# DETECTION OF SUGARCANE AFRICAN STALK BORER *ELDANA SACCHARINA* WALKER (LEPIDOPTERA: PYRALIDAE) USING HYPERSPECTRAL REMOTE SENSING (SPECTRORADIOMETRY)

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## Abstract

The South African sugar industry is one of the world's leading sugarcane producers. The stalk borer *Eldana saccharina* has for many years been the most destructive pest in the South African sugar industry and is the most important factor limiting sugarcane productivity. The pest has been monitored using a traditional visual approach whereby a representative sample of stalks is taken from a field and split longitudinally to assess damage and count the number of *E. saccharina.* This approach is time-consuming, labour intensive and sometimes biased as, in some instances, only easily accessible areas are surveyed. To investigate a more economical but equally sensitive survey methodology, this paper aims at determining the potential use of hyperspectral remote sensing (spectroradiometry) for identifying sugarcane infested by *E. saccharina*. A hand-held ASD (Field Spec® 3) spectroradiometer was used to take leaf spectral measurements of sugarcane plants from a potted-plant trial taking place under shade house conditions. In this trial, nitrogen and silicon fertiliser applications as well as varieties used were known. In addition, watering regimes and artificial infestation of *E. saccharina* were carefully controlled. Results illustrated that severe *E. saccharina* infestation increased reflectance throughout the whole spectrum range (400-2500 nm). *E. saccharina* stalk damage was also linearly related to modified normalized difference vegetation index (mNDVI) using $R_{2025}$ and $R_{2200}$ ($R^2$=0.69). It was concluded that hyperspectral data has a potential for use in monitoring *E. saccharina* in sugarcane rapidly and non-destructively under controlled conditions. A follow-up study is recommended in field conditions and using airborne and/or spaceborne hyperspectral sensors.

*Keywords*: hyperspectral remote sensing, spectroradiometry, *E. saccharina*, nitrogen, silicon, sugarcane variety, leaf reflectance

## Introduction

The South African sugar industry is one of the world's leading sugarcane (*Saccharum* spp. hybrid) producers. For example, its annual sugar production is approximately 2.5 million tons, of which 50% is exported to other African countries and other continents, including North America. Through these export markets, the production generates an average income of R6 billion a year and also contributes approximately R2 billion to the country's foreign exchange earnings (SASRI, 2007). Over the past 30 years *E. saccharina* an insect indigenous to Africa, has been the most destructive pest in South African sugarcane and the most important factor limiting sugarcane productivity. It has caused a huge annual crop losses (Meyer and Keeping, 2005).

Detection, assessment and monitoring of *E. saccharina* in sugarcane are very important for management decisions as well as prompt decision making. This has been done through traditional or visual approach (Way and Goebel, 2007). The approach involves destructive sampling of cane stalks from the field and then longitudinally splitting them for assessing stalk damage as well as internodes damage by *E. saccharina* and for counting the number of *E. saccharina* larvae and pupae found in the stalks. However, this approach is inefficient as it is time-consuming, labour intensive and it is sometimes biased as only easily accessible areas are surveyed (Apan *et al.*, 2005). According to Apan *et al.* (2005), remotely sensed data, especially hyperspectral data, can be used to supplement traditional or visual approaches for detection, assessment and monitoring of disease and pest symptoms, and such techniques have advantages over traditional approaches in that they can be used to repeatedly collect sample measurements both non-destructively and non-invasively.

Very few remote sensing studies have been undertaken in South Africa on sugarcane using multispectral sensors (broadband sensors) except recent works by Abdel-Rahman *et al.* (2008a,b) where hyperspectral data were used. A characteristic of multispectral sensors is that they have fewer channels but these have broadband (~100 µm) which make them average the reflectance over a wide range of wavelength. This means much data about narrow spectral features are lost or masked by the stronger features surrounding them (Kumar *et al*., 2003). Presumably, there are changes in narrow spectral absorption features of sugarcane leaves induced by *E. saccharina* which may go undetected by these multispectral sensors. In contrast, hyperspectral sensors with over 100 contiguous and narrow sensitive bands (~10 nm) can detect these changes in narrow absorption features (Lillesand *et al.,* 2004). This high sensitivity of hyperspectral data makes it more sensitive and capable in determining reflectance changes induced by *E. saccharina* on sugarcane leaves at leaf-level using spectroradiometry. Therefore, this paper was aimed at investigating the potential use of hyperspectral remote sensing (spectroradiometry) for identifying sugarcane infested by *E. saccharina* at leaf-level.

## Materials and Methods

*Design*

An on-going N x Si x variety trial taking place under shade house conditions at the South African Sugarcane Research Instistute (SASRI) was designed to study the combined influence of N and Si nutrients on *E. saccharina* infestation in different varieties. Seedcane material of five South African varieties that are rated as resistant (N17 and N21), intermediately-susceptible (N25 and N37) and susceptible (N14) to *E. saccharina* were collected and prepared for pre-germination. However, this paper focuses only on the susceptible and intermediately susceptible varieties (N14, N25 and N37).

