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Using remote sensing to improve canegrub management in North Queensland canefields

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ABSTRACT

Canegrubs, of which there are around 20 species, represent major economic pests of sugarcane in Australia. The greyback canegrub (*Dermolepida albohirtum*) is the main insect pest of sugarcane in Queensland and is found in cane-growing regions between Mossman and Sarina. It costs the sugarcane industry annually up to $40 million and is primarily controlled by the use of chemical insecticides. Without control, damage can be extensive, due to the root feeding behaviour of the insect larvae, but symptoms are difficult to see due to the dense canopy of a sugarcane crop and canopy symptoms are usually expressed when the crop is too high to apply insecticides. This makes management decisions difficult to implement strategically and consequently growers tend to favour the use insecticides at planting or soon after harvest as a preventative option. The development of a system whereby canegrub damage could be assessed and detected earlier over an area-wide scale could lead to a more targeted and risk-based approach to canegrub management. Ultimately, if this targeted approach could be developed it should lead to more strategic use of insecticides by the industry for canegrub management, minimising both crop losses and unnecessary insecticide application.

As a potential way to observe the symptoms of canegrub damage over large areas, the feasibility of using satellite-acquired imagery of the canopy was examined. Depending on the spatial resolution (as determined by pixel size) of the acquired imagery, the images can potentially show differences in canopy reflectance, texture, stool tipping and gaps within the crop.

Imagery was acquired from two satellite platforms, Geoeye-1 and SPOT-6, covering three major cane-growing regions, Mackay, Mulgrave and the Herbert, where canegrub is known regularly to occur. Both Geoeye-1 and SPOT-6 have the capacity to obtain panchromatic and multi-spectral (Red, Green, Blue & Near Infra Red) imagery. However, the resolution or ground sampling distance (GSD) differs, with SPOT-6 at 1.5 m and Geoeye-1 at 0.46 m. SPOT-6 imagery is also cheaper to obtain than Geoeye-1 imagery.

In this project the efficiency of Geoeye-1 and SPOT-6 imagery to detect canegrub damage was compared over two years in the Mulgrave, Herbert and Mackay regions. In the final year of the three-year project, SPOT-6 imagery alone was acquired for the whole Mackay region to assess the economic and practical feasibility of detecting canegrub damage on an area-wide basis, and maps showing potential canegrub damage were produced for the whole region. At a smaller scale, SPOT-6 imagery was also compared to cheaper but lower resolution (3 m) Planet imagery. However, Planet image data was deemed unfeasible for assessment of multi-temporal characteristics of canegrub damage due to relatively poor spatial resolution.

Validation of canegrub algorithms, developed using the geographic object-based image analysis GEOBIA and a rule set devised for use in eCognition software, was conducted. The rule set classified potential canegrub damage detected within fields as having a low, medium or high likelihood of representing actual grub damage. The rule set was validated and modified according to ground-truthing for grub presence based on site selection from imagery obtained from both helicopter and satellite sources.

Overall, although the imagery could identify sites with canegrub damage, unfortunately there were different relative amounts of false positives and false negatives and this varied between regions and seasons. This finding, combined with the requirement for annual calibration, the high cost of imagery and the phasing out of both Geoeye-1 in 2018 and SPOT-6 satellite in 2022, may ultimately prove a major limiting factor in potential utilization of this type of satellite imagery. However, this study does form the basis for future potential studies on damage mapping using spectral sensors to detected canopy changes caused by soil-dwelling insect pests of sugarcane. It also opens up the opportunity to investigate the potential use of other imagery types or different platforms for future spectral data collection.

EXECUTIVE SUMMARY

Issue and Objectives

The greyback canegrub (*Dermolepida albohirtum*) is the main pest of sugarcane in Queensland and has cost the sugarcane industry annually up to $40million. Damage can be extensive due to the root feeding nature of the insect larvae, but symptoms are difficult to see from the ground due to the dense canopy of a sugarcane crop and are most often expressed when it is too late to apply chemical insecticides due to the crop height. This makes management decisions difficult to implement strategically and consequently growers tend to favour the relatively widespread use insecticides at planting or soon after harvest as a preventative measure to avoid substantial crop losses. A more targeted approach would be economically and environmentally beneficial to industry if a reliable method of canegrub risk mapping could be developed which is not reliant on extensive, laborious and time-consuming ground inspection, a task which growers or advisors are unlikely to undertake.

The objectives of this project were to (i) examine the feasibility of using Spot 6/7 imagery to produce reliable canegrub damage risk maps and (ii) If feasibility is demonstrated, work with at least two productivity services to develop a commercialisation plan.

Project Outputs

In partnership with Queensland University, satellite imagery was obtained from Geoeye-1 and SPOT-6 satellites for several cane-growing regions. Over a three-year period, satellite-acquired imagery was processed and analysed using GEOBIA mapping analysis and rule sets were developed for use with eCognition software to map canegrub damage areas. Areas mapped included Mulgrave, the Herbert and the whole of Mackay.

Validation was based on field observations, helicopter observations and ground truthing by SRA staff.

In relation to the main project objectives, several outputs were produced as follows:

1. **Assessment of Feasibility of using Spot 6/7 imagery compared to Geoeye-1 imagery completed.** In partnership with Queensland University, satellite imagery was obtained from Geoeye-1 and SPOT-6 satellites and analysed for several cane-growing regions in North and central Queensland.
2. **Canegrub damage maps produced for several cane-growing regions in North and Central Queensland.** This included damage maps for the whole of Mackay and selected regions in the Burdekin and Mulgrave regions.
3. **Industry engagement completed.** The results of the 3 years of work were presented in 2019 to staff of Productivity Services in Mackay and discussed in depth to determine the practicality of using satellite imagery to assess grub damage.

Outcomes and Implications of the Project Findings for the Sugar Industry and the Australian Community

In a previous study (SRA Project 2011/342; Sallam 2015), using the relatively expensive Geoeye-1 imagery, it was demonstrated that there is potential for using satellite imagery to effectively map canegrub damage and accuracy was reported to be between 75-98.7% (Kasper *et al*., 2018). However, the use of Geoeye-1 imagery remains cost prohibitive for the sugar industry. This study therefore compared the cheaper SPOT-6 imagery with Geoeye-1 imagery to determine its comparative efficiency in mapping canegrub damage.

Satellite-acquired multispectral imagery was analysed by a remote sensing specialist using sophisticated image analysis and software programs to enable the production of maps showing areas of potential canegrub damage. Potential damage was further qualified as having a low, medium or high likelihood of being due to canegrubs. These maps were validated by follow up ground-truthing. However, the damage mapped may not always be due to canegrub feeding. Canegrub damage as observed from analysis of satellite imagery can also be confused with rat and pig damage, lodging, wind damage, weed presence and other factors, which reduces the sensitivity of damage maps. This can lead to reduced overall accuracy in mapping damage areas.

In addition to difficulties of false positives (overestimation of grub damage) and false negatives (under estimation of grub damage) caused by a variety of confounding factors, in order to utilise this as a method of developing canegrub damage maps for industry, regular and extensive ground truthing and subsequent modification of the algorithm and rule set developed for eCognition software analysis would be required. Furthermore, the main satellite used in this study, SPOT-6 has a limited life-span (up to 2022) and the cost of imagery acquisition is increasing, making its use in the long-term unsustainable.

