Introduction

Remote and proximal sensing in plant science

Remote or proximal sensing defines the use of optical sensors, in combination with a carrier platform, to obtain information from objects in a non-invasive manner. Optical properties of plants provide valuable information on the health status, vitality or developmental stages of plants. The difference among remote-sensing and proximal-sensing technologies is mainly characterized by the distance between the measurement system and the object of interest.

Satellites or air-borne carrier platforms enable measurements of crop stands on the field level. Proximal sensors are used in a close distance of below 2 m between the measurement system and the crop stand or plant. With remote-sensing technologies, a bigger area can be measured in a short time frame, whereas proximal sensing is more time consuming but can provide detailed information from the object of interest. Remote and proximal sensing of crop stands to assess infestation with pest, diseases and nematodes by satellite or air-borne data have proven their potential in different systems. The recent progress in sensors and carrier platforms enables new options for agricultural investigations and operations.

Nowadays, unmanned aerial vehicle (UAV) platforms, combined with camera systems, are widely available and easy to operate. Furthermore, simple optical sensors are ubiquitous in mobile telephones, carried by all of us nearly all the time and at every place. In plant pathology and nematology, these techniques can be utilized to assess nematode infested crops. However, since the sensor techniques assess the upper plant parts and not infested root parts directly, technical setups have to be critically evaluated and data interpretation demands the expertise of a nematologist (Hillnhütter et al., 2012).

During the plant breeding process, plant phenotyping in the field is highly relevant. In breeding for nematode resistance or tolerance this process is rather complex, using a recurrent
selection over a series of generations, combined with soil and root samples to identify changes due to a nematode infestation and to assess the tolerance. In contrast to common visual rating and detection methods, optical sensors are able to measure pathogen-induced changes in the plant physiology non-invasively and objectively. Among different sensor types (thermography, chlorophyll-fluorescence, RGB, multispectral and hyperspectral), multispectral and hyperspectral sensors have significant potential and several advantages for monitoring plant diseases, pests and host–pathogen interactions (Mahlein et al., 2018). For reliable results, the entire system pipeline, consisting of the type of sensor, the platform carrying the sensor and the decision-making process by data analysis has to be tailored to the specific problem. This is a hurdle not only for researchers and companies, but especially for farmers. A practical context in the field for precision agriculture for nematode management is still challenging, but not impossible. In particular, state-of-the-art remote-sensing approaches, like the European Space Agency’s (ESA) Copernicus programme, enable access to satellite data with relevant information for agriculture.

Symptom development: physiological reactions influencing optical characteristics in nematode infested plants

Symptoms in plants infested by plant parasitic nematodes mostly are unspecific. Above-ground plant parts usually show symptoms like stunting, wilting, discoloration and deformation of shoots, stem, leaves or seeds. With the exception of root knot nematodes producing distinct galls, symptoms are even less specific in roots. Thus nematode damage is difficult to detect and usually remains unrecognized especially at early symptom development. Plants remain stunted and develop nutrient deficiency symptoms later in the season. Depending on climatic conditions, a disturbed physiological reaction in nematode infected plants usually induces foliage wilt that can be detected as a nematode focus in crops. Water deficiency in plants trigger stomatal conductance of leaves to reduce transpiration. Consequently, leaf surface temperature in nematode infected plants increases and thus was shown to correlate positively with nematode infestation (Joalland et al., 2017). The plant physiological reaction towards nematode infestation is also associated with reduced chlorophyll contents of leaves, and a reduced stomatal conductance leads to a reduced photosynthesis rate and a reduced plant turgor pressure. These reactions are visible as symptom more or less clearly delimited from non-infected areas in a crop. Stunting of plants might occur very early in the season but is best visible after formation of leaves and before the plant canopy is closed due to the fact that background soil produces an easily detectable contrast towards the non-infected surrounding.

