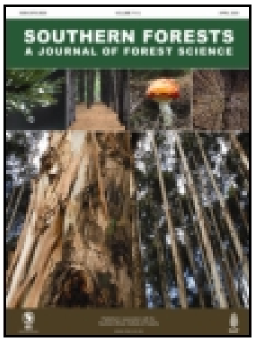

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The potential of remote sensing technology for the detection and mapping of *Thaumastocoris peregrinus* in plantation forests

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Thaumastocoris peregrinus is a sap-sucking insect that feeds on eucalyptus leaves. It poses a major threat to the forest sector by reducing the photosynthetic ability of the tree, resulting in stunted growth and even death of severely infested trees. The foliage of the tree infested with *T. peregrinus* is usually seen to turn a reddish brown colour starting at the northern side of the canopy but progressively spreading to the entire canopy. The monitoring of *T. peregrinus* and the effect it has on plantation forest health is essential to ensure productivity and future sustainability of forest yields. Internationally, a number of studies have successfully used remote sensing technology to monitor forest damage. Remote sensing technology allows for instantaneous methods of assessments whereby ground assessments would be impossible on a regular basis. This paper provides an overview of how advances in remote sensing technology can be used to detect and map the different stages of *T. peregrinus* infestations using multispectral and hyperspectral scanners. The challenges and future research regarding the mapping and detection of *T. peregrinus* are also discussed. It is concluded that remote sensing techniques need to be tested, improved upon and applied for the successful detection and monitoring of *T. peregrinus* infestations.

Keywords: hyperspectral, multispectral, *Thaumastocoris peregrinus*

Introduction

Thaumastocoris peregrinus is one of the new emerging invertebrate pests found in exotic *Eucalyptus* commercial plantations (Button 2007). *Thaumastocoris peregrinus* originates from Queensland, Australia, and has recently taken on pest populations in *Eucalyptus* species in South Africa and Argentina (Jacobs and Neser 2005, TPCP 2007). It is a small (2–4 mm) sap-sucking insect that feeds on *Eucalyptus* leaves. It poses a major threat to the forest sector by reducing the photosynthetic ability of the tree, resulting in stunted growth and even death of severely infested trees (FAO 2007). The monitoring of *T. peregrinus* and the effect it has on plantation health is essential to ensure productivity and future sustainability of forest yields on a global scale.

Current methods used to identify *T. peregrinus* infestations involve field-based studies whereby foresters and taxonomists visually confirm their presence. The use of field-based surveys to identify infested trees are costly, time consuming and spatially restrictive. Furthermore, the effectiveness of visual assessments are questionable because they are qualitative, subjective and depend on the skill of the surveyor (Ismail 2009). A number of studies have used remote sensing technology to monitor forest damage (Ekstrand 1994, Fraser and Lativofic 2005, Ismail et al. 2007, Macomber and Woodcock 1994, Radeloff et al. 1999). Remote sensing technology allows for instantaneous methods of assessments whereby ground assessments would be impossible on a regular basis (Ceccato et al. 2001, Datt 1999). Advances in remote sensing technology such as hyperspectral imagery combined with greater availability and lower cost of high-spatial-resolution imagery provide opportunities to detect and map forest pests (Coops et al. 2003). Once developed and tested, remote sensing can be applied operationally and can improve the ability to detect and map insect infestations (Coops et al. 2003). However, for remote sensing technology to accurately detect and map *T. peregrinus* infestations, knowledge of the symptoms of *T. peregrinus* across leaf, canopy and landscape level is required in order to relate infestations to different spatial and spectral resolution data. Knowledge of these symptoms will allow for the development of algorithms to detect changes in foliar characteristics using remotely sensed data. This paper provides an overview of the potential of remote sensing technology in detecting and mapping *T. peregrinus* infestations. There has been no specific review on the use of remote sensing applications for the detection and mapping of *T. peregrinus*. Hence, this paper focuses specifically on the potential of remote sensing technology to detect and map *T. peregrinus* infestations by drawing on previous work undertaken on the remote sensing of forest pests in general.

The biology of *T. peregrinus* and its impact on forest plantations

Thaumastocoris peregrinus is a member of the Thaumastocoridae, which is a small family comprising six genera and 15 described species (Jacobs and Neser

2005). The pest was originally identified as *T. australicus* by Jacob and Neser (2005) until Carpintero and Dellape (2006) described the species as *T. peregrinus*, which is morphologically similar to *T. australicus*. The identification of the *Thaumastocoris* pest in South Africa has been confirmed as *T. peregrinus* through genetic testing and in consultation with taxonomic specialists (FAO 2007).

