Chapter 10
Remote Sensing for the Detection of Soil-Borne Plant Parasitic Nematodes and Fungal Pathogens

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Abstract This chapter reviews past developments and the present state-of-the-art remote sensing for the detection of soil-borne nematodes and plant pathogens. Nematodes and soil-borne pathogens are considered ideal targets for the application of precision agriculture with non-contact sensing methodologies. The clustered occurrence and low level of mobility of nematodes and pathogens in the soil and the induction of symptoms in the leaves make them perfect targets for remote sensing detection. Data obtained with infrared thermography and hyperspectral reflectance for the remote sensing of plant parasitic nematodes and root rotting fungi in sugar beet as well as delineation of complex-disease interactions is also presented. The management of these two pest groups usually relies on full field pesticide treatments, even when only a small section of the field is infested. This underscores the need for remote sensing of disease clusters and the resulting application of site-specific management.

1 Introduction

Remote sensing (RS) for the detection of damage caused by plant parasitic nematodes and/or soil-borne pathogens for optimization of integrated pest management is a 'best-fit technology'. There are a number of biological and technical factors that favor the use of RS for these two pest groups: (I) damage caused by root infections is visible in the foliage at different times in the growing season; (II) nematode and disease infestations are clustered in the field; (III) movement out of a cluster is slow due to low nematode and pathogen mobility; (IV) introduction of new infection loci into a field are rare; (V) precision detection used in one season can be applicable for future crops and (VI) chemical and biological control technologies are available that

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allow site-specific treatment. These control methodologies include: granular pesticides for targeted treatment, single and combined fungicide and nematicide seed treatments, biopesticide soil and seed treatments as well as resistant and tolerant varieties. The use of this knowledge to develop site-specific plant health management can significantly reduce yield losses due to these two pest groups and can lead to a high cost/benefit return for the grower.

Plant parasitic nematodes have been estimated to cause crop losses of up to 20% or approximately 100 billion US$ annually worldwide on crops such as cotton, soybean, cereals, tuber crops, legumes as well as fruits and vegetables (Cai et al. 1997, Luc et al. 2005). Crop losses due to fungal and bacterial pathogens, many of them soil-borne, also are reported to inflect annual losses of 7–15% in major field crops such as wheat, rice, potato, maize and soybean (Oerke 2005).

A major limiting factor in the use of precision crop protection technology has been the complex soil-ecosystem itself and the difficulty involved in prediction of nematode or disease occurrence. The analysis of soil samples to determine whether or not nematode densities exceed the action threshold is expensive and in some cases for technical reasons not feasible. In Germany the cost for analysis of a soil sample for the sugar beet cyst nematode *Heterodera schachtii* ranges from 24 to 61€, whereas in Iowa (USA) analysis of a soil sample for the soybean cyst nematode *H. glycines* can cost 15–60 US$ (Tylka 2006). The cost of analysis of soil samples to estimated pathogen thresholds by ELISA or PCR can range from 25 to 100€.

The number of samples and follow-up laboratory examinations needed on a per hectare basis to give a reasonable estimate of potential damage when the nematode or pathogen has a cluster distribution is large and costly. Therefore, in many instances threshold estimation is limited to one extraction from a single composite soil sample that produces an average infestation level over the entire field. Considering the total cost of sampling and lab analysis, the true dimension of crop loss and the cost of conventional full scale field application of a pesticide – the use of RS that leads to site-specific variable rate application would be more efficient, economical and environmentally friendly.

The use of newly developed and/or refined components of current precision agricultural technology such as RS and soil electric conductivity (EC_a) coupled with geo-information systems (GIS) allows instant detection and generation of digital maps that clearly represent the heterogeneous distribution of soil-borne nematodes and pathogens. Based on the information obtained with these measurements, either from previous crops in a rotation or prior to planting, precision crop protection decisions can be made and proper site-specific plant protection applied.