Pots containing clean, sieved and thoroughly leached river sand allowing precise control of nutrient supply were established in an outdoor sugarcane trial. The pots were arranged in a randomised split-split plot design with N*Si treatment as a whole plot treatment and variety as a split plot treatment. There were two replications; these resulted in 54 pots. Three N treatment levels were applied as ammonium sulphate (N1=30 ppm, N2=60 ppm and N3=90 ppm) via nutriculture (hydroponic) solutions added to different pots, while three Si treatment levels were applied and incorporated thoroughly into the sand of each pot as calcium silicate (Calmasil) according to the treatment plan (Si0=0 ppm, Si1=100 ppm and Si2=200 ppm). Germinated seedcane materials were transplanted into the pots as per treatment plan. Fresh irrigation water containing two litres of nutrient stock solution and ammonium sulphate were

applied after every seven days (every Friday) using Hygrotech Seedling Mix, except on rainy days.

At the age of nine months, the sugarcane trial (using same design) was transferred to a shade house with transparent polycarbonate roofing and walls of green 40% shade cloth in preparation for subjecting the plants to water stress and inoculation with *E. saccharina* eggs. Once the plants were in the shade house, firstly, the N supply was terminated, secondly, excess stalks/tillers (<1 m) were removed, keeping a maximum of five stalks per pot and, lastly, water stress began. The irrigation schedule for water stress was as follows: first week = one litre (10 minutes) per pot per day; second week = 0.7 litres (seven minutes) per pot per day; third week = 0.5 litres (five minutes) per pot per day and fourth week = 0.3 litres (three minutes) per pot per day until harvest. At 10 months of age, the plants were inoculated with *E. saccharina* eggs, placed on tissue paper in a batch of 100 eggs, on the lower base of one stalk. Since the number of stalks varied per pot, pots with three or less stalks were inoculated with 100 eggs (one batch), while those with more than three stalks were inoculated with 200 eggs (two batches) per pot. The infestation was allowed to progress for two months.

*Leaf spectral measurements*

At harvest (12 months cane age), the leaf spectral measurements were taken using a hand-held Analytical Spectral Devices (ASD) *Field Spec® 3* spectroradiometer by pointing the fibre optic at the third leaf of the main stalk in each pot. The hand-held ASD *Field Spec® 3* spectroradiometer is a specialised spectrometer that measures spectral reflectance, spectral transmittance, spectral radiance, spectral irradiance and spectral absorbance using visible near-infrared (VNIR) and short-wave infrared (SWIR) spectra. The spectrum wavelength ranges from 350-2500 nm with a spectral sampling interval of 1.4 nm for the region 350-1000 nm and spectral sampling interval of 2 nm for the region 1000-2500 nm (ASD, 2006). There is a fragile fibre optic cable bundle which brings light from the target object into the instrument, which then passes the information to the computer notebook where the spectral curves will be captured and saved for interpretation and further analysis. There is also a spectralon panel which is used for measuring a 'white reference' reading which must reflect nearly 100% of the light before any spectral measurements can be taken. This calibration or optimisation process is done regularly every 10-15 minutes.

*Eldana saccharina detection*

After leaf spectral measurements, stalks were collected from the targeted pots and split longitudinally for recording the number of stalks damaged and counting the number of *E. saccharina* larvae and pupae in each pot. Borer damage was measured as percentage stalks bored or damaged by *E. saccharina* larvae (% Stalk Damage or % Damage) (see Equation 1) (Mutambara-Mabveni, 2007; Way and Goebel, 2007).

$$\% \text{ Stalk Damage or \% Damage} = [(\text{Total number of stalks bored by Eldana}) / (\text{Total number of stalks per pot})] * 100 \quad (1)$$

*Spectral data pre-processing*

ViewSpec software (ASD, 2006) was used for viewing graphic reflectance results as well as reflectance data pre-processing, such as averaging spectra to reduce within class variability and to increase statistical power, performing first derivatives and exporting spectra into American Standard Code for Information Interchange (ASCII) text files which were easily imported into a statistical package. The first derivative spectra were performed mainly to reduce effects of multiple scattering of radiation due to sample geometry and surface

roughness, and to locate the positions of absorption features and inflection points on the spectra (Datt *et al.,* 2006). Noisy wavebands due to water absorption features and sun-angle effects, e.g. around 1400, 1900 and 2500 nm, were identified and thus excluded from the statistical analysis.

*Statistical analysis*
In order to discriminate between healthy and *E. saccharina* infested cane using leaf reflectance, all the leaf spectral reflectance from cane that did not have any stalk damage by *E. saccharina* were averaged to yield healthy cane, while all those from damaged cane stalks were averaged to give *E. saccharina* damaged cane. Then Analysis of Variance (ANOVA) was conducted to determine whether leaf reflectance can discriminate healthy cane from *E. saccharina* damaged cane. The damage induced by *E. saccharina* on sugarcane stalks ranged from 0-100% stalk damage. In order to distinguish between damage levels, this range was categorised into four levels: (i) healthy (0% stalk damaged), (ii) low damage (1-39% stalk damaged), (iii) medium damage (40-69% stalk damaged) and (iv) severe damage (70-100% stalk damaged). Then leaf reflectance from leaf samples under each damage level were averaged together. An ANOVA was performed to detect significant differences in the reflectance spectra caused by different *E. saccharina* damage levels at all different varieties.

