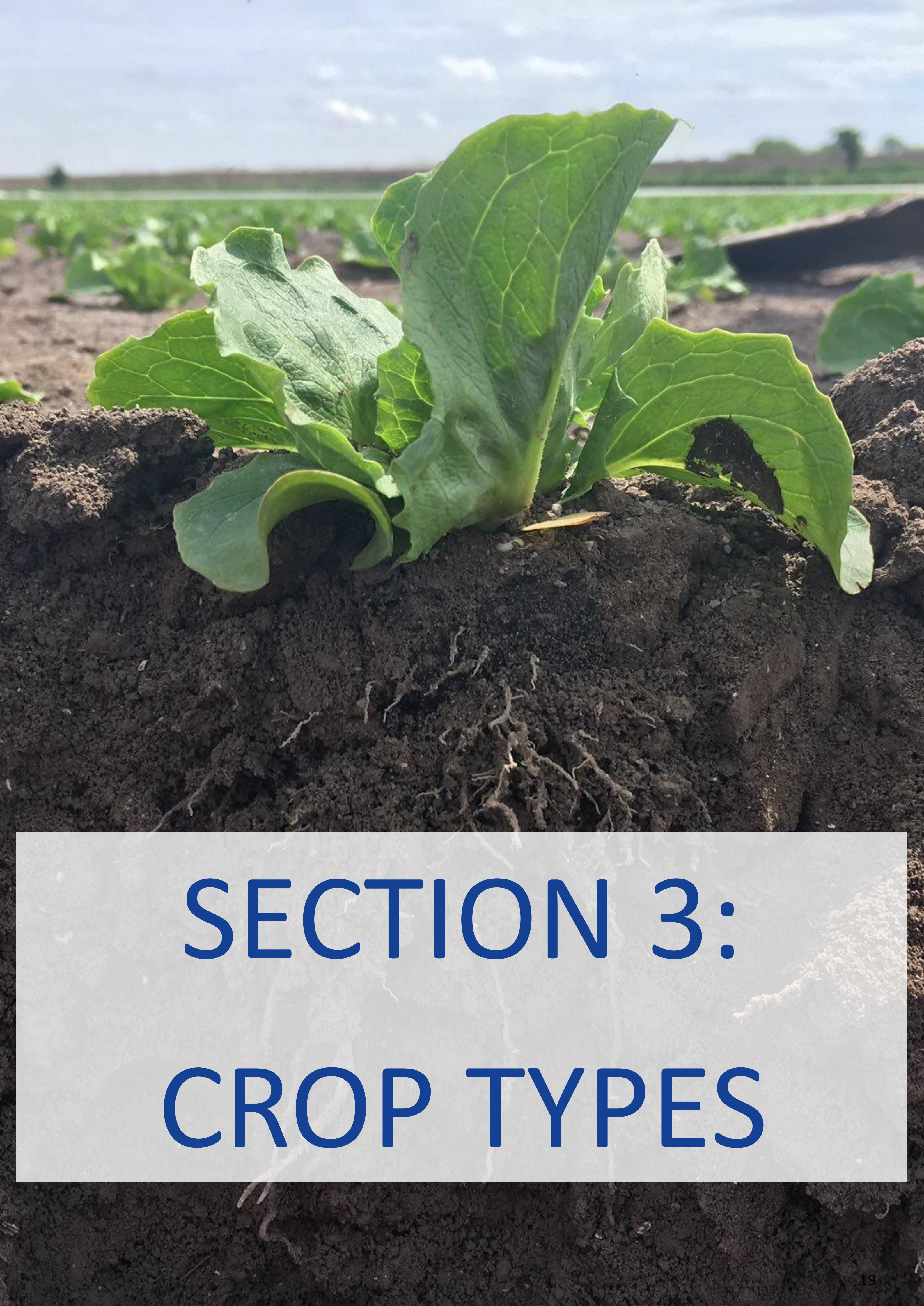
Survey area: Provide the area and location for the survey. Ideally provide the UAV company with the field or experiment boundaries as a shapefile or KML file.

Survey date: Specify the range of acceptable dates for the survey.