The use of high resolution RS equipment for the detection of insect and foliar pathogens in traditional field crops and agro forestry and has been reviewed elsewhere (Nutter 1990, Nilsson 1995, Stafford 2000, Zhang et al. 2002, Pinter et al. 2003, Lu et al. 2004). Our knowledge regarding the use of RS for detection and management of soil-borne plant parasitic nematodes and pathogens, however, is still poorly developed.

This chapter will: (I) review the state of the art of RS based on measurement of leaf and canopy reflectance for detection of nematode and pathogen damage; (II) present recent findings on RS for nematode and crown-rot in sugar beet; (III) give data on the discrimination of complex nematode-pathogen interactions; and (IV) discuss the need for future research in RS.

2 Review of Research on Remote Sensing of Plant Parasitic Nematodes and Soil-Borne Pathogens

Steddom et al. (2005) stated that RS is the practice of gathering information on an object without touching it and that most such technologies measure different parts of electromagnetic radiation such as heat or light. Plants depend on radiant energy for conversion of solar energy into organic substances. The leaf can absorb light in the visible part (VIS) of the electromagnetic spectrum (400–700 nm), where the spectrum of reflectance is quiet low, with a peak at about 550 nm in the green region. In the near infrared (NIR) short-wave region (700–1,400 nm) reflectance increases up to 50%, whereas in the long-wave (1,400–2,500 nm) reflectance decreases due to water absorbance. Leaves not only absorb and reflect light but light also is transmitted through the leaf. The far infrared (FIR) which starts at a wavelength of 5,000 nm is important in thermometry.

Disturbance or destruction of normal root functioning induced by soil-borne nematodes or pathogens causes decreases in the content of water, chlorophyll, carotinoids and anthocyanin levels in the leaves which simultaneously leads to shifts in reflectance of the electromagnetic spectrum or changes in leaf temperature. The use of reflectance in the NIR and FIR spectrum, therefore, can be effectively used to detect disease symptoms even before they are visible.

The first aerial images of damage caused by a soil-borne plant disease were made in the year 1927 when Taubenhaus et al. (1929) took pictures from an US Army airplane at an altitude of 75–150 m to detect symptom development of cotton root rot caused by *Phymatotrichum omnivorum*. Black and white panchromatic film sensitive to all wavelengths of VIS light and a light yellow filter were used for estimation of damage and yield loss. Once the use of aerial photography was established as a technique, false color infrared (IR) film, new cameras, films and filter combinations were developed and available for experimentation. The films were called false color, because healthy green vegetation appears red or pink on the positive photographic transparency. Infrared film is sensitive to light in the green and red regions at wavelengths of 500–700 nm and in the NIR region at 700–950 nm (Tarkington and Seren 1963). The first use of IR imagery for detection of plant parasitic nematodes was conducted in the early 1960s in citrus plantations by Norman and Fritz (1965) to detect the burrowing nematode *Radopholus similis* in citrus trees before visible symptom development. This work resulted in a reduction in sampling and the introduction of site-specific nematicide treatment. Heald et al. (1972) took IR aerial images of Texas cotton fields and were able to detect the reniform nematode *Rotylenchulus reniformis* as well as early symptoms of *P. omnivorum* root rot. Brodrick et al. (1971) examined the use of multispectral sensors that had a combination of four or more spectroradiometers. Each sensor records one scene of a small band which are then all combined to obtain the multispectral image. With this technique avocado trees infected with *Phytophthora cinnamomi* root rot were photographed from an altitude of 1,500 m which resulted in 100% identification of diseased trees verse only 80% with IR film. Gausman et al. (1975) using a spectroradiometer detected differences in cotton leaf reflection levels in nematode infested compared to control plants. Plants with high populations of *R. reniformis* showed lower leaf reflectance compared to the control plants in the wavelengths 500–2,500 nm. Leaves of the nematode parasitized plants were thinner and more compact in the inner cellular layers and therefore caused lower light reflection.