Plants have a species- or even cultivar-specific trait in tolerating damage by nematodes. Tolerance towards nematode infestation appears to be a non-specific adaption towards water deficiency in plants like the development of a deep rooting system (Haverkort et al., 1992). Thus tolerant plants probably mask infestation by nematodes as they do not develop clearly visible symptoms. The same physiological wilt reaction in plants also occurs in shallow soil areas, in compacted soil or in connection with light soil types that only provides limited water availability. Early attempts in the 1980s to 1990s in Germany (Kochs, 2000) to use aerial infrared pictures for detection of beet cyst nematode foci in sugar beet crops worked successfully but required detailed interpretation to exclude artefacts like shallow hill tops and artificial embankments. From these experiences it also became evident that symptoms detected by infrared filter could be best identified after periods of rainfall in warm and sunny weather conditions during summer where non-infested field areas were well watered but beet cyst nematode infested plants showed wilting.

State of the art

Remote sensing with satellites: the opportunity for retrospective analysis and field planning

Controlling nematode diseases by the application of chemicals is difficult, and in many countries prohibited. Currently, resistant or tolerant cultivars and crop rotation strategies are common
to control nematode infestation. Over the years, adapted nematodes could be selected, due to continuous growing of resistant cultivars with the same genetic resistance. It is highly relevant to develop further methods and applications, which can be integrated into the current control strategies that are environmentally friendly and sustainable. In the age of digitalization, the precise detection of primary infection sites and disease dynamics are fundamental to make a decision for a subsequent management practice.

Since the European Space Agency’s Copernicus programme and the launch of their satellites SENTINEL-2A in June 2015 and SENTINEL-2B in March 2017, multispectral remote-sensing images are freely available in a sophisticated resolution for agriculture. The spatial resolution is up to 10 m per pixel. The spectral range is from 442–2200 nm with a resolution of 12 spectral bands. Besides environmental monitoring and vegetation observation, they enable monitoring for crop diseases and pests. Free data access is possible using different commercial software as well as with no-charge browser solutions like the EO Browser by the ESA (https://www.sentinel-hub.com, accessed 30 July 2020). The image frequency depends on the revisit frequency of each single SENTINEL-2 satellite, which is 10 days and in combined constellation 5 days. On a cloudless day, the image will be perfect to examine the field of interest. If clouds are present and cover the field of interest, between 5 and 10 days will pass before the image can be captured again (Fig. 58.1). For some plant diseases and pests this time span is critical and short-term applications in the field cannot be conducted, which is currently the main drawback of the free satellite data available. Nevertheless, for research investigations of plant breeding processes and retrospective field assessments, spectral images from a satellite are a real benefit to map landscapes with relevant crop and cultivation parameters, identify vulnerable spots, assess the vegetation period and the conducted measures for future precision field management.

From the perspective of plant protection, farmers of North Rhine-Westphalia and Norway can already use the H₂Ot-Spotmanar (http://synops.julius-kuehn.de/synops-2/#/dashboard, accessed 30 July 2020) to calculate the environmental risk for waterbodies and their living organisms due to specific plant protection measures, based on updated satellite data. Such applications indicate the manifold opportunities to use satellite data even with a resolution that cannot represent a single plant. Plenty of commercial field management programs that use satellite data are available. In these programs, farmers give access to their field data or their whole field index. These data are combined with weather and satellite data to give the farmer a complete overview and information (e.g., about plant nutrition, water status, plant healthy status and necessary protection) around their crop growing. In the near future, these programs could be trained to generate ‘computer-based solutions’ and consulting before and during the vegetation season.

Robots and drones: flexible in-field assessment

Recently, unmanned ground-based or air-based vehicles (UGV and UAV, respectively) equipped with sophisticated cameras have become increasingly relevant and available. These platforms are able to screen a field site automatically, with little human intervention (Fig. 58.1). This offers huge potential also for small-scale farmers. The main advantage of UAV or UGV applications compared to satellites is a comparatively higher spatial resolution. Due to the low distance between the object and the camera, the ground pixel size can be below 1 cm, which means that data can be assessed to the leaf or single plant level. This might help to differentiate between causal agents by changes in optical properties. UAVs may be so-called fixed wing or copters. Fixed-wing UAVs are able to fly over a higher area in short time, whereas copters offer the ability to hover across a specific area to do more detailed investigations. Regardless of the vehicle, in all cases the combination of the platform and the camera is crucial. UAVs and UGVs can be equipped with thermal cameras, simple RGB cameras or multispectral or hyperspectral cameras. For the assessment of stress and symptoms caused by nematodes, thermal and multispectral imaging offers huge potential, in combination with an adapted analysis pipeline.
Analysis and interpretation of remote-sensing data