Image resolution: Discuss image resolution; UAVs are often capable of providing higher resolution data than is required, and higher resolution data will take longer to download and process.

Geo-referencing: Agree how the data will be geo-referenced and what level of accuracy is required. Standard UAV GPS is usually accurate to 2-3m (section 4.4). Agree where Ground Control Points (GCPs) will be positioned and who is responsible for positioning them.

Data processing: There are normally two stages to data processing. The first is the initial post processing of the images into a single orthomosaic map and geolocation of the image. This is normally done by the drone company using a photogrammetry software package such as Pix4Dmapper or Agisoft PhotoScan. The second stage is the extraction of crop reflectance data for specific plots or field areas and calculation of Vegetation Indices. Most drone companies will be able to process the data to provide this if required. Make sure you are clear on what processing you require, and how and in what format the data will be transferred to you. Alternatively, you may wish to extract plot data and calculate Vegetation Indices yourself using a GIS software package.



SECTION 3: CROP TYPES

Brassicas

Brassica vegetables include includes broccoli, Brussels sprouts, cabbage, cauliflower, collard greens, kale, and turnips. The INNO-VEG project included measurements on Brussels sprouts, cabbage, and cauliflower crops. These brassica vegetables are typically planted as transplants. Brussels sprouts are usually planted in the spring to summer period for a winter harvest. Cabbage and cauliflowers can be planted and harvested all year round depending on the local climate.

The INNO-VEG project included three experiments on Brussels sprouts in the Netherlands in 2019, two experiments on cabbage (one red and one white variety) in Belgium in 2019 and four experiments on cauliflower in the UK and Belgium in 2019.

Cauliflower: the four experiments on cauliflower investigated the effect of nitrogen fertiliser rate on yields and there was only a significant effect of treatment on yield at one of the four sites. At the site which showed a yield response to nitrogen fertiliser treatments, there was a strong and statistically significant relationship between vegetation indices and marketable yield with maximum R2 values of 0.55-0.65. At this site, there was a good relationship between vegetation index and yield on all measurement dates for the MTCI, CI Green, CI Red edge, NDRE and REIP vegetation indices. In contrast NDVI and MCARI2 showed a poor relationship with yield on two of the three measurement dates. At the three sites where there was no effect of nitrogen treatment, there was also no relationship between vegetation indices and marketable yield.

Cabbage and Brussels sprouts: All experiments showed a poor relationship between vegetation indices and yield. This may in part be because these experiments did not show a significant yield response to the treatments. Previous work done by INNO-VEG project partner ADAS (as part of a different project) has shown a relationship between vegetation indices and yield for Savoy cabbage and Brussels sprouts. Because of the poor relationship between vegetation indices and yield observed for brassica vegetations in this project, we recommend that anyone wanting to use crop sensing data to assess brassica crops should ground truth their data (section 4.7).

INNO-VEG project partner Delphy measuring crop reflectance from Brussels sprouts using a frame mounted multispectral sensor

Carrots

Carrots are a popular vegetable crop grown across Europe. Carrots are normally sown in beds and can be sown at different times of the year. First early crops are normally sown under polythene in late Autumn. Second early crops are also normally sown under polythene in the winter, typically from December to February. Main crop carrots are sown in the open from March to July. Harvest of the early crop begins in June. Some maincrop carrots are overwintered (often under straw to protect them from frost) and harvested the following spring.

The INNO-VEG project included eleven experiments on carrots across UK, Belgium and the Netherlands in 2019 and 2020 (two on second early carrots in the UK and the rest of main crop carrots). Some, but not all, experiments showed a statistically significant relationship between vegetation indices and marketable yield. The best relationships were measured in the second early crops in the UK with a maximum R^2 value of 0.73. However, most main crop carrot experiments showed lower R^2 values of around 0.2-0.5.

The NDVI vegetation index provided the overall best and most consistent relationship with marketable yield across the sites. Some of the other vegetation indices performed well at certain sites, although none were as consistent as NDVI.

The best relationship between the vegetation indices and marketable yield was obtained from measurements taken after canopy closure but before any senescence of the leaves.