Pinter et al. (1979) conducted the first experiments on the detection of biological stress in plants by IR thermometry. The soil-borne root rotting pathogens *Pythium aphanidermatum* on sugar beet and *P. omnivorum* on cotton caused a measurable increase in leaf temperature of 3–5°C before visible disease symptoms occurred. Toler et al. (1981) and Lee (1989) published two short reviews on aerial IR imagery, economic cost-benefits and future perspectives of remote sensing. They summarized most of the work conducted on soil-borne organisms up to 1980.

Based on earlier work, Gebhardt (1989) demonstrated differences in water availability in agricultural crops by aerial thermometry. Plant parasitic nematodes and many soil-borne pathogens cause reduced water uptake in infested plants. A decrease in water uptake results in decreased leaf transpiration and influences overall plant temperature which is usually lower than the surrounding environment. The decreased transpiration due to biotic stress causes an increase in leaf temperature that is detectable by IR thermometry.

IR thermometry has been sporadically used in nematology. Berg (1980) working in nematode infested sugar beet fields in Germany and in Italy was able to differentiate *H. schachtii* infested symptomless patches from healthy areas. Gebhardt (1984) also showed differences in canopy temperature of potato plants infested with the potato cyst nematode *Globodera rostochiensis*. On winter wheat Nicolas et al. (1991) detected significantly higher canopy temperatures in areas moderately infested with *H. avenae* as compared to low infestations and considered this effect to be caused by increased stomatal resistance.

Using multispectral video imagery Cook et al. (1999) were able to discriminate between damage by the root-knot nematode *Meloidogyne incognita* and root rot due to *P. omnivorum* alone as well as in combination. This was the first attempt to detect a complex-disease interaction with RS.

Heath et al. (2000) conducted experiments to predict the number of *G. pallida* and *G. rostochinensis* parasitizing potato plants using non-destructive hyperspectral measurements. High correlations were found between the numbers of juveniles per gram of potato roots and the Normalized Difference Vegetation Index (NDVI) values calculated from handheld FieldSpec® FR (Analytical Spectral Devices Inc., Boulder, USA) spectroradiometer reflectance data. Hyperspectral sensors offer contiguous band placement over a wide spectral range and are superior to multispectral sensors with fewer spectral bands (Schowengerdt 1997).

The development of narrowband hyperspectral sensors was an important development in RS due to the greater amounts of data obtained. With the combination of

GIS and RS technologies Nutter et al. (2002) was able to map the spatial distribution of soybean cyst nematode, *H. glycines*, in soybean fields. Appropriate calibrations were made for different atmospheric conditions by collecting data at different times in the growing season simultaneously by satellite, aircraft and ground-based multispectral sensors. With the same nematode and crop but increasing nematode densities, Asmus and Ferraz (2002) tried to detect differences in leaf area, leaf color, photosynthetic rate and chlorophyll fluorescence in greenhouse trials. Leaf area, chlorophyll content and photosynthetic rate were reduced by *H. glycines*.

Wheeler and Kaufman (2003), however, obtained negative results in the prediction of *M. incognita* damage in cotton by IR aerial imagery. At that time, multiple flight campaigns and data analysis for variable-rate nematicide application was more expensive than uniform treatment of the entire field. Using multispectral canopy and hyperspectral leaf reflectance data Steddom et al. (2003) were unable to differentiate differences between yellowing of sugar beet leaves due to a lack of nitrogen and the yellowing caused by rhizomania, a soil-borne virus disease.

Lawrence et al. (2004) using aerial and handheld hyperspectral sensors to detect *R. reniformis* in cotton and data analysis with the MATHLAB program in combination with self-organizing maps developed by Kohonen (1998), obtained a prediction accuracy that ranged between 83 and 97%. They suggested the need for research on the effects of different soil types and in scaling leaf level measurements into a commercially viable orbital or suborbital system to validate the robustness of this approach (Lawrence et al. 2007).