Thaumastocoris peregrinus (Figure 1a), also known as the 'bronze bug', is a gregarious, sap-sucking bug that has become an economically important pest in the *Eucalyptus* plantations of South Africa (FAO 2007). The bug is now found in all *Eucalyptus* growing regions and is feeding on the majority of the commercially available *Eucalyptus* species and clones in younger and older trees (TPCP 2007). The female bug lays eggs in clusters on *Eucalyptus* leaves where they are visible as black spots (Figure 1b). The presence of such black spots is often the easiest way to identify infested trees (Jacobs and Neser 2005). The female bug produces about 60 eggs in her life cycle, which lasts for about 35 d. The symptoms of infestation are referred to as 'winter bronzing' or 'winter dieback'. The symptoms of infestations are visible annually but they vary depending on location. Figure 2 shows a monitoring trial carried out by the TPCP throughout the *Eucalyptus* growing regions of South Africa revealing that *T. peregrinus* infestations vary according to site (TPCP 2008a).

The *Eucalyptus* hybrids that are affected by the bug in South Africa are *E. grandis* × *E. camaldulensis* and *E. grandis* × *E. uropylla*, and *E. smithii* and *E. grandis* are also found to be severely infested (Nadel et al. 2007). Trees and leaves that are lightly infested may show little or no sign of damage. Heavily infested trees display a reddening of the leaves and have a 'washed out' pale appearance when affected. According to Jacob and Neser (2005), heavily infested trees drop their leaves and branches may die back or the entire tree may die. The infested trees, however, do appear to recover when *T. peregrinus* populations are reduced as soon as unfavourable conditions for their survival occur (Button 2007). Table 1 shows the stages of *T. peregrinus.*

There are currently no effective control measures in operation and no insecticides have been registered for use against infestations of this insect (Jacobs and Neser 2005). Biological control is currently deemed to be the only viable possibility to control *T. peregrinus* populations (TPCP 2008b). This is the chosen route taken to deal with most forest pests because it offers a safe and effective means to reduce insect population (Nadel 2007). Research on biological control of *T. peregrinus* is being currently carried out by the Tree Protection Co-operative Programme (TPCP) with the recent discovery of the egg parasitoid *Cleurchoides noackae*. Due to scarcity of information about the parasitoid more research regarding the biology and host preference is still to be undertaken (TPCP 2008b). However, successful implementation and testing of these control measures depends on the ability to spatially quantify trees affected by *T. peregrinus*. Additionally, there is a need to spatially quantify *T. peregrinus* infestations so that forest managers can take appropriate intervention before the death of severely infested trees. The mapping of *T. peregrinus* in plantation forests is therefore essential to detect trees that are infested and to ensure forest sustainability.

Mapping *T. peregrinus* using remote sensing

Remote sensing technology has been explored as a cost-effective and instantaneous method of assessing insect infestation (Fraser and Lativofic 2005). The ability to detect *T. peregrinus* infestations in plantation forest using remote sensing would be beneficial to several aspects of plantation forest management including timber harvest and salvage operations. The early detection of *T. peregrinus* infestations would provide forest managers with rapid assessments of current damage so that stands of high mortality can be salvaged. Furthermore, remote sensing technology provides the opportunity to study *T. peregrinus* damage over large areas so that outbreaks can be related to other environmental parameters using spatial modeling techniques in a geographic information system (GIS) environment. Environmental variables such as rainfall, altitude and host species will give insight on the build up and decline of *T. peregrinus* populations thus enabling future outbreaks to be modeled.

Forest damage usually appears as a change of colour on the forest canopy. The foliage of trees that are infested by insects changes colour from green to yellowish red and these trees are referred to as faders (Ciesla 2000). In advanced stages of insect infestation whereby defoliation begins, the forest canopy takes on a red-brown or grey hue. The ability to detect subtle changes in the colour of the forest canopy is a key requirement when using remote sensing methods to detect and map forest damage (Ciesla 2000). When light interacts with leaves it may be reflected, absorbed and/or transmitted. Leaves that depict changes in colour, reflect a different spectral response in the electromagnetic spectrum as compared to healthy leaves (Carter and Knapp 2001). Figure 3 shows the reflectance between a healthy and a discoloured leaf caused by *T. peregrinus* infestation indicating lower reflectance throughout the spectrum owing to the effects of chlorosis. Leaves that undergo stress and discoloration because of the loss of chlorophyll show an increase in reflectance in the visible portion of the electromagnetic spectrum (400–700 nm) (Carter 1993).