## Results

*Discrimination between healthy and E. saccharina damaged cane using leaf reflectance*
In order to determine whether leaf level spectral reflectance can detect changes influenced by *E. saccharina* infestation, all the leaf spectral reflectance measurements from cane that did not have any stalk damage by *E. saccharina* were averaged to yield healthy cane, while all those from damaged cane stalks were averaged to give *E. saccharina* damaged cane at all varieties combined (Figure 1). Figures 1a and b indicate that there were highly significant differences in leaf reflectance from healthy and *E. saccharina* damaged cane throughout the spectrum ($P<0.001$ and 0.01, respectively) (Table 1).

The red-edge region was further assessed to investigate the effects of *E. saccharina* damage on leaf pigments such as chlorophyll and N. Figure 1c shows that there was a shift of the red-edge slope towards shorter wavelengths for *E. saccharina* damaged cane. This is known as blue shift. This indicates that *E. saccharina* stalk damage caused a decrease in leaf chlorophyll and N concentrations, as this shift is the result of low chlorophyll concentrations. However, this shift was not significant as $p>0.05$, $p=0.297$ (Table 1). Figure 1d highlights that both healthy and *E. saccharina* damaged cane had their maximum red-edge peaks around 720 nm, with *E. saccharina* damaged cane having higher peaks.

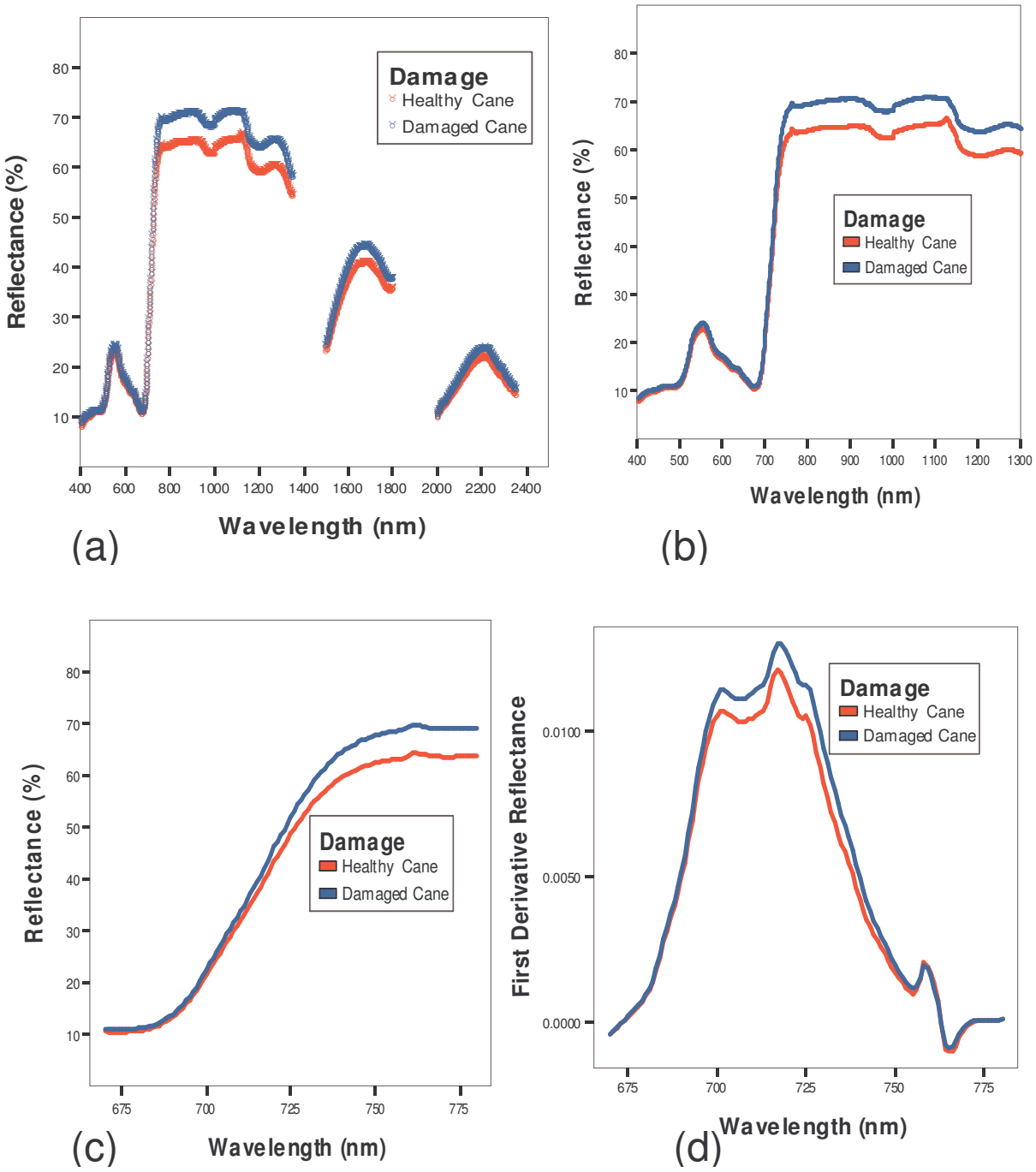


**Figure 1. Mean leaf spectral reflectance curves highlighting healthy and *E. saccharina* damaged cane. (a) spectrum without noisy wavebands, (b) only visible-NIR portion of spectrum range (400-1300 nm), (c) and (d) red-edge region.**