Hyperspectral data is highly adaptable to the identification of soil-borne pests and diseases because of the higher amount of data available as a result of the narrower bands and the possible use of hyperspectral vegetation indices. In addition, the identification of the most sensitive bands of hyperspectral data for a specific pest group seems promising. Rupe et al. (2005) for example, isolated four bands out of 300 which were most responsive to *H. glycines* in soybean fields. These bands were found in near range reflectance by the Maximum R^2 procedure. Hillnhütter and Mahlein (2008) noted the importance not only of high spectral resolution, but also that spatial resolution and the temporal factor are important in detection of small areas in a field before yield loss increases.

3 Remote Sensing of Nematodes and Fungal Root Rot in Sugar Beet

The European Union is one of the world's most important sugar producers with a yearly harvest of 19–20 million tons. The vast majority of this sugar is obtained from the sugar beet *Beta vulgaris*. Sugar beet covers 2.1 million hectares and is 1.4% of the agricultural area (European Commission 2006). Sugar beet will become even more important as the need for bioethanol production increases.

The cyst nematode *H. schachtii* is a major constraint to the sugar beet crop in most European countries. The nematode is found in all sugar beet growing regions and losses of up to 50% have been reported. Management of the nematode is very important, but varies from country to country and includes the use of: rotation with non-hosts, resistant and tolerant cultivars, resistant green manure break crops and the use of nematicides (Schlang 1991). *Rhizoctonia solani* crown and root rot is the most important soil-borne disease impacting yield (Kiewnick et al. 2001). Yield losses can range from 5 to 10% in the EU and USA (Büttner et al. 2004). Control is usually attained by planting tolerant cultivars or through the use of fungicides even though the latter are only partially effective. In most cases field symptoms develop in patches due to the clustering nature of the pest and the disease. In some cases both pests occur simultaneously in a field. This makes *H. schachtii* and *R. solani* ideal for RS and site-specific application of pesticides, biopesticides and the site-specific sowing of resistant cultivars to reduce input costs and increase yield.

The sugar beet crop is highly suited for RS analysis because it is a complanate growing plant with a planophile leaf structure. Furthermore, there is a direct relationship between root development and plant vitality (Nowatzki et al. 2009). This makes *B. vulgaris* a good target for research into the use of RS for control of nematodes and fungi. In addition, damage to the root has direct effects on the leaves (Franke 1997). The sugar content of the beet also is negatively affected by root damage or direct damage to the root by both pest groups. The development of complex-diseases when these two pests simultaneously infect the plant also can lead to synergistic interactions and additional root damage and crop loss.

Very few studies have been conducted on the use of RS for the detection of soil-borne pests in sugar beet. *Heterodera schachtii*, studied by Sanwald (1979) using IR aerial images resulted in the lack of significant changes in spectrometric reflectance. Using high spatial resolution digital multispectral video Hope et al. (1999) detected root rot in sugar beet caused by *R. solani*. Their goal was to use reflectance data to determine the most valuable vegetation index for classification of sugar beet root rot. The NDVI developed by Rouse et al. (1974) was considered the best predictor of root rot infestation and is the most commonly used vegetation index. Spatial and temporal distribution as well as the economic impact of *R. solani* on sugar beet using multi- and hyperspectral, airborne and handheld data was successfully used to differentiate infected areas within a field (Laudien et al. 2004). The integration of a multi-temporal knowledge based approach might increase detection of a disease. The use of an internet based spectral library for diseases is also important and was simulated by Laudien et al. (2006).

Investigations in the field, greenhouse and climate chambers were conducted in Germany on the use of IR thermography and leaf reflectance for the detection of *H. schachtii*, *Ditylenchus dipsaci* and *R. solani* in sugar beet. The use of thermal imaging has been shown to be suitable for the detection of foliar plant pathogens elsewhere (Chaerle et al. 2004, Lindenthal et al. 2004, Oerke et al. 2006, Lenthe et al. 2007) and is discussed in Chapter 11. Research using IR thermometry to detect soil-borne organisms is less developed (Pinter et al. 1979). Schmitz (2005) showed significantly higher leaf temperatures in sugar beet varieties susceptible to *H. schachtii* (Table 10.1). The nematode parasitizes the roots of the plants over the entire growing season, producing a cell syncytium responsible for disruption