Trees that undergo defoliation show a decrease in reflectance across the electromagnetic spectrum owing to an increase of shadow and background within the field of view (Schmidt 2003). Barry et al. (2008) used a series of spectral indices to evaluate discolouration and defoliation on eucalypt species under controlled conditions. When defoliation treatments in *E. globulus* or stress in *E. pilularis* resulted in large differences in leaf cover, indices such as the red edge, normalised difference vegetation indices (NDVIs) and the modified chlorophyll absorption ratio index 2 (MCARI2) were strongly correlated with leaf cover. Red leaves resulting from stress were strongly correlated with anthocyanin reflectance index (ARI) and the red-green index (RGI) in *E. grandis* and *E. pilularis* leaves (Barry et al. 2008). Crown discolouration (chlorosis) and defoliation along with a reduction in leaf area index (LAI) are therefore two important indicators of stress in eucalypts (Barry et al. 2008). Spectral indices such as the red edge, normalised difference indices and LAI need to be tested upon at leaf, branch and tree level in *T. peregrinus* infested plantations to assess the importance in upscaling to airborne and spaceborne platforms.

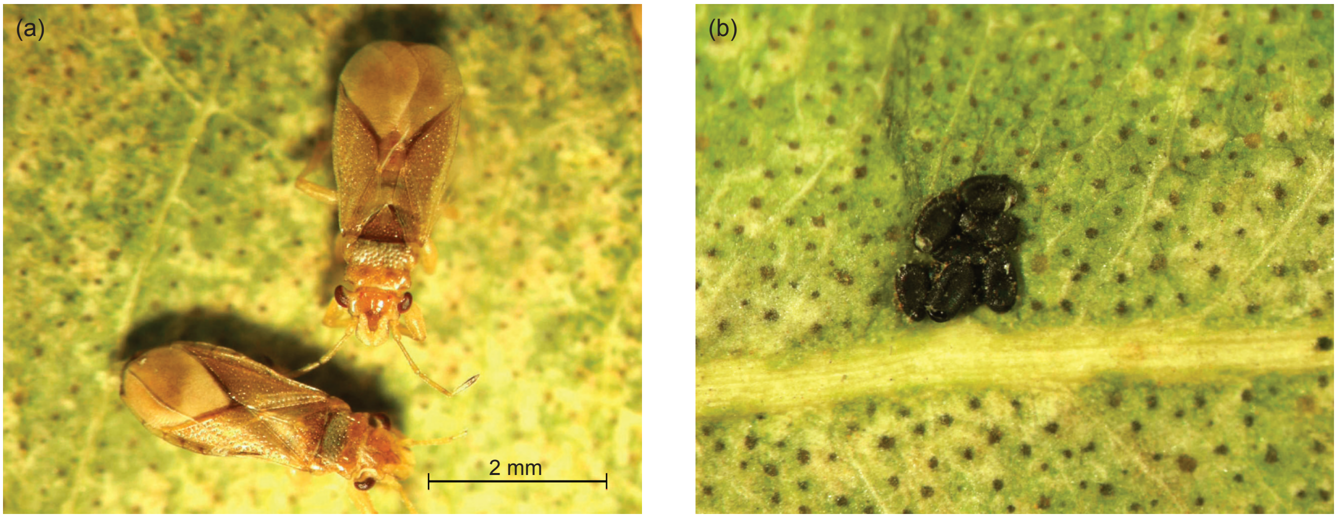

Figure 1: *Thaumastocoris peregrinus* (a) and presence of eggs (b) on *Eucalyptus* leaves (Nadel 2008)