**Table 1. Results of ANOVA illustrating whether wavebands from the whole spectrum as well as different portions of the spectrum can significantly discriminate between healthy and *E. saccharina* damaged cane.**

| Portion of spectrum range | F | Sig. |
|---|---|---|
| Whole spectrum range | 14.454 | .00001 |
| VNIR portion of spectrum range | 10.064 | .002 |
| Red-edge (670-780 nm) | 1.094 | .297 |

*Differences in leaf reflectance as influenced by various E. saccharina damage levels for all varieties combined*

The damage induced by *E. saccharina* on sugarcane stalks ranged from 0-100%. In order to distinguish between damage levels, this range was categorised into four levels: healthy (0% stalk damaged), low damage (1-39% stalk damaged), medium damage (40-69% stalk damaged) and severe damage (70-100% stalk damaged) (Figure 2). Leaf reflectance from leaf samples under each damage level were then averaged together. Figure 2 shows that there was a slight difference or variation in leaf reflectance at different wavebands as influenced by *E. sachharina* stalk damage levels throughout the spectrum.

Severely damaged sugarcane gave the highest reflectance, followed by medium damage and then low damage, and healthy plants were overlapping (Figure 2a). This further validates that stress, whether biotic or abiotic, increases reflectance from 1300 to 2500 nm as well as in the range of 400 to 1300 nm (Carter, 1991; 1993). An ANOVA was performed to test whether these damage levels showed significant differences on leaf reflectance spectra. The differences were highly significant throughout the spectrum range ($P<0.001$) (Table 2).

Figure 2b clearly indicates that severely *E. saccharina* damaged cane had the highest leaf reflectance followed by medium *E. saccharina* damaged cane in the NIR region. This implies that *E. saccharina* damage on the cane stalks did not break down cell structures in the cane leaves as a decrease in leaf reflectance in the NIR region is associated with breakdown of leaf cell structures (Datt *et al.,* 2006).

Figure 2c shows that there was slight (not significant, $p = 0.41$, see Table 2) effect of various *E. saccharina* stalk damage levels at the red-edge region of the spectrum; that is, red-edge slopes of both severe and medium *E. saccharina* damage moved towards the shorter wavelengths, indicating reduction in chlorophyll and N concentrations. These slight differences (Figure 2), are due to the effects of variety, as different varieties have different spectral reflectance signatures (Apan *et al.,* 2004a; Galvão *et al.*, 2005). Therefore this made it worthwhile to consider *E. saccharina* stalk damage to each variety. This is illustrated in Figure 3.

Figure 2e-f shows highly significant differences ($p<0.0001$, Table 2) in leaf reflectance as influenced by various *E. saccharina* stalk damage levels in the SWIR (1500-1800 nm and 2000-2350 nm, respectively). Figure 2e shows that highest significant reflectance peaks for all damage levels were centred on 1660 nm, with severe damage having the highest reflectance. Figure 2f highlights that highest reflectance peaks were around 2200 nm, still with severe damage level having the highest reflectance; however, there was no clear distinction between healthy and medium damage levels in this region.

**Table 2. Results of ANOVA highlighting whether leaf reflectance from the whole spectrum can statistically distinguish between various *E. saccharina* damage levels on different varieties.**

| Variety | F | Sig. |
|---|---|---|
| N14 | 3.330 | .019 |
| N25 | 2.347 | .071 |
| N37 | 29.713 | .0001 |