Collecting crop reflectance data from carrots using a drone mounted sensor.

Courgettes

Courgettes are a fruiting crop which are typically planted as transplants between April and June. In the UK, most of the courgette crop is planted into black plastic to suppress weeds. Harvest starts around 2 months after planting of transplants. The courgettes are picked by hand every 2 to 3 days over a period of around 2 months. The courgettes are picked when they reach a specified size which is determined by buyer requirements. Marketable yield is measured both in total fresh weight and number of courgettes picked.

The INNO-VEG project included three experiments on courgettes in the UK in 2019. Each of these experiments investigated the effect of nitrogen fertiliser rate on yields and there was a significant effect of treatment at two of the three sites. At the two sites which showed a yield response to nitrogen fertiliser treatments, there was a strong and statistically significant relationship between all of the measured vegetation indices apart from MCARI2 and marketable yield (total fresh weight and number of courgettes harvested). There was not a relationship between the measured vegetation indices and yield at the third site, but this may be due to the lack of yield response to the treatment.

The best relationship between the vegetation indices and marketable yield was obtained from measurements taken in the middle of the harvest period with maximum R^2 values of 0.55 and 0.78 at each site.

Courgettes are normally planted in beds into black plastic to suppress weeds

Leady Salad

Lettuce and Spinach

Courgettes are a fruiting crop which are typically planted as transplants between April and June. In the UK, most of the courgette crop is planted into black plastic to suppress weeds. Harvest starts around 2 months after planting of transplants. The courgettes are picked by hand every 2 to 3 days over a period of around 2 months. The courgettes are picked when they reach a specified size which is determined by buyer requirements. Marketable yield is measured both in total fresh weight and number of courgettes picked.

The INNO-VEG project included three experiments on courgettes in the UK in 2019. Each of these experiments investigated the effect of nitrogen fertiliser rate on yields and there was a significant effect of treatment at two of the three sites. At the two sites which showed a yield response to nitrogen fertiliser treatments, there was a strong and statistically significant relationship between all of the measured vegetation indices apart from MCARI2 and marketable yield (total fresh weight and number of courgettes harvested). There was not a relationship between the measured vegetation indices and yield at the third site, but this may be due to the lack of yield response to the treatment.

The best relationship between the vegetation indices and marketable yield was obtained from measurements taken in the middle of the harvest period with maximum R^2 values of 0.55 and 0.78 at each site.

All measured vegetation indices provided a good relationship with marketable yield apart from MCARI2, which performed poorly at both sites. This may be due to spectral interference from the black plastic which the courgettes are planted into specific to this vegetation index, but this has not yet been tested.

Iceberg lettuce

Apollo lettuce

Leeks

Leeks can be grown from seed or transplants. Leeks have a longer growing period with some crops in the ground for up to 12 months. Planting typically starts during early spring and harvest takes place from July through to the following May. Marketable yields are typically 15-25 t/ha.

The INNO-VEG project included four experiments on leeks in the UK and Belgium in 2019. Each of these experiments investigated the effect of nitrogen fertiliser rate on yields and there was a significant effect of treatment at two of the four sites. At the two sites which showed a yield response to nitrogen fertiliser treatments, there was a strong and statistically significant relationship between all of the measured vegetation indices and marketable yield, with maximum R2 values of 0.5-0.6.

The best relationship between the vegetation indices and marketable yield were obtained from measurements taken closer to harvest, even for late harvested crops where measurements were taken overwinter. At both sites the first measurements taken sooner after planting showed the weakest relationship with yield, but all later season measurement taken within about 2 months of harvest showed a good relationship with yield.

All measured vegetation indices provided a good relationship with marketable yield, with none performing consistently better or worse when viewed across all sites. None of the vegetation indices developed a significant skewed distribution indicative of saturation of the index as the season progressed. Consequently, it is not necessary to try and select a Vegetation Index that does not saturate for leeks.