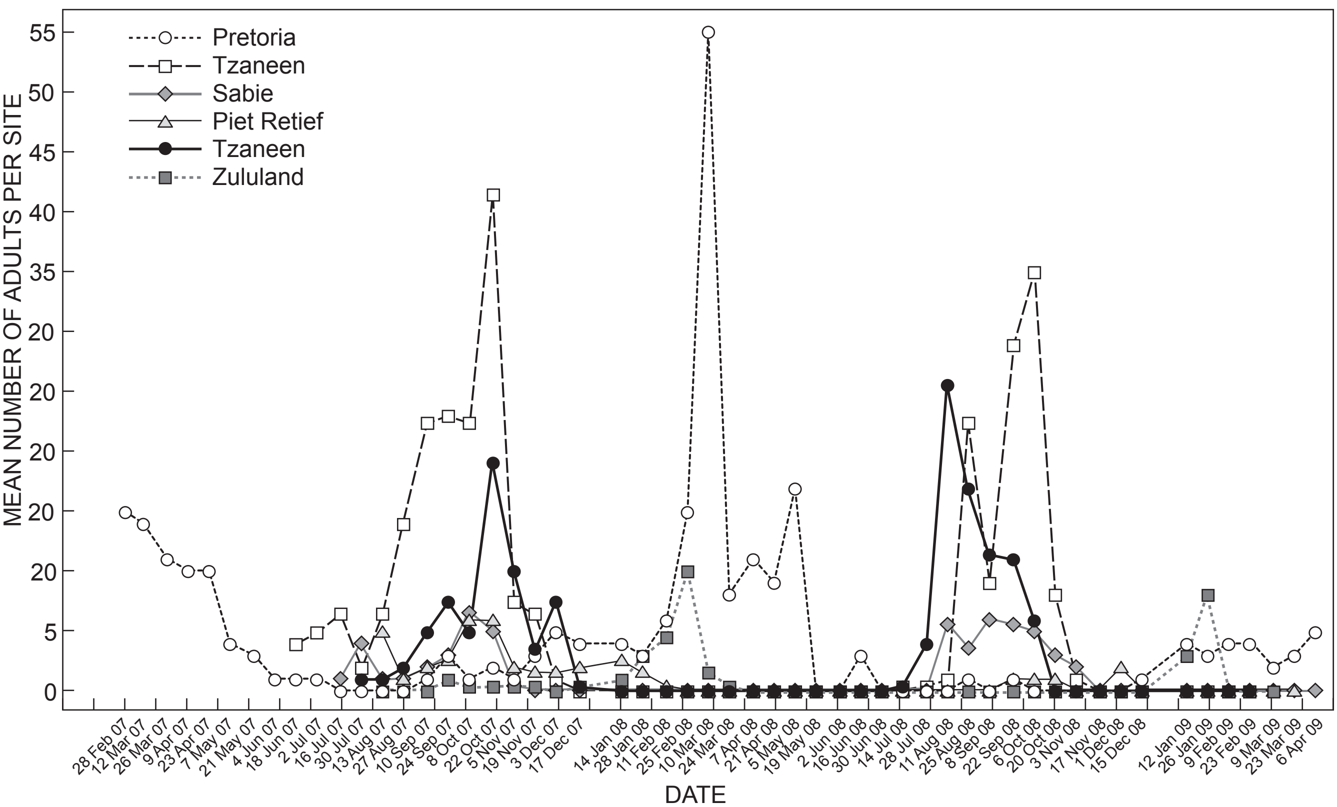

Figure 2: Monitoring trial carried out by the Tree Protection Co-operative Programme over a two-year period showing fluctuations of *Thaumastocoris peregrinus* populations in the *Eucalyptus* growing regions of South Africa (TPCP 2008a)

Various remote sensing airborne and spaceborne scanners have been developed to map forest damage based on the reflectance properties of the electromagnetic spectrum (Radeloff et al. 1999, Coops et al. 2003, 2004, White et al. 2005, Coops et al. 2006, Dye et al. 2008, Ismail 2009). Table 2 shows the different scanners that are commercially available and their respective spatial, spectral and temporal resolutions. The temporal coverage of a specific image allows for the monitoring and spread of forest damage over time. Sensors such as Landsat Thematic Mapper (TM), which has a repeat coverage of 16 d, have been used to create transition maps that indicate the extent of forest damage over time (Bonneau et al. 1999). Other sensors that have shorter revisit times, as indicated in Table 2, can be

Table 1: Symptoms of *Thaumastocoris peregrinus* infestation

Stages of infestation	Symptoms
Light infestation	
 Source: Nadel (2008)	Trees and leaves that are lightly infested may show little or no sign of damage.
Heavy infestation	
 Source: Jacobs and Neser (2005)	Trees that are heavily infested turn a deep red-brown colour, starting at the northern side of the canopy, sometimes referred to as 'winter bronzing'. Canopy has a 'washed out' pale appearance when heavily infested (Jacobs and Neser 2005).
Very severe infestation	
 Source: Nadel (2008)	Trees that are severely infested result in defoliation and die back of branches and in some cases the trees die (Jacobs and Neser 2005).

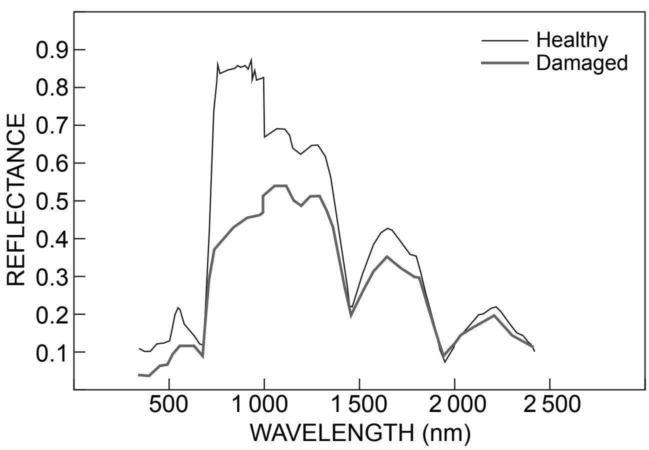

Figure 3: Reflectance of a healthy and a discoloured *Eucalyptus* leaf caused by *Thaumastocoris peregrinus* infestation

promising to assess the spread or seasonal variation in *T. peregrinus* infestations. This will serve as a spatial guide in monitoring *T. peregrinus* outbreaks. The next section will discuss how various remote sensing scanners that differ in spatial and spectral resolution can be applied to detect and map the different stages of *T. peregrinus* infestation.