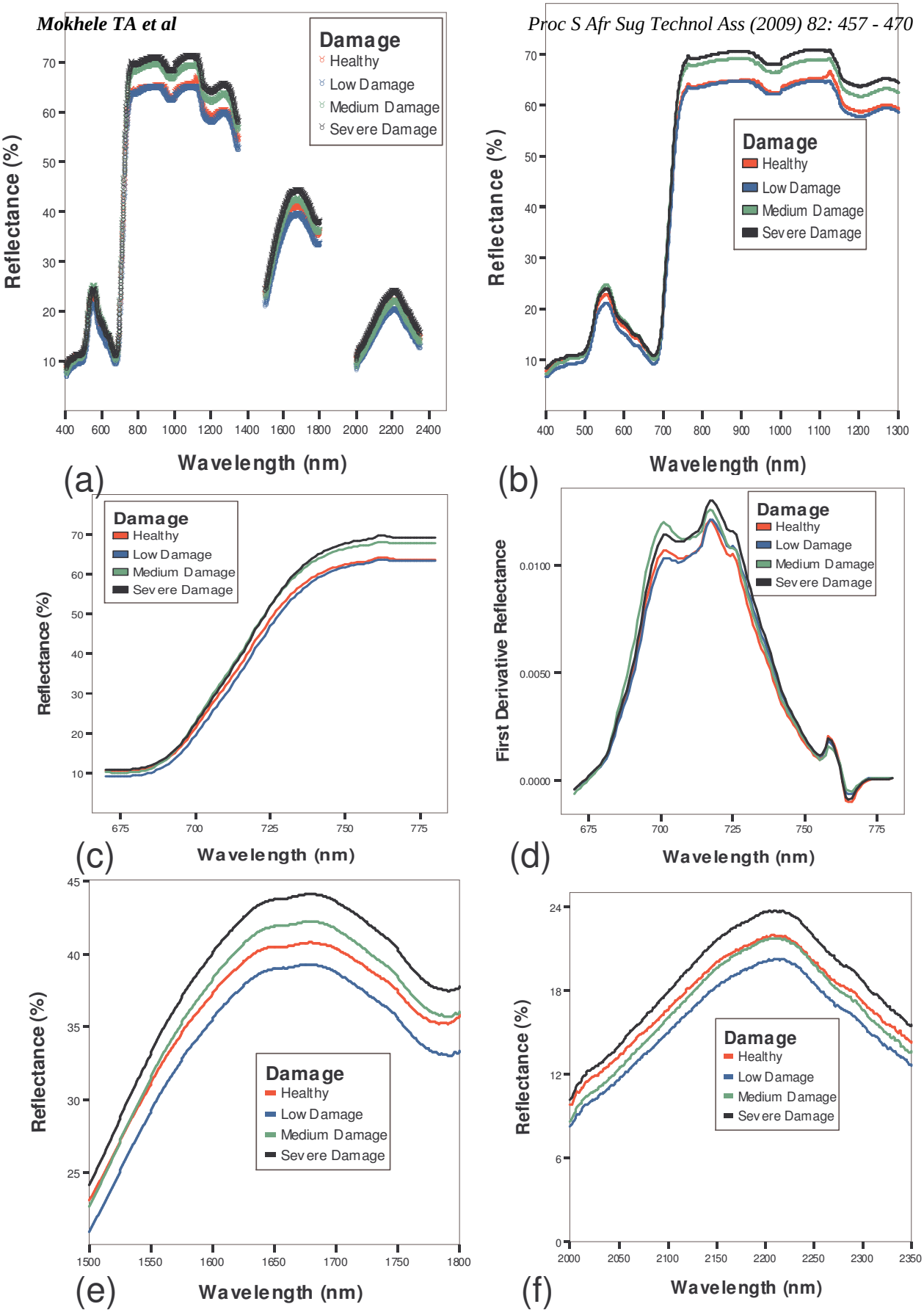


**Figure 2. Leaf spectral reflectance curve showing different E. saccharina damage levels on 12 months old cane. (a) spectrum without noisy wavebands, (b) only visible-NIR portion of spectrum range (400-1300 nm), (c) and (d) red-edge region, (e) 1500-1800 nm range and (f) 2000-2350 nm range.**

*Effects of E. saccharina stalk damage levels on leaf reflectance of varieties N14, N25 and N37*

Figure 3 shows differences in leaf spectral reflectance of different sugarcane varieties as induced by various *E. saccharina* stalk damage levels. Figure 3a shows that there was a difference in leaf reflectance of N14 caused by various damage levels by *E. saccharina* ($p=0.019$ for whole spectrum); however, severe damage level by *E. saccharina* reflected higher throughout the spectrum (Figures 3a, b and c; Table 2). Figure 3b shows that, although severely damaged cane had the highest reflectance and healthy cane had the lowest reflectance throughout the spectrum, there was no significant difference in leaf reflectance on N25 as influenced by various damage levels by *E. saccharina* ($p=0.071$ for whole spectrum, Table 2).

Figure 3c shows that various *E. saccharina* damage levels had highly significant impacts on leaf spectral signature of N37 cane variety (the most damaged compared to N14 and N25) ($p<0.0001$, Table 2). Although there was a significant difference between all damage levels, it is interesting to note that there was no level for healthy cane in this variety. This indicates that all cane stalks from this cane variety were damaged by *E. saccharina*. This confirms that this variety was the most damaged despite being rated the least susceptible. It is worth noting that the difference between severe damage and medium damage levels was small, especially in the VNIR region (Figure 3c). Figure 3c clearly illustrates that both severe and medium damage levels increased reflectance in the visible region, which confirms that there was a reduction in leaf pigments caused by *E. saccharina* damage to the cane plant, as this region is characterised by leaf pigment and nutrient absorption peaks (carotenoids, chlorophylls and N). This confirms that any physiological stress, pest and disease or reduced amount of photosynthesis increases red and blue reflectance (Nilsson, 1995).