The project overall has shown that, whilst there is potential with further development to use remote sensing for targeted management of canegrubs, several factors would need to be considered. These include (i) developing a system which could clearly differentiate between canegrub damage and other forms of cane damage - this may require either the use of other types of image sensors such as hyperspectral to give a more specific canegrub spectral signature or combining different types of data sets (such as soil maps) with spectral imagery thereby enhancing their efficiency or (ii) using alternative platforms such as UAVs for collection of spectral imagery, either to gather ground truth data for calibrating satellite data (for area-wide damage assessment) or as an alternative to the use of satellite imagery (for farm-scale assessment).

The project has built a foundation for further development of a risk-based approach for detection of areas where canegrub damage is likely to occur and, ultimately, development of targeted management options not only for canegrubs but other economically important root-feeding pests. Further work is required to develop an economically viable and user-friendly system.

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1. BACKGROUND

1.1. Root-feeding Pests - Detection and Management

Root-feeding pests, including sugarcane grubs, are generally difficult to detect and often require visual inspection of affected plants in the field. This can involve extensive sampling and digging up of plants to undertake a visual inspection of the host plant root system. Feeding damage by canegrubs on the root system that results in expression of damage symptoms in the sugarcane foliage occurs when the crop is well established, making sampling of grubs all the more difficult. In addition, it is usually too late to apply control measures, as the crop is too high to allow machinery access for insecticide applications. This project addressed the potential of using remote sensing via satellite-acquired imagery to detect grub damage areas and produce damage maps for growers. The use of remote sensing for pest and disease detection is a developing area and has been used by a number of research groups and industries worldwide using either multispectral or hyperspectral sensors (Apan *et al*., 2004; Abdel-Rahman *et al*., 2017; Housman *et al*., 2018).

This project was built on previous research findings (Sallam, 2015; Johansen *et al*., 2018) where Geoeye-1 satellite imagery, using multispectral sensors, combined with the use of GEOBIA image analysis and eCognition software, showed relatively good accuracy in predicting canegrub damage but was deemed too expensive for uptake by industry. In this project, a cheaper form of acquired imagery sourced from the SPOT-6 satellite, also using multispectral sensors, was compared with Geoeye-1 image analysis and used to develop damage maps for three sugarcane-growing areas. To add value to the project, Planet imagery, currently available at no cost, was also compared to SPOT-6 imagery to determine its effectiveness. We also assessed the potential for use of the technology by industry.

1.2.Significance of Canegrub Detection to the Sugarcane Industry

Canegrubs are the major insect pest of sugarcane in Australia and cost up to AUS$40 million per annum in years of high infestation. Because damage is observed relatively late in the growing season, this makes losses high and the option of applying a chemical control option very difficult. Conventional field sampling to estimate canegrub populations levels (and hence predicting potential damage) is labour intensive and time consuming (e.g. Samson and Eaton, 2012). Without a cost-effective method of assessing the risk of canegrub damage, losses can be substantial and therefore an area-wide monitoring and early-detection system is extremely important for growers to improve their management of canegrubs. Remote sensing offers a potential novel approach to mapping canegrub damage and, if effective at predicting hot spots for canegrub damage, could lead to a much more efficient use of chemical insecticides using a targeted approach to timely application (e.g. Sallam and Lowe, 2012; Samson and Eaton, 2012). This project examined the potential use of satellite imagery for predicting canegrub damage in the sugarcane growing regions Mulgrave, Burdekin and Mackay.

This project has focused on the potential in using remote platforms, such as satellites, for spectral imagery collection and subsequent data analysis, to improve our predictive capabilities of where canegrub damage may occur. With further development, remote sensing should ultimately lead to the production of risk maps that would allow for a more targeted approach for management of economically important root feeding pests such as greyback canegrub, where insecticides are generally used routinely because of uncertainties as to where and when damage will occur

1.3. Previous research on remote sensing of canegrubs

This project builds on a previous SRA-funded research study (SRA 2011/342; Sallam, 2015) in which Geoeye-1 satellite imagery was obtained for four participating cane-growing regions (FNQ, Burdekin, Central and Southern districts). In that study, a Geographic Object-Based Image Analysis (GEOBIA) and eCognition software were used for image analysis and subsequent production of damage maps for these areas. Use of this image analysis software coupled with extensive ground truthing indicated that up to 97% level of accuracy was observed. During that project, some regions of the industry expressed willingness to financially support and ultimately adopt the technology. However, the cost of Geoeye-1 imagery was relatively expensive compared to SPOT-6 imagery. This current project was therefore developed to determine the comparative efficacy of using the cheaper lower resolution SPOT-6 imagery to reduce the cost without substantially reducing efficacy, and to assess its likely acceptance by industry.

2. PROJECT OBJECTIVES

2.1. Overall Objective

The project aim was to develop a system for remote sensing of canegrub damage that is economically acceptable to the industry.

2.1.1. Specific Research Objectives

There were two specific objectives for the project:

1. Examine the feasibility of using SPOT-6/7 imagery to produce reliable canegrub damage risk maps.
2. If feasibility is demonstrated, work with at least two productivity services to develop a commercialisation plan.

3. OUTPUTS, OUTCOMES AND IMPLICATIONS

3.1. Outputs

3.1.1. GEOBIA and eCognition Software Validation

GEOBIA image analysis and the eCognition rule set (previously developed in project 2011/342 when analysing Geoeye-1 imagery) for classifying canegrub damage was applied to SPOT-6 imagery and modified based on new imagery examined and ground truthing. This allowed for the development of new canegrub risk maps for three cane-growing regions. The algorithm and rule set produced in this project is available to SRA and could be modified in any future project activity.

3.1.2. Area-wide Canegrub Risk Maps

Another output of the project was the delivery of a range of damage maps for canegrub damage in the Mulgrave, Herbert and Mackay regions. However these maps, once ground truthed and discussed with Productivity Services, highlighted differences in the level of predictive accuracy. This was particularly evident in the damage category of 'low likelihood of canegrub damage', where in some instances at these sites there was no evidence of canegrubs or other damage. It is not surprising that the low level of likelihood of damage category also has the larger number of false positives. However, determining a low level of likelihood is nonetheless important if early canegrub damage is to be detected to ensure that control strategies can be implemented in a timely manner. The medium- and high-damage likelihood maps are useful in a sense, as they do highlight areas where there is some significant damage occurring in the crop (although the damage may not necessarily be due to canegrubs) and would therefore be areas of interest for the grower to follow up. Overall differences were observed between geographical regions and was impacted by local weather and other damage variables (e.g. weeds, rats, bird, pig, water and wind damage and lodging); this resulted in both false positives (overestimates of grub damage) and false negatives (underestimates of grub damage) occurring. In contrast to results obtained in project 2011/342 (Sallam, 2015; Johansen 2018) when analysing Geoeye-1 imagery, the relative accuracy varied widely when using SPOT-6 imagery depending on the region and season. This finding would make it difficult to implement and gain acceptance of the technology in its current form as a predictive tool across the whole sugarcane industry.