The detection and mapping of *T. peregrinus* using multispectral scanners

Multispectral remote sensing has been used to collect data of the Earth's surface from airborne or spaceborne platforms since the 1960s (Landgrebe 1999). Earth observation technologies such as satellites provide local to global coverage of remote areas where ground assessments are impossible on a regular basis. Different sensors are onboard Earth observation satellites and may be used to monitor vegetation, forestry, water and other natural resources.

Table 2: Commercially available scanners and their resolutions

Satellite/sensor	Spatial resolution (m)	Spectral resolution	Temporal resolution (repeat coverage) (d)
Landsat 7 + ETM	30	Blue, green, red, near-infrared and mid-infrared	16
ASTER	15	Visible near-infrared, shortwave-infrared, thermal-infrared	16
Quickbird 2	2.44	Blue, green, red, near-infrared	1–3.5
IKONOS	4	Blue, green, red, near-infrared	3
World View2	2	Blue, green, red, near-infrared, red-edge, coastal, yellow, near-infrared 2	1.1
SPOT 5	10	Green, red, near-infrared, shortwave-infrared	2–3
GeoEyE 2	1.65	Blue, green, red, near-infrared	2–3

Table 3: Selected studies using multispectral satellite imagery for disease detection

Study/reference	Satellite	Method	Results
Identifying changes in hemlock forest health infested with the woolly adelgid (Bonneau et al. 1999)	Landsat TM	Classification and temporal analysis	A series of transition maps that indicate how forest damage changed over time
Detecting defoliation levels of jack pine budworm (Radeloff et al. 1999)	Landsat TM	Spectral mixture analysis	Increase in near-infrared reflectance in defoliated stands, strong negative correlation between images and budworm population ($r = -0.94$)
Mapping insect-induced defoliation caused by eastern hemlock looper (Fraser and Lativofic 2005)	SPOT Vegetation	Change detection using logistic regression model	Mapped insect-induced tree mortality in forest patches larger than 5–10 km^2
Estimating mountain pine beetle attack (Bentz and Endreson 2003)	Landsat, ETM, IKONOS	Classification based on linear discriminant analyses, quadratic discriminant analysis, regression trees and *k*-nearest neighbour	IKONOS image achieved lowest misclassification rate and over 95% red trees were correctly classified
Detecting red attack stage of mountain pine beetle (White et al. 2005)	IKONOS	Unsupervised classification	70.1% accuracy for low attack and 92.5% for medium attack
Assessing red attack damage due to mountain pine beetle (Coops et al. 2006)	Quickbird	Classification and vegetation indices	Relationship between red attack pixels and red crowns based on an independent validation set resulted in $r^2 = 0.48$, error = 2.8 crowns

According to Coops et al. (2006), satellite remote sensing has the ability to detect advanced stages of insect infestation over large spatial areas owing to physiological changes present in the infested forest stands.

During the heavy and severe stages of *T. peregrinus* infestation the canopy turns a reddish colour and the foliage changes to a yellow-brown colour coupled with the loss of leaves. This yellowing effect whereby the leaves change colour is known as chlorosis as the green chlorophyll pigments are lost and the canopy exhibits a reddish colour (Ekstrand 1994). Stone et al. (2001) state that leaves that undergo insect damage succumb to a variety of processes that include damage or removal of the waxy cuticle, destruction of cell walls, reduction of moisture and a decline in chlorophyll content. The decline in the chlorophyll content reduces the photosynthetic ability of the tree and in severe infestation rates large areas of forest lands are lost. The change in canopy colour of the infested trees will exhibit a different spectral response in the visible and near-infrared regions of the electromagnetic spectrum. Multispectral systems commonly collect data in three to six spectral bands within the visible and mid-infrared regions of the electromagnetic spectrum and have been applied to detect and map advanced stages of insect infestation (White et al. 2005, Coops et al. 2006). Table 3 summarises selected studies that have used multispectral satellite imagery to map insect damage.