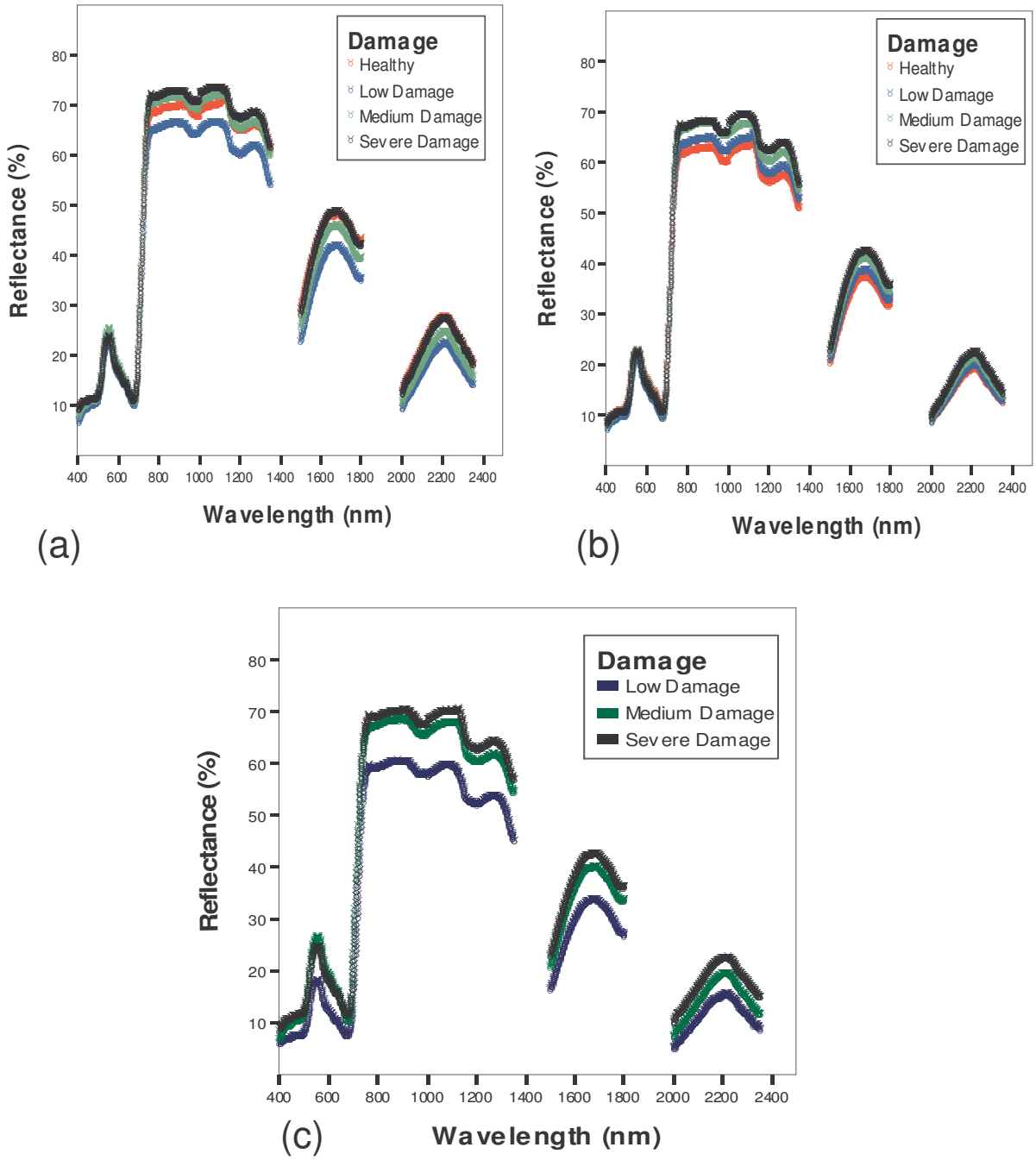


**Figure 3. Leaf spectral reflectance curve showing different *E. saccharina* damage levels on different cane varieties (a) N14, (b) N25 and (c) N37.**

Figure 4 shows that wavebands 410-430 nm and 2010-2340 nm could significantly distinguish between the *E. saccharina* damage levels ($p \leq 0.05$). The significant differences in leaf reflectance in the visible region (410 – 430 nm) are due to differences in leaf pigments such as chlorophyll and N concentrations, while differences in leaf reflectance in the SWIR (2010-2340 nm) are due to water absorption effects as well as some pigments such as N.