3.1.3. Satellite Imagery

Satellite images were obtained for three cane-growing regions and this imagery was utilised in the production of damage maps and is accessible for any future research activities if required. This imagery could be made available to SRA (Appendix 1).

3.2. Adoption of Project Outputs

The target audience for adoption of the project outputs during the project was Productivity Services and potential future research collaborators. Productivity Services have been involved with the project since commencement and advice was sought from groups in Mackay, Mulgrave and the Herbert as to which areas to survey. Productivity Services also provided all the relevant block boundary shape files that allowed enabled accurate mapping of the cane-growing regions.

The results of the 3-year project were presented to the Mackay Area Productivity Services (MAPS) group in January 2019 (see Section 4.1). The consensus among workshop participants was that the system was not sufficiently attractive or accurate to be adopted.

3.3. Third Party Involvement

At this stage, because of the uncertainty around the level of accuracy of risk prediction maps and lack of specificity towards canegrubs, the increasing cost of satellite imagery and the phasing out of SPOT-6 satellite imagery in 2022, no third party or commercial provider has been identified. Should this type of detection approach or a modified version be explored in future research programs, a number of highly experienced research organisations have been identified and could be approached to collaborate.

3.4. Outcomes and Implications

The outcome of this project is that a comparison of two main types of satellite imagery were examined for both (i) accuracy to assess canegrub damage and develop accurate risk maps and (ii) economic acceptability by industry and availability to industry.

3.4.1. Accurate Damage Maps

The overall outcome was that maps could be developed for canegrub damage in different regions. However, the level of accuracy was impacted by the requirement for regular ground truthing, relative abundance of canegrub populations, requirements for regular modification of eCognition rule sets (based on ground truthing data), and limited ability to distinguish some other types of stool damage (resulting in false positive results). Consequently, overall accuracy of damage maps varied between geographic regions and seasons.

3.4.2. Potential for Industry Uptake

Apart from the relative level of accuracy between regions, two other factors would determine if this type of technology would be taken up by industry: accessibility and relative costs now and in the future. Overall, the observed variability in accuracy of grub detection in this project, due to abiotic and biotic factors, and the cost and future availability of SPOT-6 imagery, are likely to limit uptake of this particular remote-sensing approach by industry.

3.4.3. Access to and Availability of Satellite Imagery.

SPOT-6 imagery can currently be accessed by payment to commercial providers. SPOT-6 imagery at a current cost of $18 per km^2 for both the multispectral and panchromatic images is considerably less expensive than GeoEye-1 imagery ($50-80 per km^2) but its costs are beginning to increase as the decommissioning timeline for this satellite draws nearer. Alternative satellite options such as Planet imagery could be explored further but do have a lower spatial resolution so are likely to be less accurate than both SPOT-6 and Geoeye-1 imagery. The timing of access is likely to be critical and could be costly if more than one set of imagery is required at different time points. If imagery is collected and cloud cover masks key areas, further imagery will need to be purchased which could substantially increase cost (although a threshold can be set with the supplier for an acceptable image capture). In addition, the SPOT-6 satellite has a limited 'life-span' and is scheduled for decommission by 2022.

4. INDUSTRY COMMUNICATION AND ENGAGEMENT

4.1. Industry Engagement

Productivity services were kept informed of the project activities during the course of the project. The final outputs of the 3-year project were presented to the Mackay Area Productivity Services group in January 2019 at a half-day workshop organised by Phil Ross, SRA Mackay, and the damage maps generated for discussions. The general conclusions of the workshop were that, although there is certainly a need for predicting levels of canegrub damage to reduce costs to the industry, the current damage maps were not sufficiently accurate at this stage. There was also uncertainty around who would manage such a system, the level of remote sensing capability that would be required and where funding would come from to implement it on a regional basis, particularly as the cost of acquiring the satellite imagery is increasing.

4.2. Industry Communication Messages

This project work was conducted in major sugarcane growing regions of Queensland including Mulgrave, Herbert and Mackay and the focus was to investigate the potential of using SPOT-6 satellite imagery to predict areas of canegrub damage.

Results have shown that area-wide remotely sensed spectral imagery of the sugarcane canopy can be used to identify areas within the crop which have been damaged. The damage observed, although primarily due to canegrub presence, could also be due to other factors that influence textural, morphological and spectral features of the canopy. These include damage caused by biotic factors such as animals (pigs, birds and rats), weeds, and abiotic factors such as lodging, waterlogging and wind damage.

Although the degree of accuracy in identifying canegrub damage was relatively high, it differed between regions, was influenced by weather conditions, and hence is unlikely to be adopted across the industry.

The project shows that there is potential in developing a remotely sensing approach for the production of damage maps for key insect pests of sugarcane, such as canegrubs, and ultimately lead to a targeted management approach.

Ultimately, a more robust user-friendly system and economically viable remote sensing system will need to be developed and this project has provided the foundation for future research activities in this field.

5. METHODOLOGY

The main activities undertaken in the project were as follows:

1. Obtain, analyse and compare SPOT-6 or 7 and Geoeye-1 satellite-acquired imagery from the Mulgrave, Herbert and Mackay regions.
2. Pre-processing of (including radiometric correction and orthorectification) and further preparation (including pan-sharpening) of the images to a set standard prior to GEOBIA.
3. Application of rule sets in the eCognition software for canegrub damage detection.
4. Ground-truthing areas identified by both satellite- and helicopter-acquired imagery for cane grub damage.
5. Produce grub damage maps based on imagery analysed and compare with ground-truth data.
6. Engage growers and productivity services to assess future prospects of adopting this technology.

5.1. Collection of Satellite Imagery

SPOT-6 and GeoEye-1 imagery was collected in 2013, 2016 and 2018 and Planet CubeSat data for 2018 only for selected focus regions, including the Herbert, Mackay, and Mulgrave (Table 1). All purchased SPOT-6 imagery was delivered as geometrically corrected and ortho-rectified imagery. In addition, the SPOT-6 imagery was pan-sharpened, i.e. combining the high spatial resolution panchromatic band (1.5 m pixels) with the lower spatial resolution multi-spectral bands (6 m pixels) to achieve multi-spectral bands with higher spatial resolution (1.5 m pixels), prior to delivery, using the University of New Brunswick method in PCI Geomatica. The GeoEye-1 imagery was pan-sharpened (0.5 m pixels) and then geometrically aligned with the SPOT-6. The block boundary layers for each region were provided as a shapefile by Productivity Services and aligned with the SPOT-6 imagery to ensure all data layers could be integrated and compared (Figure 1). The difference in spatial resolution of the SPOT-6 and GeoEye-1 imagery is shown in Figure 2.

Table 1 Imagery and corresponding acquisition dates for selected areas of North and Central Queensland.