Multispectral and hyperspectral images record the electromagnetic spectrum that is reflected from crops and the environment. The optical information summarizes the plant compartments, type of leaf, the surface texture, the leaf age, and so on. To extract relevant information on the crop status, the reflectance signature needs to be analysed and characterized. This can be done manually with a high human effort and

Fig. 58.1. A 7-hectare area with sugar beet in the Grevenbroich region of Germany. In contrast to the satellite image from 11 July, the image from 26 June can be used to examine the field of interest (EO Browser v3.0.20, ESA). In the marked area, sugar beet varieties with different tolerances to cyst nematode, *Heterodera schachtii*, are tested. The images below were taken with a drone (DJI Phantom 4, 12.4 megapixels 4k camera) from 30-m height over approximately 7 minutes. The spatial resolution is higher and enables an analysis in detail. Furthermore, the altitude of the drone can be changed to examine spots of interest. Arrows indicate the altitude of the sensor carriers and the spatial resolution per pixel. Author's own figure.
expertise. Data-driven and machine-learning approaches can reduce the labour intensity and could enable the detection of attributes on the images such as pre-detection and allocation of diseased crops. Among machine-learning approaches, unsupervised and supervised methods for classification and clustering can be applied. Unsupervised machine learning tries to find key patterns in the data without additional manual input. In contrast, supervised machine learning requires a set of labelled training data, which consists of described examples, e.g. image annotations and pixel allocations.

Further opportunity to visualize differences in the field is the combination and calculation of narrow or broad wavelengths ratios. These were developed to establish relationships of multispectral and hyperspectral reflectance signatures to plants and their biophysical variables in remote sensing. These are described as spectral vegetation indices and result in a reduction of data dimension. The Normalized Difference Vegetation Index (NDVI) is a common spectral index to assess plant vitality by the green biomass and chlorophyll content from remote sensing. The NDVI is a normalized difference calculation of reflectance from the near infrared (NIR) and from the red range \( \text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})} \). During the last decades, further spectral vegetation indices were developed and adapted for plant sensing approaches. The calculation of single indices as well as a combination can be used for a fast identification of nematode infested crops in multispectral and hyperspectral images. In addition, the characterization of susceptible and tolerant sugar beets against \( H. \text{schachtii} \) can be characterized in the field (Joalland et al., 2018). In common analysing software a pre-set of indices is given, which calculates indices by a cursor click. Machine-learning algorithms can be implemented into open-source software such as R or Phyton. A database for remote-sensing indices and satellite sensors can be found at https://indexdatabase.de (accessed 30 July 2020). This database is a useful tool to find the required index, sensor and application.

Case studies

The pine wood nematode (PWN), \( Bursaphelenchus \text{ xylophilus} \), is involved in the pine wilt disease (PWD) complex which is fatal to conifer trees primarily belonging to the genus \( \text{Pinus} \). The PWN enters mature trees via feeding sites of \( \text{Monochamus} \) spp. beetles. Nematodes rapidly invade large areas inside the tree which results in cavitations of the xylem vessels and rapid wilting, accompanied by physiological break down and distinctive discoloration of the foliage, which finally leads to complete defoliation. After invasion of PWN, susceptible mature trees die within a couple of weeks enhanced by higher temperatures and restricted water availability. Due to the fact that PWN is considered an invasive species, it is regulated via the EU eradication programme (2012/535/EU). Hence early detection is a major target to identify infested trees and delimit high-risk areas. An EU pilot study was conducted to establish the feasibility of the remote-sensing-based detection of trees affected by PWN in the 2.2 Mha buffer zone established along the border between Portugal and Spain (Beck et al., 2015). By analysing hyperspectral bands from aerial and satellite images, this study identified five wavelengths that are suitable for calculation of spectral indices to detect progressive stages of canopy decline: 450 nm, 490 nm, 670 nm, 710 nm and 800 nm. These indices include two reflectance band ratio indices, the (re) Normalized Vegetation Index, and a blue-green index. The study showed that repeated image acquisition at high resolution is required to distinguish trees with PWD from other damage as PWD shows rapid progression within weeks. Images should be georeferenced to spot out individual trees. Yet, current satellite image resolution restricts detection to trees with complete defoliation or canopy diameter of less than 2 m.