Several authors have used medium spatial resolution imagery, which collects data between 4 and 30 m to accurately detect and map insect damage with accuracies ranging from 70% to 85% (Ekstrand 1994, Franklin et al. 1995). Ekstrand (1994) used Landsat TM data to assess forest defoliation in stands comprising Norway spruce. The results showed that the best estimate of forest defoliation was acquired with an algorithm based on Landsat TM band 4. Fraser and Latifovic (2005) used SPOT Vegetation imagery to map tree defoliation and mortality caused by insect infestation in Canada. A logistic regression model based on satellite change metrics was developed to map defoliation and mortality. The results indicated that coarse spatial resolution imagery can be effective in mapping large-scale forest mortality caused by insect infestation and can also be used for real-time monitoring of severe defoliation but with 2–3 times greater error of commission (Fraser and Lativofic 2005). Bentz and Endreson (2003) used Landsat TM, Enhanced Thematic Mapper (ETM) and IKONOS imagery to predict pine mortality caused by mountain pine beetles. Bentz and Endreson (2003) argue that medium spatial resolution imagery such as Landsat (30 m) is not suitable for the detection of endemic-level populations of insect damage and is more suited for detection at the building or epidemic phases of infestation. Medium spatial resolution imagery therefore has drawbacks due to the limited bandwidth, errors of commission and its inability to detect individual or small groups of infested trees (Bentz and Endreson 2003; Fraser and Lativofic 2005). In terms of *T. peregrinus*, medium spatial resolution imagery can be used to detect large outbreaks of infestations in the heavy stage as *T. peregrinus* is usually found across the whole compartment. The commercial availability of high spatial resolution satellite data offers the potential to detect and map individual or small groups of insect infestation compared to medium resolution imagery (Coops et al. 2006).

Coops et al. (2006) have shown that high spatial resolution satellite imagery has the ability to detect and map advanced stages of insect infestation with relatively high accuracies, as data is collected between 0.5 and 4 m. Coops et al. (2006) used Quickbird high spatial resolution satellite imagery (2.4 m) to detect and map mountain pine beetle red attack. Quickbird pixels that were classified as red attack were significantly correlated with the number of tree crowns identified as red attack damage. Bentz and Endreson (2003) used IKONOS high spatial resolution satellite imagery (4 m) to detect individual or small groups of pine mortality with relatively high accuracy as compared to Landsat imagery. The results suggest that high spatial resolution satellite imagery offers an alternative to medium resolution imagery for the location and estimation of advanced stages of insect damage. Ismail et al. (2007) also used high spatial resolution multispectral airborne imagery to detect and map *Sirex noctilio* (Eurasian woodwasp) infested plantations. The study demonstrated the potential of using high spatial resolution airborne imagery coupled with vegetation indices to discriminate between healthy and infested trees. Airborne imagery is advantageous in that it offers the potential to mobilise quickly at user-specified locations as compared to satellite imagery, which often has shorter times available for detection (Ismail et al. 2007). This is essential for forest health monitoring as insect outbreaks are often linked to disturbance in compartments or climatic events making the date of image acquisition important (Stone and Coops 2004, Ismail et al. 2007).

High spatial resolution satellite imagery offers the potential to accurately detect and map advanced stages of insect infestation with greater accuracies and reduced errors of commission. This is promising for the detection of the heavy and severe stages of *T. peregrinus* infestation using classification and statistical techniques combined with spectral indices so stands can be salvaged before they reach a point of non-recovery (Coops et al. 2004, 2006, Ismail et al. 2007). However, even though medium and high spatial resolution satellite imagery have been successful in detecting and mapping moderate to severe stages of infestation, the early detection of insect infestation using these technologies have been difficult (Coops et al. 2003, Pontius et al. 2005). The strength of any forest health monitoring program would be greatly improved if it were possible to detect the initial, often previsual, strain that is caused by insect infestation (Coops et al. 2004). Remote sensing developments in hyperspectral technology have overcome the limitation of multispectral scanners and have made it possible to assess the initial stages of insect infestation. The next section will discuss the use of hyperspectral remote sensing in the detection and mapping of the initial stages of *T. peregrinus* infestations.

The detection and mapping of *T. peregrinus* using hyperspectral remote sensing

Hyperspectral refers to spectra consisting of a large number of very narrow contiguous bands in the electromagnetic spectrum and is also referred to as spectroscopy or spectrometry (Mutanga 2004). Spectroscopy is the branch of physics concerned with the production, transmission and interpretation of electromagnetic energy. Spectrometers are used in laboratory, field, aircraft or satellite studies to measure the reflectance spectra of natural surfaces (Mutanga 2004). Because hyperspectral data have a variety of narrow spectral band features of less than 10 nm, phenological changes in forest health can be detected. In the initial or light phases of *T. peregrinus* infestation, trees may show little or no sign of infestation (Carpintero and Dellape 2006). The ability to detect light or previsual stages of infestation depends on using high spectral resolution data to assess subtle changes in leaf reflectance that would be otherwise masked by broadband scanners (Hoque et al. 1992, Pu et al. 2008). Remote sensing developments in hyperspectral technology provide the potential to detect subtle changes in leaf reflectance. These narrow wavebands (visible, near-infrared, and red edge) within the electromagnetic spectrum regions have been recommended for the early detection of forest damage (Hoque et al. 1992).