Imagery	Acquisition Date	Area
SPOT-6	27 June 2013	Mackay - 75 km^2
GeoEye-1	26 May 2013	Mackay - 75 km^2
SPOT-6	4 July 2016	Mulgrave - 550 km^2
GeoEye-1	30 June 2016	Mulgrave - 125 km^2
SPOT-6	21 June 2016	Herbert - 560 km^2
GeoEye-1	23 June 2016	Herbert - 100 km^2
SPOT-6	31 May 2018	Mackay - 2650 km^2
Planet CubeSat	31 May 2018	Mackay - 200 km^2

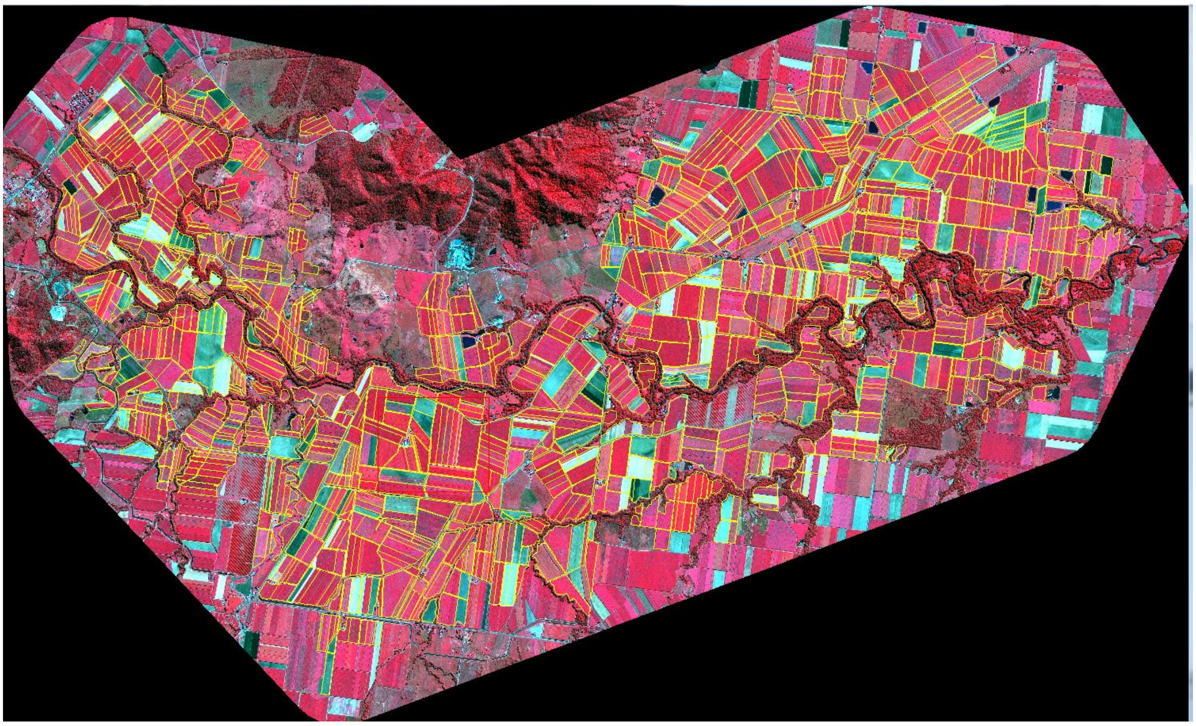

Figure 1. False colour composite of the SPOT-6 image collected on 27 June 2013 of the Mackay region with block boundaries (yellow) overlaid.

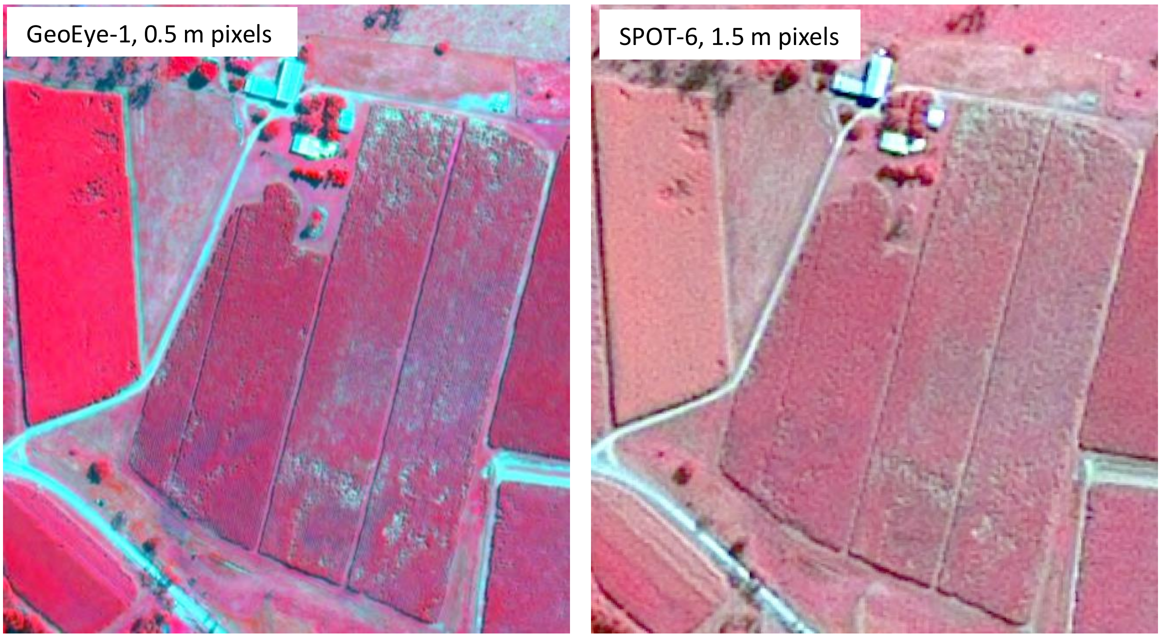

Figure 2. False colour pan-sharpened composites of GeoEye-1 and SPOT-6 imagery of a selected site with canegrub damage in the Mackay region in 2013.

The SPOT-6 and GeoEye-1 imagery was radiometrically corrected to represent Top of Atmosphere reflectance values using the following equation:

$$P_\lambda = \frac{\pi * d^2 * ((DN_\lambda * Gain_\lambda) + Offset_\lambda)}{\cos\theta_s * Esun_\lambda}$$

Where:

λ = Specific spectral band of image (Near-Infrared, Red, Green, Blue or Panchromatic)

P_λ = Top of Atmosphere Reflectance for band λ

d = Earth-Sun distance factor (ratio of actual distance to the mean distance)

DN_λ = Digital number in image for band λ

$Gain_\lambda$ = Radiometric calibration gain ($mW/cm^2/\mu m/str/DN$) for band λ

$Offset_\lambda$ = Radiometric calibration offset ($mW/cm^2/\mu m/str/DN$) for band λ

θ_s = Solar Zenith Angle (degrees)

$Esun_\lambda$ = Mean solar exoatmospheric irradiance for band λ ($mW/cm^2/\mu m$)

5.2. Collection of Ground-truthed Field Data

The collection of ground-truthed field data should ideally be evenly distributed throughout the imaged area to be mapped. However, this was not always possible due to time, labour and accessibility constraints. The collection of field data was undertaken both independently of the image data and based on the mapped results from the image data from sites: (1) with canegrub damage; (2) other types of disturbance; and (3) with healthy sugarcane.