Table 10.1 Mean leaf temperature of the nematode susceptible sugar beet cultivar Monza inoculated with increasing densities of *Heterodera schachtii* over time (growth period 2003, Schmitz 2005)

Nematode density [eggs and juveniles per 100 ml soil]	Time of assessment			
	June 13th	July 17th	July 29th	August 7th
<500	21.45°C a	24.87°C a	25.30°C n.s	35.63°C n.s
500–1,500	21.86°C ab	25.08°C ab	25.41°C n.s	36.37°C n.s
>1,500	22.28°C b	25.28°C b	25.76°C n.s	36.53°C n.s

Means with different letters in one column are significantly different, Tukeys HSD-Test ($p < 0.05$; $n = 10$), n.s. = not significant

of the xylem tissue and reduction in nutrient and water uptake. Nematode damage results in stunted growth, leaf yellowing and wilting under water stress conditions. Nematode infestation, therefore, is responsible for a significant reduction in leaf transpiration which leads to increased leaf temperature. These symptoms usually appear in elongated patches in the field or in bands caused by soil cultivation later in the growing season.

Significant differences also were detectable between the lowest and highest nematode density in greenhouse tests (Table 10.1) as well as in field experiments (Schmitz et al. 2004a, Schmitz 2005). These results confirmed those obtained by the European Community in Germany and Italy in the early 1980s (Berg 1980). On potato Gebhardt (1984) showed significant canopy temperature differences induced by *G. rostochiensis*. However, Schmitz et al. (2004a) were the first to show these canopy temperature differences in sugar beet induced by *H. schachtii* by aerial images taken with a helicopter from an altitude of 200 m at a correlation of $r = 0.6$ (Fig. 10.1).

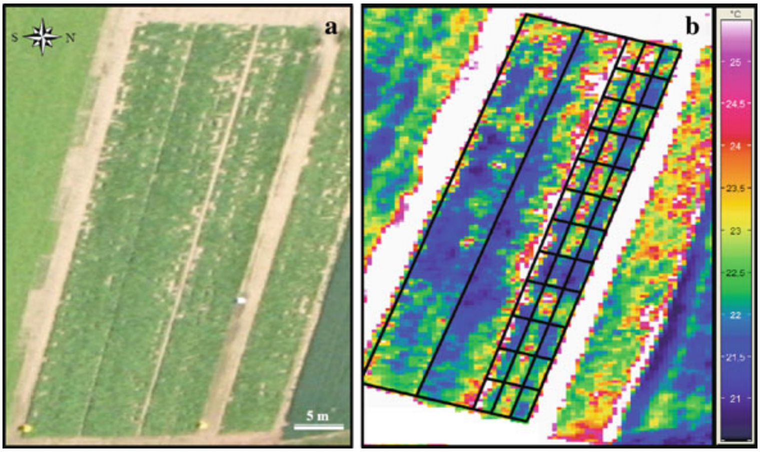

Fig. 10.1 Digital RGB picture (**a**) and digital IR thermography picture (**b**) of a field infested with pre-adjusted *Heterodera schachtii* population densities in the rectangular plots (Schmitz 2005)

Laser-induced chlorophyll fluorescence (LIF) and also pulse amplitude modulated chlorophyll fluorescence (PAM) are two other non-contact methods used to detect biotic and abiotic plant stress (Lichtenthaler and Miehé 1997, Apostol et al. 2003, Asmus and Ferraz 2002, Cervantes-Martínez et al. 2002, Chaerle et al. 2004). LIF and PAM are methods that gather data on photosynthesis and chlorophyll content (Tartachnyk and Rademacher 2003). Schmitz et al. (2006) conducted greenhouse experiments to test LIF and PAM for the detection of damage caused by increasing densities of *H. schachtii* on sugar beet. Plants showed a strong reduction in CO_2 assimilation with increasing nematode densities. Nematode infection led to a degradation of leaf chlorophyll in later stages of infestation and led to an increase in the F_{680}/F_{740} ratio and ground fluorescence (Fo) and a decrease in photochemical efficience (Fv/Fm) (Schmitz et al. 2004b). Discrimination analysis of the combined data from LIF and PAM resulted in a 100% correct classification of control plants and 60–100% classification of nematode infested plants at all sampling dates (Schmitz et al. 2006).