The sugar beet cyst nematode (BCN), \( H. \text{schachtii} \), is a major pest of sugar beet with high damage potential (see Chapter 55 in this volume). In several studies, physiological leaf symptoms of different sugar beet cultivars were detected using hyperspectral signatures (HSS) and the data was correlated to initial population densities \( (\text{Pi}) \) of BCN after processing via the Nemaplot-population model (Schmidt, 2015). \( \text{Pi} \) densities were pre-set by cultivation of resistant and susceptible catch crops prior to the sugar beet crop, resulting in \( \text{Pi} \) ranges between nearly zero and >5000 eggs and juveniles per 100 g of soil. HSS were detected using a handheld sensor connected to different spectrometers (Agrospec, ASD FieldSpec 4) at different times.
throughout the vegetation period between April and September. Wavelength data from HSS was transformed to numeric parameters and fitted to the Nemaplot model. Transformed data were analysed by multivariate methods as principal compound analysis and general linear modelling. A sufficient correlation ($r = 0.74–0.84$) was found in sensitive, but not in tolerant cultivars, between population densities assessed by the model and ground truth data. Effective wavelength was identified to be higher than 1100 nm. Due to the multiple interactions between BCN population densities, cultivar, year and vegetation period, measurements of HSS over time did not yield consistently good correlations at different vegetation stages.

**Outlook: a vision for the future**

The above-mentioned technologies offer huge potential for future nematode control. A new research project in co-operation between the Julius Kühn-Institute and Nemaplot is in development which aims to progress the Nemaplot model to detect the development of new virulent pathotypes of *Globodera pallida* early in the field, using reference data from the *Heterodera schachtii* model. This will be realized by correlating Nemaplot model processed data of hyperspectral signatures of various severely infected plants and plant stands with factors of climate, management and nematode population as a variation in time and space. Hyperspectral bands will be contributed to a databank for a collection of various host–pathogen systems which should serve as a source for further development of applications. Studies on detection of plant symptoms even in field scenarios by using remote-sensing technologies have demonstrated basic feasibility for many nematode pests like *Globodera pallida, H. glycines, H. schachtii, B. xylophilus* and *Rotylenchus reniformis* as well as *Meloidogyne incognita* both in cotton. However, most of the concepts are not yet established or integrated into decision support solutions and are still in their infancy or are prototypes. Depending on the crop, specific approaches need to be developed. An interpretation with agricultural expertise is a prerequisite. Detailed investigations and specific analytics of soil probes cannot be substituted by these technologies. Since tools for direct control of nematodes are limited, air-borne and imaging technologies can support the breeding process or field planning process.

For implementation into agricultural practice, the basic requirement is an intuitive data input, control, analysis and output. This is a hurdle for many farmers because of the manifold and intensive labour during the vegetation and the state-of-the-art technologies that need to be developed and performed by scientists and trained experts. It is more likely that these technologies become available to farmers via companies, start-ups or the advisory service. Small and simple solutions, as mobile phone-based services, e.g. farmerJOE or Xarvio for field management or the ISIP Leaf Scan for foliar disease identification, are already available. Satellite images are to some extent available for free, but standardized and easy analysis pipelines are still missing for the farmer. Nevertheless, the progress in digital technologies is extremely fast and digital transformation, where software development is only one aspect, is entering agriculture rapidly. We are curious how the invention of remote and proximal sensing in a farmer’s everyday work will proceed.

**References**