The recommended number of field sites to be visited per imaged area to get an appropriate data sample for validation purposes included:

- 50 sites with healthy cane condition (with no previous disturbance) collected independently of the imagery;
- 50 sites with canegrub damage of various levels (low, moderate, heavy) collected independently of the imagery;
- 50 sites with no canegrub damage but other types of disturbance collected independently of the imagery;
- 50 sites identified from the image classification with healthy cane condition; and
- 100 sites identified from the image and classified with various levels of canegrub damage (low, moderate, and heavy).

However, these recommendations were in many cases difficult to achieve because of the relative absence of canegrub damage in both 2016 and 2018, which, e.g., resulted in only 11 and 7 sites with confirmed canegrub damage identified for the Herbert and Mackay regions respectively.

At each field site, a 10 m x 10 m area was assessed to ensure the spatial scale of field assessment matched that of the SPOT-6 imagery. First, a GPS reading of the centre point of each field site was obtained. At the centre point and at four additional points, e.g. locations 5 m to the north, south, east and west of the centre point (so 5 points in total), cane was assessed for grub damage until the presence or absence of canegrub damage could be confirmed. A description of each site was also undertaken to include any relevant information, such as any identified disturbance or abnormal growth patterns. The level of grub damage was categorised into low, moderate or heavy based on ground truthing and the relative abundance of canegrubs or canegrub damage. The GPS reading from the centre point was carried out for at least 3 minutes using an averaging function to collect GPS points every 1 second or until the estimated positional error was less than 3 m. Each averaged GPS reading was recorded in Eastings and Northings, using the UTM projection (selecting the appropriate UTM zone, which was zone 55 in most cases) and the WGS84 datum. Four horizontal photos showing the cane condition and appearance were taken at the centre point, pointing towards the other four points, i.e. in the direction of north, south, east and west. These photos were numbered so that the photos could be matched with the site location. Each site selected in the field independently of the imagery was as homogenous as possible within the 10 m x 10 m area, e.g. the whole area consisted of healthy cane or was affected by grub damage, to ensure suitable integration with the SPOT-6 imagery.

In the absence of fully processed imagery (due to an initial delay in delivery by the commercial provider), fieldwork was undertaken between 11 June 2018 and 13 July 2018 to acquire information on location and representation of canegrub damage and other damage symptoms within the Mackay region. Two helicopter flights were flown on 13 June, following two flight paths (i) TeKowai North via Gargett to Calen and (ii) TeKowai South via Gargett to Kinchant Dam to Sarina. This allowed acquisition of further imagery to identify additional potential canegrub damage sites for further validation purposes. The helicopter true-colour imagery was visually examined by SRA to identify potential damage sites for additional ground truthing (Figure 3). Potential grub-damaged sites were located based on analysis of GPS-referenced photographic images taken from the helicopter.

Figure 3. Example of 'potential' grub-damaged sites observed from helicopter flight (June 2018).

5.3. Rule Set Development for Detection of Canegrub Damage

The objective of geographic object-based image analysis (GEOBIA) was to develop and apply theory, methods and tools for replicating and improving human interpretation of remotely sensed image data in an automated manner. GEOBIA consists of image segmentation, i.e. clustering of pixels into homogenous objects, and subsequent classification or labelling of the objects, and modelling based on the characteristics of objects. In high spatial resolution image data, individual features on the ground usually consist of multiple pixels, which may exhibit variable spectral reflectance characteristics. As a result, the fundamental assumption of per-pixel image classification, i.e. homogenous features with homogenous and unique spectral reflectance values, is not met. GEOBIA overcomes problems of traditional pixel-based techniques of high spatial resolution image data, by firstly defining segments rather than pixels to classify, and allowing spectral reflectance variability to be used as an attribute for discriminating features in the segmentation approach. In addition, GEOBIA allows inclusion of additional information to guide the classification and modelling processes, by the use of: object average reflectance; object standard deviation; object maximum, minimum and median values; area and shapes of objects; texture of objects; location of objects in relation to other objects and land cover classes in the landscape; relation of objects to the image scene characteristics; exploitation of existing geographic information from spatial data infrastructures; and many other contextual information properties not available in traditional pixel-based approaches. GEOBIA also enables a hierarchical multiple spatial scale approach when mapping, which takes advantage of characteristic nested scales of environmental features occurring across different spatial scales in all environments.

The eCognition Developer software versions 9.1-9.3 was used to develop an approach for mapping of canegrub damage by designing a rule set of conditions based on the pan-sharpened SPOT-6 imagery. Initially, the existing GIS layer of block boundaries was used to segment the sugarcane block boundaries (Figure 4a). Subsequently, all areas with sugarcane within the block boundaries were mapped to exclude fallow and already harvested areas from further analysis based on the Normalized Difference Vegetation Index (NDVI) (Figure 4b). In some cases, only parts of a sugarcane block had been harvested, so to exclude these harvested areas as well, a fine scale segmentation was produced and NDVI was used once again to exclude those parts of individual sugarcane blocks that were already harvested from further analysis. All neighbouring objects classified as sugarcane fields were then merged, while still using the block boundary layer as a restriction to prevent individual blocks from being merged. This step caused some sugarcane blocks to appear smaller than those in the block boundary layer, as harvested parts of blocks were now excluded.

In the next step, a fine scale segmentation at a new level was produced to divide each block into smaller homogenous objects. As reduced growth, stool tipping and exposure of bare ground often manifest canegrub damage, the cane occurring within an object representing canegrub damage appeared less green than healthy undamaged cane. Hence, from the original image (Figure 4c) an NDVI based on the red and near infrared bands was produced (Figure 4d) to automatically locate those parts of a block with the lowest 50 quantile of NDVI values. As well as having a reduced NDVI value, the damaged areas often displayed a 'rougher' texture than healthy cane. Hence, an edge detection filter was used to identify distinct brightness edges. To reduce noise, a Gaussian smoothing filter of 9 x 9 pixels was used to highlight areas with rough texture (Figure 4e). Subsequently, the 50 quantile (50% of highest values) of the smoothed edge layer was used to identify the 50% brightest objects, indicating areas with many edges, i.e. rough texture/large variation in pixel values, which can be expected in areas with damaged sugarcane. This calculation was also done for each individual block to avoid confusion caused by different cane varieties. The 50 quantile (50% of highest values) of the standard deviation of the red layer objects was also used to identify those areas with the roughest texture, potentially representing damaged sugarcane.

After several processing trials with significant classification errors along the block boundary edges, a step was introduced to reduce these edge effects. The outermost six pixels, e.g. 9 m, were initially excluded from being classified as potential grub damage (Figure 4f).

The thresholds for NDVI, the edge detection layer and the standard deviation of the red band were empirically derived. The analysis was done at the block level to avoid confusion caused by different cane varieties due to their different reflectance properties. If all three conditions (NDVI, edge detection and red standard deviation thresholds) were fulfilled, the fine scale objects within each sugarcane block, excluding the outermost edges of the sugarcane blocks, were considered to be potential grub damage (Figure 4g). The same process was repeated, but now applying the three conditions to only the outermost edges (9 m) of the fine scale objects within the sugarcane blocks. If those outermost edge objects that fulfilled the conditions (Figure 4h) did also touch an object classified as potential grub damage, these were merged and included as potential grub damage (Figure 4i). Those outermost edge objects that fulfilled the conditions but did not touch potential grub damage objects remained classified as sugarcane fields.