A sugar beet field study using IR picture was conducted in an experimental field with pre-adjusted preplant nematode densities in an attempt to estimate damage in the growing season and this damage to the preplant densities (Schmitz et al. 2003). The field was divided into 4 × 5 m quadrates, whereby each quadrate had a different infestation level of *H. schachtii*. The NDVI was calculated by using the near IR and the red bands of the IR picture with a spatial resolution of 70 cm for each pixel. Their results showed differences in spectral patterns between the infested and healthy sugar beets by supervised classification of the IR picture, but were unable to detect differences caused by the pre-adjusted nematode densities. The preplant densities were probably not sufficiently large enough for this type of separation (Fig. 10.2).

The use of precision agriculture techniques to detect *H. schachtii* damaged sugar beets for site-specific treatment can be complicated by the simultaneous infestation with the stem nematode *D. dipsaci*. This nematode causes high yield losses in

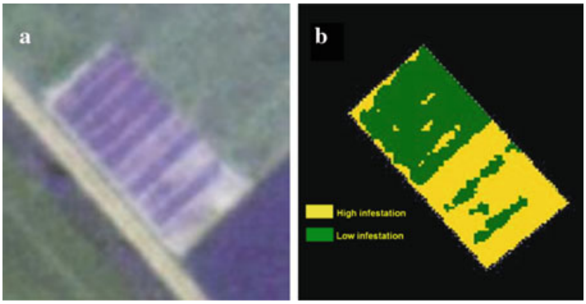

Fig. 10.2 IR airborne image (**a**) of a sugar beet field infested with *Heterodera schachtii* in 1999 (provided by LIZ: Landwirtschaftlicher Informationsdienst Zuckerrübe/Elsdorf), (**b**) Spectral classification into high and low nematode infestations (Schmitz et al. 2003)

central European sugar beet production areas (Kühnhold et al. 2006). Symptoms include malformed and bloated cotyledon petioles and swollen stem tissue. As the season progresses the beet develops cankers and secondary fungal infections (Dunning 1957, Griffin 1974). A correlation between soil clay content and the occurrence of *D. dipsaci* was observed by Seinhorst (1956).

Mapping of spatial nematode distribution by electric conductivity (EC_a) values and variable rate nematicide application for precision plant protection were successfully used in the USA for the root-knot nematode (*M. incognita)* and the ectoparasite *Hoplolaimus columbus* by Muller et al. (2002) and for root-knot and the reniform nematode (*R. reniformis)* on cotton (Wolcott et al. 2004, Davis et al. 2008, Lawrence et al. 2009) see Chapter 24. Estimation of the effects of soil type on the spatial distribution of the stem nematode, *D. dipsaci,* and the cyst nematode *H. schachtii* were investigated for the first time in field trials in Germany (Kühnhold, Kiewnick and Sikora unpublished data) using EM38 (Geonics Limited, Ontario, Canada) measurements. The EM38 measures apparent EC_a of the soil and leads to production of geo-referenced maps of EC_a (Mertens et al. 2008). According to Sudduth (2005) and Friedmann (2005) the main parameters which correlate directly or indirectly with EC_a values are clay and sand content, soil moisture, soil salinity and organic carbon.