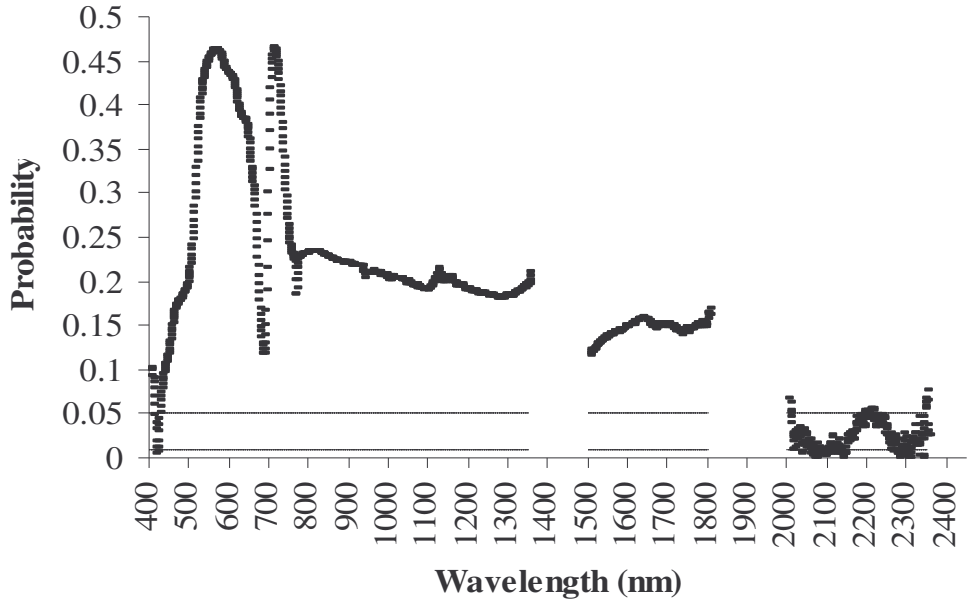


**Figure 4. Results of one-way ANOVA illustrating wavebands of the spectrum range that can significantly distinguish various damage levels on N37 at age 12 months. Dotted and solid horizontal lines indicate 0.01 and 0.05 significance levels, respectively.**

Figure 5 indicates that *E. saccharina* stalk damage is linearly and negatively related to modified NDVI $(R_{2200}-R_{2025})/(R_{2200}+R_{2025})$ ($R^2$=0.69; RMSE=19.351). This further proves that differences in leaf reflectance in the SWIR (2010-2340 nm) are due to N concentrations (Figure 4). This implies that *E. sachharina* damage to the stalk had effects on leaf N concentrations. However, there was higher error (RMSE) in this regression model ($R^2$=0.69; RMSE=19.351) (Figure 5). This might be due to the fact the bands used in the index are from SWIR (2000-2350 nm), which is characterised by water absorptions, lignin, N, starch and cellulose (Kumar *et al*., 2003). Therefore, it is assumed that water stress could have some carry-over effects on these N absorption bands.

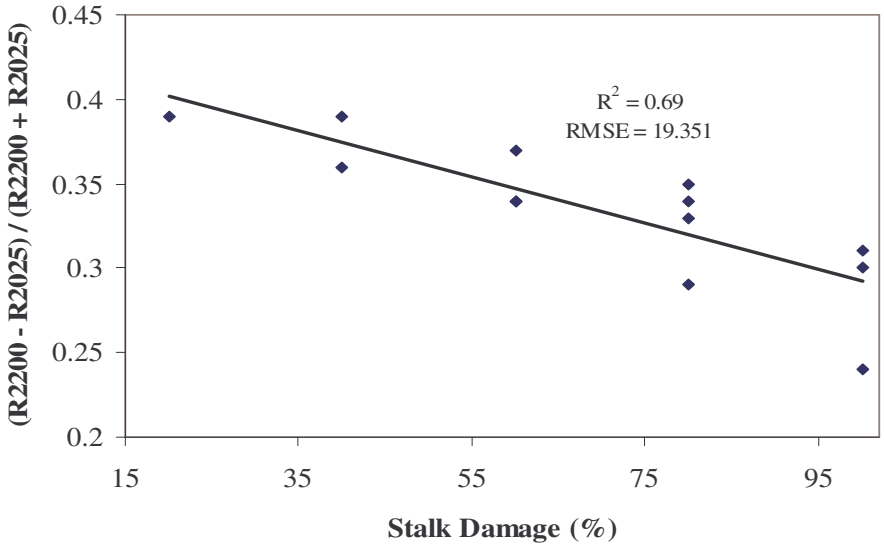


**Figure 5. Linear regression model of spectral index against *E. saccharina* stalk damage on N37.**

## Discussion

As recent studies showed that hyperspectral remote sensing can offer an opportunity to monitor pests and diseases rapidly and non-destructively in agricultural crops (Apan *et al.*, 2004, 2005; Mirik *et al.*, 2006a,b; Datt *et al.*, 2006; Abdel-Rahman *et al*., 2008b), the findings from this paper further confirm that hyperspectral data, with its narrow sensitive wavebands, successfully discriminated between healthy and various *E. saccharina* damaged cane under controlled conditions.

Although hyperspectral data could distinguish between healthy and various *E. saccharina* stalk damage levels at combined varieties, it is important to note that the best results were obtained when focusing on each variety, as different varieties had different spectral reflectance (Apan *et al.,* 2004a; Galvão *et al.,* 2005). This was confirmed in this study. In addition, different varieties had different *E. saccharina* susceptibility and different uptake of nutrients, especially Si, which increased resistance of varieties to *E. saccharina* stalk damage. This was illustrated by the fact that the most *E. saccharina* stalk damaged cane variety (N37) showed best significant results throughout the whole spectrum when distinguishing between healthy and various *E. saccharina* stalk damage levels. The successful estimation of *E. saccharina* stalk damage from hyperspectral data was also from this variety as indicated earlier.