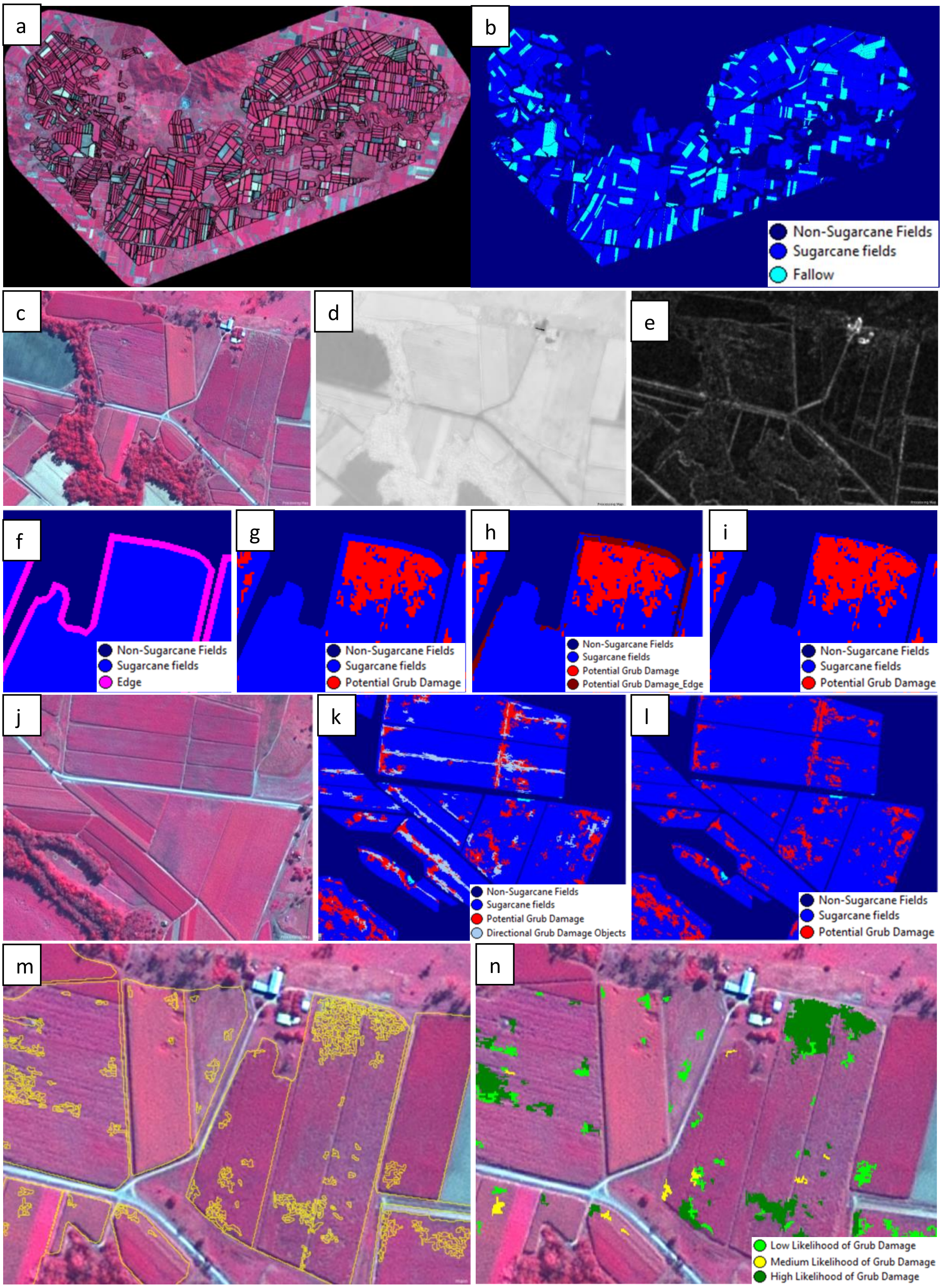

Figure 4 (a) Block boundaries; (b) sugarcane block classification; (c) image subset; (d) NDVI; (e) edge detection filter; (f) block edge classification; (g, h ,i) potential grub damage mapping; (j) image subset; (k, l) removal of directional objects; (m fine scale segmentation, (n) grub damage map.

In some cases, areas with canegrub damage appeared with dark areas (often along the boundary of affected and non-affected sugarcane, exhibiting different image texture). Hence, another condition was set to include dark objects. First, the value for the 30-quantile darkest objects was identified within each sugarcane block. If the difference between the 30-quantile darkest object value and the mean brightness value of an object was below a set threshold, these objects were also included as potential grub damage.

Since tracks (see Figure 4j) between individual blocks were often incorrectly classified as grub damage (Figure 4k), they were subsequently excluded if the objects were elongated, narrow, had smooth edges and had a direction of ± 5 degrees of the main block direction, or if they had a length/width ratio > 3.5 (Figure 4l).

Subsequently, all potential grub damage areas were re-segmented at a fine scale to allow further discrimination of the level of grub damage (Figure 4m). As the potential 'grub damaged' objects only represented those areas with the lowest NDVI values and roughest texture within each block at this stage in the mapping approach, it was considered important to assess the absolute NDVI and texture difference between potential grub damage objects and the remaining parts of each individual block. Hence, a number of conditions were specified in the rule set to classify potential grub damage into low, moderate and high likelihood of an object representing grub damage based on how different the NDVI and texture values were in relation to the remaining parts of the block. For an object to be classified as 'high' likelihood of grub damage, absolute differences above a set threshold in both NDVI and texture values were required. Less stringent conditions were applied for mapping 'moderate' and 'low' likelihood of grub damage. Ideally, these thresholds are set based on calibration information obtained from field identification of canegrub damage, although generic thresholds may be applied in the absence of calibration data. Further refinements to the classification was also performed, e.g. by excluding very small objects and, if an object classified as low likelihood grub damage was completely enclosed by likely grub damage objects, the 'low likelihood' objects were reclassified as 'likely grub damage' (Figure 4n).

5.4. Evaluation of Mapping Accuracy and Image Comparison

Mapping accuracies of the image data were assessed against field-derived observations. Accuracy assessment requires obtaining field validation data that represent a range of symptoms. At least 50 samples for each category/land-cover class are generally required for validation of remote sensing maps. The 'overall accuracy' is a mapping accuracy measure that estimates the number of correctly classified reference sites (field sites used for ground-truthing) in relation to the total number of selected field sites. From the comparison of field and image data, it was possible to assess the number of false positives (overestimation) and false negatives (underestimation) of canegrub damage. The mapping accuracies derived from the SPOT-6 and GeoEye-1 image data sets were compared to evaluate their performance. The distribution and area of mapped canegrub damage was also assessed and compared for the two image data sets for each region.

6. RESULTS AND DISCUSSION

6.1. Initial Assessment of Mackay Region Based on 2013 Imagery

Comparing the mapping results in Table 2 and Table 3, the correctly classified locations with grub damage were very similar using the SPOT-6 and GeoEye-1 images. However, a reduction in false positives was noted when using the SPOT-6 image, indicating that the use of the SPOT-6 may reduce the likelihood of overestimating the extent of grub damage.