According to Carter and Miller (1994), the early detection of vegetation stress depends on identifying the spectral regions in which vegetation reflectance is most responsive to unfavourable growth conditions. Recent research has established relationships between leaf reflectance and foliar biochemicals, especially the photosynthetic pigments that provide information on the physiological status of vegetation (Zarco-Tejada et al. 2002, Coops et al. 2003, Pontius et al. 2005). The availability of narrow, contiguous wavebands present in hyperspectral data make it possible to reveal physiological changes that characterise early stress responses and provides an early indication of decline in stand vigour and productive capacity (Zarco-Tejada et al. 2002). This is because of the tendency of stressed leaves to undergo a reduction in chlorophyll content and thereby alter the reflectance at chlorophyll-sensitive wavelengths (Zarco-Tejada et al. 2002). Leaf reflectance in the visible and near-infrared portions of the electromagnetic spectrum can provide an early indication of plant stress or the

Table 4: Selected studies using hyperspectral sensing for disease detection and forest damage

Study/reference	Hyperspectral sensor	Method	Results
Assessing Dothistroma needle blight in *Pinus radiata* (Coops et al. 2003)	Compact Airborne Spectrographic Imager (CASI-2)	Spectral indices based on severity classes	Independent accuracy assessment allowed for the detection of three levels of Dothistroma needle blight with an accuracy of over 70%
Mapping previsual decline of hemlock stands owing to hemlock woody adelgid (Pontius et al. 2008)	AISA Eagle	Spectral wavelengths and stress indices used in a stepwise linear regression model	AISA Eagle classified hemlock health at tree level with a one-class tolerance accuracy of 88%. The model predicted decline with $R^2 = 0.75$ and RMSE = 0.81
Detecting initial damage in Norway spruce (Campbell et al. 2004)	Airborne Solid-State Array Spectroradiometer (ASAS)	Reflectance indices and derivative analysis	Spectral indices were strongly correlated to damage. The 673–724 nm spectrum provided the highest potential for identifying forests with initial levels of damage
Discriminating *Sirex noctilio* infestations (Ismail et al. 2008)	ASD Spectrometer	ANOVA and Jeffries-Matusita (J-M) distance analysis	Spectral bands located in the visible portion (350–700 nm) and red edge (670–737 nm) could discriminate different levels of attack. The J-M analysis indicated 99.22% separability between classes
Discriminating early stages of *Sirex noctilio* infestations (Ismail 2009)	ASD Spectrometer	Random forest algorithm	Wavelengths located at 1990 nm, 2009 nm, 2028 nm, 2047 nm and 2065 nm have the potential to discriminate green stage of attack
Early detection of Douglas-fir beetle infestation (Lawrence and Labus 2003)	Probe 1 sensor	Stepwise discriminant analysis (DISCRIM) and classification and regression tree analysis (CART)	Predictive accuracy of CART using cross-validation resulted in a classification accuracy of 69%. Classification among healthy, attacked and living trees gave an accuracy of 50–70%
Detecting forest mortality caused by *Phytophthora ramorum* (Pu et al. 2008)	Compact Airborne Spectroraphic Imager (CASI-2)	Classification algorithms, principal components	Principal components derived from the visible and near-infrared bands successfully classified stressed from non-stressed trees with a classification accuracy of 75.55%

onset of disease (Coops et al. 2003). In the visible part of the spectrum (400–700 nm) an increase in leaf reflectance generally indicates stress in vegetation (Carter and Miller 1994) and narrow waveband reflectance within the 690–700 nm range is sensitive to stress-induced decreases in leaf chlorophyll content (Carter 1993).

A number of studies have used hyperspectral data to detect and monitor early stages of insect infestation and forest damage (Entcheva Campbell et al. 2004, Ismail et al. 2008, Pontius et al. 2005). Table 4 summarises selected studies that have used hyperspectral remote sensing for insect infestation and forest damage.

Ismail et al. (2008) used high spectral resolution data to discriminate different levels of *Sirex noctilio* infestation in pine plantations. The results showed that bands in the visible (350–700 nm) and the red edge (670–737 nm) portion of the electromagnetic spectrum could discriminate the different levels of attack. Ismail (2009) also used reflectance measurements in the shortwave infrared to discriminate between healthy and early stages of *Sirex noctilio* infestation. The results show that there is a link between the shortwave infrared wavelengths and the existing physiological conditions thereby making it possible to detect early stages of *Sirex* infestation. Bands located at 1990 nm, 2009 nm, 2028 nm, 2047 nm and 2065 nm were able to discriminate between healthy and early stages of *Sirex* infestation (Ismail 2009). Campbell et al. (2004) used canopy hyperspectral imagery to separate healthy from initially damaged canopies using spectral indices. The region between 673 and 724 nm showed maximum sensitivity to initial damage and the results demonstrate the potential of hyperspectral canopy data in separating healthy from the initial stages of forest damage. Hyperspectral data collected at branch or canopy level takes into account variation in leaf area (LAI), leaf angle distribution and percentage ground coverage (Blackburn 2007). This data is useful in estimating defoliation levels in forest stands as compared to leaf hyperspectral data, which is used to assess stress in leaves based on pigment concentration. Pontius et al. (2005) used hyperspectral imagery (AISA Eagle) to map previsual decline of hemlock stands caused by hemlock wooly adelgid infestation. The AISA Eagle imagery was able to predict decline based on previsual changes in chlorophyll content and early stress.