In general, NIR showed the highest separability between healthy and various *E. saccharina* stalk damage levels at combined varieties as well as at each variety, especially N37 which was the most damaged variety. The results highlighted that in the NIR region severely *E. saccharina* damaged cane had the highest leaf reflectance followed by medium *E. saccharina* damaged cane. This implies that *E. saccharina* damage on the cane stalks did not break down cell structures in the cane leaves, as this would have been noticed by a decrease in leaf reflectance in the NIR region which is associated with breakdown of leaf cell structures (Apan *et al.,* 2004b, 2005). The SWIR showed that wavebands 2010-2340 nm could significantly distinguish between the *E. saccharina* damage levels. The significant differences in leaf reflectance in the SWIR (2010-2340 nm) are due to water absorption effects as well as some pigments such as N.

One of the N indices tested in this study, modified NDVI $(R_{2200}-R_{2025})/(R_{2200}+R_{2025})$, showed highest significant correlation with *E. saccharina* stalk damage on N37. This modified NDVI successfully estimated *E. saccharina* stalk damage on N37 from hyperspectral data with determination coefficient ($R^2$=0.69; RMSE=19.351) (see Figure 5). The higher RMSE was assumed to be the effects of water absorptions, lignin, starch and cellulose, more especially water stress which could have some carry-over effects, as bands used on this index were from SWIR (2000-2350 nm) which is characterised by water absorptions, lignin, N, starch and cellulose (Kumar *et al*., 2003). As *E. saccharina* infestation is related to water stress, it is assumed that formulation and development of *E. saccharina*-Water Stress Indices can be the best for estimation and detection of *E. saccharina*, possibly with low errors (RMSE). This index $(R_{2200}-R_{2025})/(R_{2200}+R_{2025})$, was developed by Abdel-Rahman *et al.* (2008a) for estimation of sugarcane N concentration on 6 -7 months N19 cane and was linearly related to N concentration ($R^2$=0.87). This further implies that *E. sachharina* damage on the stalk had some effects on leaf N concentrations. It is worth highlighting that both bands used in this index were related to *E. saccharina* stalk damage in this paper. Both bands (2025 and 2200 nm) were within the range of 2010-2340 nm, which significantly distinguished between the *E. saccharina* damage levels on N37. On the other hand, one of the highest reflectance peaks for

all *E. saccharina* damage levels in the SWIR region were centred on 2200 nm (Figure 2f) on combined varieties.

The proposed use of hyperspectral data can overcome the issue of bias, as not only easily accessible areas will be surveyed. Sometimes after heavy rains water stays in the fields, which prevents monitors and surveyors from getting into the fields, and causes late monitoring and detection of pests, which could lead to great crop loss (Abdullah and Umer, undated; Apan *et al.*, 2005). However, remote sensing is not meant to replace the traditional method; instead it can be used to supplement traditional or visual approaches to assessment, monitoring and detection of disease and pest symptoms (Abdullah and Umer, undated; Apan *et al.*, 2005).

## Conclusions

The results from this paper highlight that hyperspectral remote sensing using hand-held spectroradiometers can provide a means of rapid assessment and monitoring of *E. saccharina* of many sugarcane samples, non-destructively, within a short time. Results show that there were highly significant differences in leaf reflectance from healthy and *E. saccharina* damaged cane throughout the spectrum (400 – 2500 nm). The *E. saccharina* stalk damaged cane reflected higher than healthy cane throughout the spectrum, with more separability in the NIR region. The red-edge slope and REP of the *E. saccharina* damaged cane shifted towards shorter wavelengths. This is known as blue shift. This indicates that *E. saccharina* stalk damage caused a decrease in leaf chlorophyll and N concentrations, as this shift is the result of low chlorophyll concentrations.

In general, NIR showed the highest separability between healthy and various *E. saccharina* stalk damage levels at combined varieties as well as at each variety, especially N37 which was the most damaged variety. The results highlighted that in the NIR region severely *E. saccharina* damaged cane had the highest leaf reflectance, followed by medium *E. saccharina* damaged cane. This implies that *E. saccharina* damage on the cane stalks did not break down cell structures in the cane leaves as this would have been noticed by a decrease in leaf reflectance in the NIR region which is associated with breakdown of leaf cell structures.

One of the N indices tested in this paper, modified NDVI $(R_{2200}-R_{2025})/(R_{2200}+R_{2025})$, showed the highest significant correlation with *E. saccharina* stalk damage and successfully estimated *E. saccharina* stalk damage on N37 from hyperspectral data with determination coefficient ($R^2$=0.69; RMSE=19.351). Although this index successfully detected *E. saccharina,* many indices, not necessarily N indices, using different waveband combinations, can still be developed to estimate and monitor this pest. More importantly, as *E. saccharina* infestations are related to water stress, it is suggested that *E. saccharina*-Water Stress Indices are developed which can estimate *E. saccharina*, possibly with low errors (RMSE). Generally, it was concluded that hyperspectral data has a potential for use in monitoring *E. saccharina* in sugarcane rapidly and non-destructively under controlled conditions. A follow-up study is recommended in field conditions and using airborne and/or spaceborne hyperspectral sensors.

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