In 2005, Kühnhold, Kiewnick and Sikora (data unpublished) used Spatial Analyses by Distance Indices software (SADIE®, Perry 1995) to analyze aggregation and spatial correlation of nematodes with soil properties. The nematode count data and the cluster indices obtained with SADIE® are presented in Fig. 10.3 in a geo-referenced map. The results provided new insights into the spatial distribution

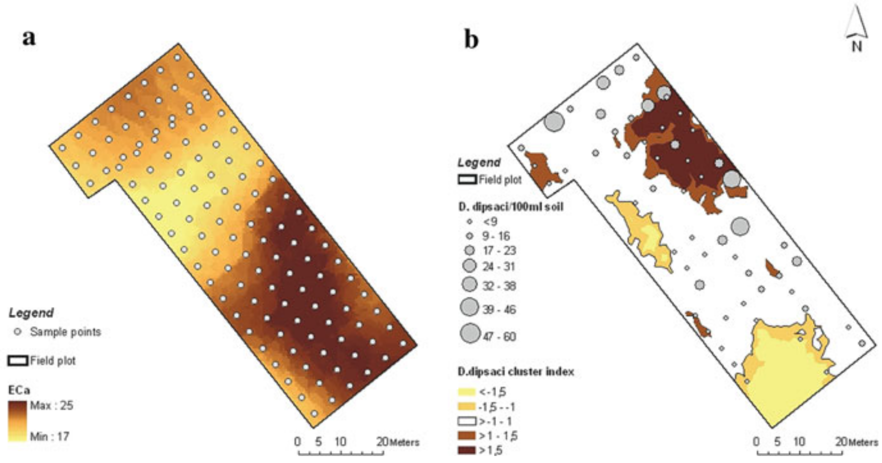

Fig. 10.3 Sample points and apparent electrical conductivity (EC_a) of the sampling area (**a**), spatial distribution of *Ditylenchus dipsaci* counts and the interpolated SADIE cluster analysis (**b**) (Kühnhold, Kiewnick and Sikora, unpublished data)

of *D. dipsaci* and *H. schachtii* in sugar beet. The data demonstrated that site-specific management is an appropriate tool for *H. schachtii* management. However, no clear correlation was found between EC_a values and the nematode densities of the two species. The differences in EC_a values characterizing soil properties (range 8 mS s^{-1}; Fig. 10.3) is considered to be low (Domsch and Giebel 2004). In contrast, Scholz et al. (2009) established a good correlation between the density of *H. schachtii* and EM38 values in sugar beet fields. This discrepancy may be due to the greater range of EC_a values within the field investigated by Scholz et al. (2009). They detected the highest density of cysts of *H. schachtii* in the sandy soils as identified by EM38 values.

The number of interactions that can occur between nematodes and pathogens in the sugar beet rhizosphere is great and such interactions can distort RS efficacy if only a single pest is targeted. To determine whether or not RS can be applied to complex interactions Hillnhütter et al. (2009) used hyperspectral data acquisition on sugar beet plants grown in the greenhouse inoculated with *H. schachtii* or *R solani* alone and in combination. Similar experiments were conducted with *D. dipsaci* and *R. solani.* Data was recorded with a handheld spectrometer with a foreoptic contact probe and a leafclip holder (ASD FieldSpec® Pro, Analytical Spectral Devices Inc.). The results showed that disease-complexes can be detected by hyperspectral measurements. The plants treated with *H. schachtii* and *R. solani* exhibited accelerated disease development over the plants inoculated with only one pathogen (Fig. 10.4). In addition, a *Rhizoctonia* crown and root rot rating index was developed to detect correlations between disease etiology and vegetation indices in order to find the most suitable index for pathogen development and disease severity. IR thermal images also were recorded. The results supported the findings obtained with hyperspectral measurements (Fig. 10.5).

Further experiments with an imaging hyperspectral line sensor in combination with a mirror scanner (ImSpector V10, Spectral Imaging Ltd., Oulu, Finland) also were conducted with the nematode-fungal disease complex. ImSpector captures a line image of a target and disperses light from each line image pixel to spectrum. Each spectral image then contains line pixels in the spatial axis and spectral pixels in the spectral axis. With this imaging system, a more detailed analysis of etiopathology was obtained (Hillnhütter et al. 2010).