Collecting crop reflectance data from leeks using a drone mounted sensor

Onions

Most bulb onions are planted from seed or sets in beds. Most bulb onions are planted in the spring from around February and harvested in autumn typically in August or September. A smaller area of bulb onions are planted in early autumn, overwintered and harvested the following summer. Onions are ready for harvest when around 80% of the tops have fallen over and yields are typically 40-70 t/ha.

The INNO-VEG project included nine experiments on onions across UK, Belgium and the Netherlands in 2019 and 2020. Most of the sites showed a strong and statistically significant relationship between all of the measured vegetation indices and marketable yield

The best relationship between the vegetation indices and marketable yield was obtained from measurements taken just prior to when the onion tops started to bend over with maximum R2 values of 0.90. The proportion of variation in yield explained by the vegetation indices tended to increase up until this point and then dropped significantly after the tops had bent over.

All measured vegetation indices provided a good relationship with marketable just prior to the tops bending over, with none performing consistently better or worse when viewed across all sites.

The onion crop has a relatively low above ground leafy biomass and therefore the Vegetation Indices did not develop a skewed distribution or 'saturate' as the season progressed. Consequently, it is not necessary to try and select a Vegetation Index that does not saturate for onions

Bulb onions are planted in rows and grown in beds

Aim to take crop sensing measurements just **before** the onion tops bend over (as shown here)

Potatoes

The INNO-VEG project included potatoes trials in 3 countries (France, Netherland and Belgium) during years 2019 and 2020 (some are also scheduled for 2021).

The first results seem to show that sensor measurements can discriminate treatments like cultivar and Nitrogen fertilizer application rate, if these treatments imply different patterns in the last part of the potato growth cycle: the senescence phase. The investigations made in the trials showed different ways to phenotype the crop accordingly:

- Find one or two dates of measurement typical of the beginning of the senescence phase and use a VI directly linked to biomass in no a saturated cover crop. This could be achieved with a simple VI like NDVI. This technic implies to monitor the trial carefully to make the measurement not too early (when the crop cover is still full and green) and not too late (when the senescence is so advanced that most treatments are totally senescent).
- If the technology used allows it at a reasonable price, multiply the number of measurements during the growth cycle to obtain a full curve of sensor variable. By doing this, we could choose the best date to discriminate the treatments. And, more interesting, it could allow the experimental team to calculate some integrative indicators using the curve like the slope of the senescence phase or even the mathematical integral of the curve (the AUC = Area Under the Curve). This approach could be achieved with a single VI like NDVI but, too avoid the saturation problem in the middle of growth cycle, it is probably better to use some less saturating VI like CI-green or CI-rededge. These aspects will be investigated more deeply during the project .

INNO-VEG project partner Arvalis measuring crop reflectance from potatoes using a vehicle mounted hyperspectral sensor

Vining Peas

Vining peas are harvested fresh for canning or freezing. Pea yields are typically 6-8 t/ha fresh weight and the fresh weight pea yield is typically about 20% of the total harvested above ground biomass.

The INNO-VEG project included four experiments on vining peas in 2019 and 2020 in the UK; two on Amalfi and two on Oasis.

There was a statistically significant relationship between all of the measured vegetation indices and both total biomass and marketable yield at all sites.

The best relationship between the vegetation indices and marketable yield was obtained from measurements taken when the crop was at full flower around 2 weeks before harvest. The proportion of variation in yield explained by the vegetation indices tended to increase up until flowering and then decline slightly for the final measurements taken immediately before harvest.

All measured vegetation indices provided a good relationship with marketable yield at full flower, with none performing consistently better or worse when viewed across al sites. Maximum R^2 values at full flower at each site varied between 0.68 and 0.93.

Most of the vegetation indices showed an increasing right-skewed frequency distribution as the season progressed. Yield data tends to be normally distributed and a significant right skew to the vegetation index data can indicate saturation of the vegetation index. At all sites, the CI Green and CI Red Edge vegetation indices were closest to a normal distribution at full flower.

Aim to take crop sensing measurements when the crop is at full flower

ADAS

ARVALIS
Institut du végétal

Delphy

inagro
ONDERZOEK & ADVIES IN LAND- & TUINBOUW

west-vlaanderen
de gedreven provincie