Table 2 Accuracy assessment of imaged grub damage at the Mackay site, June 2013 based on SPOT-6 image data.

	Actual grub damage		
Predicted grub damage	Yes	No	
Yes	46	9	16.4% false positives (9/55)
No	6	9	
	11.5% false negatives (6/52)		

Table 3 Accuracy assessment of imaged grub damage at the Mackay site, June 2013 based on GeoEye-1 image data.

	Actual grub damage		
Predicted grub damage	Yes	No	
Yes	49	14	22.2% false positives (14/63)
No	3	4	
	5.8% false negatives (3/52)		

Comparing the mapping results of the GeoEye-1 and SPOT-6 image data in relation to the grub counts for the Mackay site in 2013, only small differences were observed. For areas with low grub counts, there was a tendency of mapping these areas as low or moderate likelihood of grub damage using the SPOT-6 image, whereas these were assigned a higher likelihood of grub damage using the GeoEye-1 image (Table 4).

Table 4 Grub counts compared with map detection using the 2013 GeoEye-1 and SPOT-6 images of Mackay.

Grub counting within 20 m x 20 m block	Map detection - GeoEye-1	Map detection - SPOT-6
2	Moderate likelihood of grub damage detected within polygon	Low likelihood of grub damage detected along edges of polygon
11	No grub damage detected	No grub damage detected
7	High likelihood of grub damage detected within 3 m	No grub damage detected, but low likelihood of grub damage detected within 8 m and high likelihood of grub damage detected within 11 m
22	No grub damage detected	No grub damage detected
34	High likelihood of grub damage detected within 15 m	Low likelihood of grub damage detected within polygon, and high likelihood of grub damage detected within 15 m
16	High likelihood of grub damage detected within polygon	Low likelihood of grub damage detected within polygon
47	High likelihood of grub damage detected within polygon	High likelihood of grub damage detected within polygon
0	No grub damage detected	No grub damage detected
10	High likelihood of grub damage detected within polygon	Low and high likelihood of grub damage detected along edges of polygon
9	High likelihood of grub damage detected within polygon	Block harvested. High likelihood of grub damage detected 3 m from polygon edge
0	High likelihood of grub damage detected within polygon	Moderate likelihood of grub damage detected within polygon
12	High likelihood of grub damage detected within polygon	High likelihood of grub damage detected within polygon
31	High likelihood of grub damage detected within polygon	Moderate likelihood of grub damage detected within polygon
22	High likelihood of grub damage detected within polygon	High likelihood of grub damage detected within polygon
9	High likelihood of grub damage detected within polygon	Block harvested.
27	Moderate likelihood of grub damage detected within polygon	High likelihood of grub damage detected within polygon
14	High likelihood of grub damage detected within polygon	High likelihood of grub damage detected within polygon

Figure 5 provides a comparison of the GeoEye-1 and SPOT-6 image spatial resolution and the derived mapping results for a subset of the area mapped in 2013. From these figures and from assessing the entire mapped area in Mackay for 2013, some common characteristics were identified:

- Larger areas were mapped as grub damage in the Geo-Eye-1 image (Table 5);
- Blocks with grub damage mapped in the Geo-Eye-1 image also seemed to be mapped with grub damage in the SPOT-6 image, although covering a smaller proportion of the blocks;
- Fewer edge effects were identified in SPOT-6 image derived map, e.g. along tracks within blocks and block edges, which in many cases were mapped as grub damage by the GeoEye-1 image;
- A similar distribution of grub damage was mapped from the two image data sets;
- Smaller patches with potential grub damage were omitted by the SPOT-6 image, possibly because of the lower spatial resolution;
- Areas with 'Indian file' structured sugarcane, i.e. very thin erect stalks of cane, seemed less likely to be mapped as grub damage using the SPOT-6 image compared to the GeoEye-1 image; and
- Processing of the SPOT-6 image data was faster.

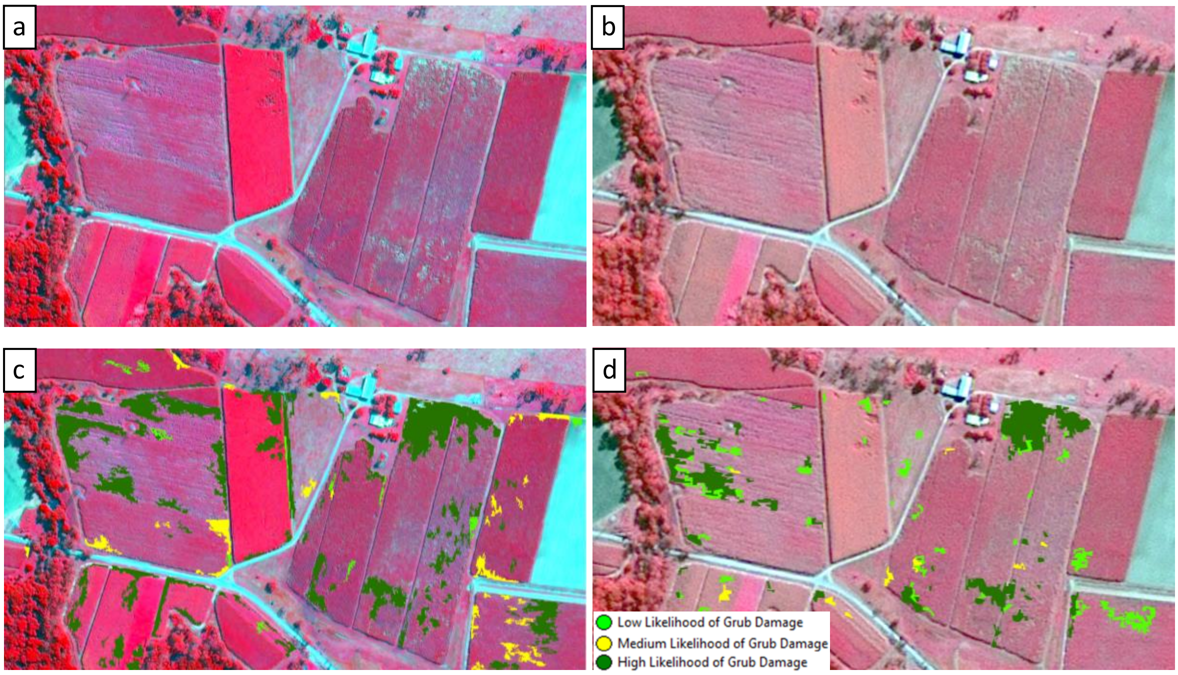

Figure 5 Subset of the (a) GeoEye-1 and (b) SPOT-6 images collected in 2013 within a month apart, and the corresponding classification results of canegrub damage for the (c) GeoEye-1 and (d) SPOT-6 imagery.

Table 5 Comparison of area mapped as grub damage for the Mackay site in 2013 using the GeoEye-1 and SPOT-6 imagery.

Because of harvesting occurring between the image capture of the GeoEye-1 and SPOT-6 images, 41.31 km^2 and 37.27 km^2 of sugarcane occurred in the GeoEye-1 and SPOT-6 images, respectively. To adjust this offset, a multiplication factor of 41.31/37.27 = 1.1094 was used.