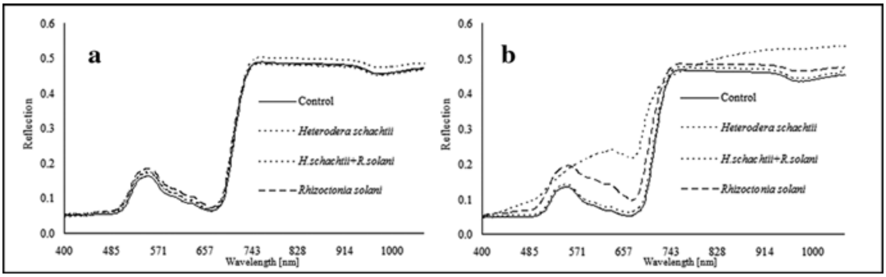

Fig. 10.4 Effect of *Heterodera schachtii*, *Rhizoctonia solani* alone and in combination on spectral reflectance of sugar beet plants, (**a**) 0 dpi, (**b**) 14 dpi (Hillnhütter et al. 2009)

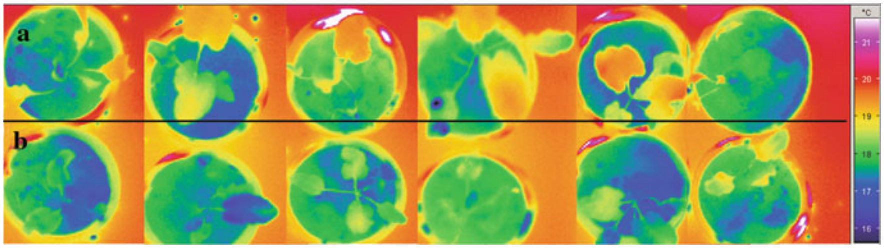

Fig. 10.5 Infrared thermographic images of sugar beet plants inoculated with *Rhizoctonia solani* showing *orange* and *yellow* leaf coloring (**a**) compared with non-inoculated *green* to *blue* control plants (**b**) 9 days after inoculation

4 Outlook

Experience obtained in the past with remote sensing to determine temporal and spatial distribution of nematodes and soil-borne diseases has produced a significant amount of baseline information. The development of new sensor technology will stimulate fundamental and applied research that will significantly improve RS and site-specific treatment methodologies for integration into plant protection programs. The research results presented here for two sugar beet nematodes and fungal crown rot demonstrated that RS and the use of site-specific application of crop protection is feasible in sugar beet production. In addition to economic benefits of this technology, improved environmental protection would be considerable. Nematodes and soil-borne fungal pathogens are good targets for site-specific control, because of clustered forms of aggregation, limited mobility and characteristic aboveground symptoms. Detection and localization of these organisms in clearly delineated patches in a field and the fact that these patches are reasonably stable in long term rotations over many years makes site-specific management to prevent yield losses a long term proposition.

However, improvements in the analysis of hyperspectral data are still required. This will require evaluation of larger amounts of data and the need for expanded computer capacity (Lawrence et al. 2004). The detection of spectral wavebands for specific symptoms caused by soil-borne pathogens and nematodes is also required. Such wavebands could be identified by simple or multiple regressions, principal component analysis or by partial least squares regression analysis. These disease-specific wavebands could be derived from spectra obtained under environmentally controlled conditions and then adapted to field situations. Based on these wavebands, indices could be calculated in order to predict the damage of each organism in the growing season. In addition, disease-specific wavebands also may allow detection of complex-disease interactions.

Collecting and analyzing soil and root samples for quantitative determination of nematode and pathogen action threshold levels is extremely expensive and in many cases still impractical. The costs incurred through sampling and the waste often associated with full scale field application of pesticides could be greatly reduced if multiple biotic stress factors and the clusters could be effectively detected by sensor technology. The future use of new megaspectral sensors coupled for example with PCR or ELISA would also improve site-specific plant protection acceptability (Ophel-Keller et al. 2008). These technological developments could make precision plant protection of soil-borne nematodes and pathogens a reality in the near future.

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