Hyperspectral instruments (AISA Eagle, ASAS, CASI-2 and Probe1 sensor) have the capability to identify the early signs of stress in forest plantations and in some cases before visual symptoms are apparent (Pontius et al. 2005). This is promising for the detection of the light and early stages of *T. peregrinus* infestation. Using hyperspectral data, key vegetation wavelengths could be identified to detect the onset of light stages of *T. peregrinus* infestation. Once techniques have been developed and tested, hyperspectral airborne imagery could be used to accurately detect and map areas of high infestation.

Challenges in mapping *T. peregrinus* and future research

Although considerable progress has been made in sensor development and the application of remote sensing technology for insect infestation, there are still challenges to be met. Firstly, to the best of our knowledge there has been no work done on applying remote sensing applications for the detection and mapping of *T. peregrinus* infestation in plantation forests. Despite the lack of research, there is a challenge to develop accurate operational techniques (airborne and spaceborne) to detect and map the stages of *T. peregrinus*; taking advantage of improvements in sensor characteristics and processing techniques such as atmospheric correction algorithms, spectral resampling, spectral sharpening and classification algorithms.

Secondly, with the advancements in hyperspectral technology, there is a challenge to identify key vegetation wavelengths that can discriminate between healthy and infested trees. Vegetation indices that use information in the visible and near-infrared portions of the electromagnetic spectrum need to be tested to assess their strength in classifying *T. peregrinus* infestations. Robust spectral indices need to be developed to assess *T. peregrinus* infestations. Spectral regions such as the 'red edge', which characterises stress in vegetation (Dawson and Curran 1998, Filella and Penuelas 1994), have not been tested to assess its relationship with *T. peregrinus* infestations. It is crucial to test these techniques at leaf, branch and tree level to develop sensitive bands that can be used in the scaling-up process for the detection of *T. peregrinus* infestations using airborne and spaceborne platforms.

A third research challenge would be to test the utility of the South African satellite, SumbandilaSat, to detect and monitor *T. peregrinus* infestations in plantation forests. SumbandilaSat, which was launched in February 2010, has six wavebands with a swath width of approximately 40 km and a ground sampling resolution of 6.5 m (Scholes and Annamalai 2006, Oumar and Mutanga 2010). It is imperative to test the utility of data acquired using this satellite in monitoring plantation health and forest diseases in South Africa as the sensor comprises key vegetation wavelengths such as the red edge (690–730 nm) and the xanthophylls (520–540 nm), which are not currently available on current operational multispectral satellite sensors but on hyperspectral sensors that are expensive to acquire (Oumar and Mutanga 2010). In this regard, the development of techniques that can make use of the SumbandilaSat bands to detect and map *T. peregrinus* infestations in plantation forests are critical.

A fourth research challenge would be to develop models that predict plantations that are susceptible to potential infestation. Statistical techniques and machine learning algorithms are used as important tools to help us model and predict the spread of insect infestation (Ismail 2009). By incorporating a variety of factors (environmental, climatic and species preference) within a GIS model, the prediction of the onset and possible spread of *T. peregrinus* in plantation forests could be better understood. The ability to model areas that are vulnerable to threat will empower forest managers to focus their detection methods and make cost-effective decisions related to the management of forest plantations (Radeloff et al. 1999, Coops et al. 2004). Forest managers will have the ability to adopt the most appropriate remediation measures (such as *Cleurchoides noackae*) before *T. peregrinus* can colonise uninfected forests.

Given all these challenges, it is essential to apply remote sensing techniques (identifying key vegetation wavelengths, potential of vegetation indices and the red edge in estimating insect infestation, texture measures and LAI to assess defoliation, and multispectral and hyperspectral sensing at leaf, branch and tree level) to accurately detect and map *T. peregrinus* infestations in forest plantations. There is no doubt that remote sensing technology will play a pivotal role in the detection and mapping of *T. peregrinus*. Once these techniques have been tested and developed they can be used operationally as an effective method to quantify, detect and monitor *T. peregrinus* infestations in plantation forests.

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