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Research Paper

Spectral assessment of two-spotted spider mite damage levels in the leaves of greenhouse-grown pepper and bean

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The two-spotted spider mite (*Tetranychus urticae* Koch; TSSM) feeds on the under-surface of leaves, piercing the chloroplast-containing cells and affecting pigments as well as leaf structure. This damage could be spectrally detectable in the visible and near-infrared spectral regions. The aim was to spectrally explore the ability to assess TSSM damage levels in greenhouse-grown pepper (*Capsicum annuum*) and bean (*Phaseolus vulgaris*) leaves. Several vegetation indices (VIs) provided the ability to classify early TSSM damage using a one-way analysis of variance. Hyperspectral (400–1000 nm) and multispectral (five common bands) data were analysed and cross-validated independently by partial least squares-discriminant analysis models. These analyses resulted in 100% and 95% success in identifying early damage with hyperspectral data reflected from pepper and bean leaves, respectively, and in 92% with multispectral data reflected from pepper leaves. Although the TSSM activity occurred on the underside of leaves their damage can be spectrally detected by reflected data from the upper side. Early TSSM damage identification to greenhouse pepper and bean leaves, that their sole damage was by TSSM, can be obtained by VIs, hyperspectral data, and multispectral data. This study shows that by using sub leaf spatial resolution early damage by TSSM can be spectrally detected. It can be potentially applied for greenhouses as well as fields as an early detection method for TSSM management.

1. Introduction

The two-spotted spider mite (*Tetranychus urticae* Koch; TSSM) feeds on various plants; currently 1110 host species have been reported worldwide outdoors as well as in greenhouses (Migeon & Dorkeld, 2015). Annual yield losses can be severe: 15% for strawberries in the USA, 14% for maize in France (Attia et al., 2013) and 20–45% for okra fruit in India (Kumar, Raghuraman, & Singh, 2015). To provide protection from solar ultraviolet light, to allow better web construction, and to protect itself from predators, the TSSM spends most of its time

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Nomenclature

ANOVA	analysis of variance
B	blue spectral region or band (490 nm)
G	green spectral region or band (560 nm)
GLSW	generalised least squares weighting
GNDVI	green normalised difference vegetation index
HD	high damage
LD	low damage
LVs	latent variables
MD	medium damage
ND	no damage
NDVI	normalised difference vegetation index
NIR	near-infrared spectral region or band (790 nm)
NRENDVI	near-infrared red-edge normalised difference vegetation index
PLS-DA	partial least squares-discriminant analysis
R	red spectral region or band (666 nm)
RE	red-edge spectral region or band (715 nm)
REBNDVI	red-edge blue normalised difference vegetation index
REGNDVI	red-edge green normalised difference vegetation index
REIP	red-edge inflection point
TCARI	transformed chlorophyll absorption reflectance index
TGI	triangular greenness index
TSSM	two spotted spider mite
VI	vegetation index
VIP	variable importance in projection
VIS	visible
ρ_i	reflectance, transmittance or absorbance in i wavelength (nm) or band

on the under-surface of leaves (Sakai & Osakabe, 2010) where, amongst other activities, it lays eggs and feeds. Feeding occurs by piercing the chloroplast-containing cells in the mesophyll layer (Fraulo, Cohen, & Liburd, 2009), thus decreasing the leaf chlorophyll content. Nihoul, Vanimpe, and Hance (1991) presented a positive exponential correlation between TSSM density and leaf damage, while Alatawi, Margolies, and Nechols (2007) found a correlation between cumulative TSSM density and leaf damage. The severity of the damage as inflicted by the amount and rate of change in leaf chlorophyll depends on TSSM density and duration of feeding (Alatawi et al., 2007) and the defensive reaction of the plant host (Kant, 2006). Leaf damage caused by TSSMs can be seen by the human eye and therefore can be potentially detected by spectral means in the visible (VIS; 400–700 nm) spectral region. The spectral data obtained from a leaf is influenced by the chemical, as well as the physical, properties of the leaf. The leaf spectrum is highly affected by pigmentation in the VIS region (Yoder & Pettigrew-Crosby, 1995; Zhao et al., 2014), while the near-infrared (NIR; 700–1000 nm) region is mainly influenced by the cell arrangement and density (Gausman, 1985; Karnieli et al., 2013). The red-edge (RE) region, located between the red and the NIR wavelengths of vegetation reflectance, is known to be sensitive to chlorophyll content (Curran, Dungan, & Gholz, 1990). TSSMs feed by piercing cell walls and consuming their content; through this process, they change the leaf chemical and physical properties, potentially allowing the identification of TSSM damage by the VIS and NIR spectral regions (Herrmann et al., 2012; Mirik et al., 2006; Reisig & Godfrey, 2007). Therefore, it was hypothesised that, under the optimal plant growth conditions that can be provided in greenhouses, spectral measurements of the upper surface of the leaves, in the range of 400–1000 nm, can lead to TSSM damage identification.

Previous studies have mainly explored the spectral relationship to the number of arthropods (Fitzgerald, Maas, & Detar, 2004; Mirik et al., 2006; Reisig & Godfrey, 2010; Yang, Rao, Elliott, Kindler, & Popham, 2009). Since TSSM are mobile and can move from leaf to leaf as well as to other plants the focus of the current study was on the damage level they inflict. Although it was not possible to find a unique spectral signature for TSSM or aphid stressed cotton at the leaf scale (Reisig & Godfrey, 2007), Yang et al. (2009) reported ability to separate between stress inflicted by greenbug (*Toxoptera graminum*) and the Russian wheat aphid (*Diuraphis noxia*) on wheat at the canopy scale using multispectral means. This separation ability was based on comparisons made for equal durations after infestation by both pests. There were no results presented or discussion regarding damage levels. If optimal growing conditions are available for plants in a greenhouse, the main stress sources to identify will be insects and diseases. Small-scale studies using close range devices for sub-leaf analysis are useful as a first step towards large-scale applications by ground, airborne, and even satellite-based sensors on the canopy or sub-field level (Reisig & Godfrey, 2007). Since TSSMs prefer young leaves (Nihoul et al., 1991) that are usually found at the outer part of the canopy, TSSM damaged leaves can potentially be identified by spectral devices with adequate spatial resolutions.

Specific bands or vegetation indices (VIs) sensitive to damage inflicted by a particular species of arthropods or stress have not yet been discovered (Fitzgerald et al., 2004; Mirik et al., 2006; Reisig & Godfrey, 2007; Yang et al., 2009). Lan, Zhang, Hoffmann, and Lopez (2013) research has determined four bands (550, 560, 680 and 740 nm) that are important for detecting the spectral differences among mite-infested cotton plants treated with various levels of miticide. They concluded that the amount of miticide used for spider mite control can be reduced, since applying a half dose of miticide resulted in the same spectral reflectance of infested cotton plants as the full portion. Spider mites can rapidly develop resistance to pesticides (Dekeyser, 2005); therefore, other control methods should be considered. Another method of pest control, mainly used in greenhouses, is to release their natural enemies in order to suppress the pests (Legowski, 1966). Nansen, Sidumo, Martini, Stefanova, and Roberts (2013) presented results that showed a negative relationship between potassium content in dry leaf matter and the attractiveness of maize leaves to mites. Since the relative reflectance of 740 nm was revealed to be significantly negatively correlated with potassium content, it was suggested that this reflectance could be used for pest infestation risk assessment.

It is essential to detect insect damage as early as possible in order to facilitate efficient corrective action (Fraulo et al., 2009; Yang et al., 2009). Identification of TSSM damage should be