Satellite Imagery Source	High Likelihood	Medium Likelihood	Low Likelihood	Total
GeoEye-1	2.898 km^2	0.670 km^2	0.661 km^2	4.229 km^2
SPOT-6	0.966 km^2	0.918 km^2	0.960 km^2	2.076 km^2
SPOT-6 adjusted	1.072 km^2	1.018 km^2	1.065 km^2	2.303 km^2

Based on the existing field data, it is difficult to conclude with certainty if the use of the GeoEye-1 image data represents an overestimation of grub damage or if the use of the SPOT-6 image data causes an underestimation of grub damage. However, based on the observations and interpretation when comparing the results of the two image data sets, it is likely that the GeoEye-1 image does result in an overestimation of grub damage, especially along block edges and tracks within sugarcane fields. The lower spatial resolution of the SPOT-6 image may result in the omission of small patches of grub damage, although some small patches identified by the SPOT-6 image were not identified from the GeoEye-1 image. Figure 6 shows the distribution of sugarcane blocks with various levels of mapped canegrub damage in the two image data sets.

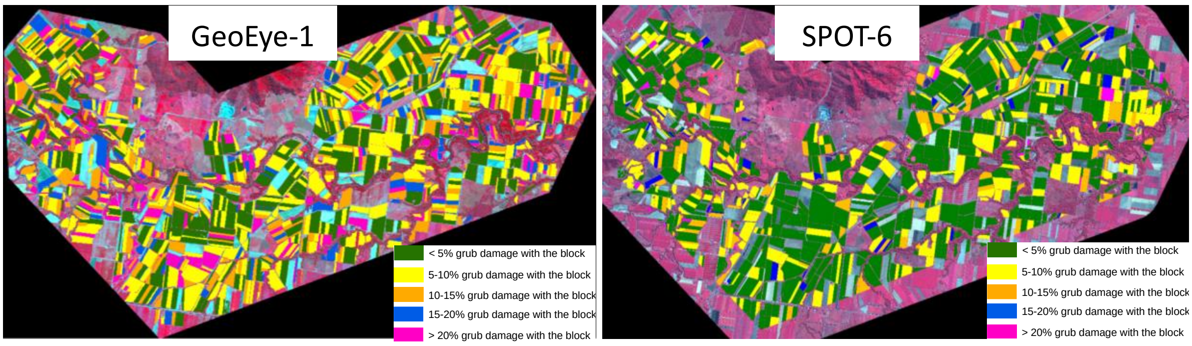

Figure 6 Distribution of blocks with different levels of canegrub damage based on the mapping results of the GeoEye-1 (a) and SPOT-6 (b) imagery for the Mackay site in 2013.

6.2. Assessment of Mulgrave and Herbert Regions Based on 2016 Imagery

SPOT-6 and GeoEye-1 imagery were collected at similar times for both the Mulgrave and Herbert regions in June/July 2016. Figure 7 shows the image data sets.

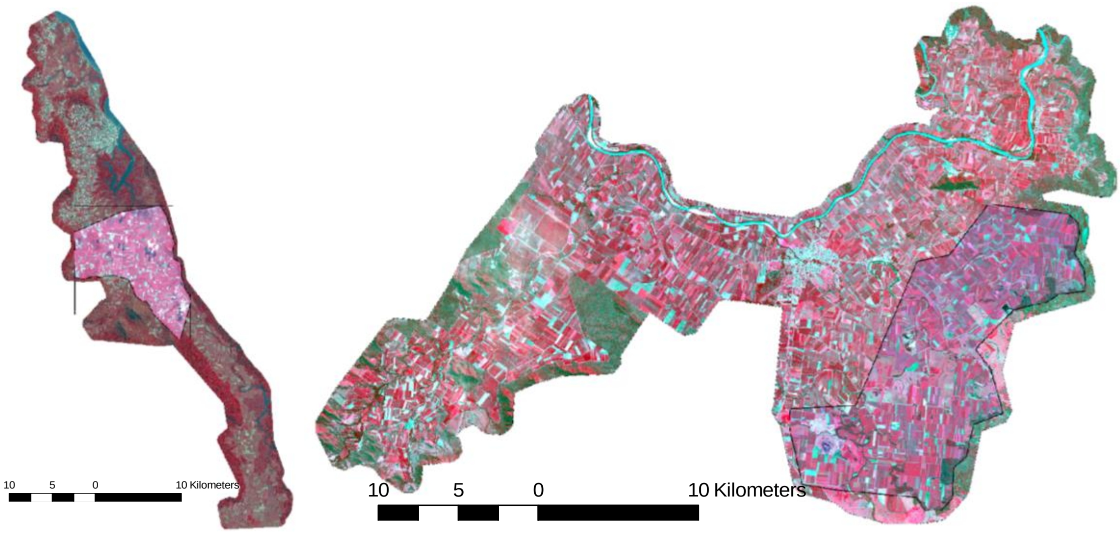

Figure 7. SPOT-6 imagery of the Mulgrave and Herbert regions with overlaying GeoEye-1 imagery.

177 reference field samples were used for the accuracy assessment of the Mulgrave region. Eighty of these were sourced from the helicopter flight (25 of these were located outside the GeoEye-1 image but within the SPOT-6 image). Two other helicopter samples were at locations with cloud cover in the GeoEye-1 image. In total, 159 field reference sites were selected for ground-truthing. For the Herbert region, 74 field reference sites were ground-truthed.

Comparing the mapping results in Table 6-9 based on the field data, the correctly classified locations with grub damage were higher using the GeoEye-1 images compared to the SPOT-6 images. However, a significant reduction in false positives was noted when using the SPOT-6 image, indicating that the use of the SPOT-6 imagery may reduce the likelihood of overestimating the extent of grub damage. This also resulted in higher overall accuracies for both Mulgrave and Herbert sites when using the SPOT-6 images. The mapping accuracies were higher for the Mulgrave site than the Herbert site. This was probably due to blocks showing more heterogeneity in the Herbert region compared to Mulgrave, resulting in more false positives in the final map.

Table 6 Accuracy assessment of imaged grub damage at the Mulgrave site, June 2016 based on SPOT-6 imagery.

	Actual grub damage		
Predicted grub damage	Yes	No	
Yes	38	28	42.4% false positives (28/66)
No	9	102	
	19.1% false negatives (9/47)		

Overall accuracy = 79.1%. The main issues causing false positives were lodging/wind and pig/rat/cockatoo damage.

Table 7 Accuracy assessment of imaged grub damage at the Mulgrave site, June 2016 based on GeoEye-1 image data.

	Actual grub damage		
Predicted grub damage	Yes	No	
Yes	43	62	59.0% false positives (62/105)
No	1	44	
	2.3% false negatives (1/44)		

Overall accuracy = 58.0%. The main issues causing false positives were lodging/wind and pig/rat/cockatoo damage, while old ratoons, vines, grasses and canopy gaps also contributed.

Table 8 Accuracy assessment of imaged grub damage at the Herbert site, June 2016 based on SPOT-6 image data.

	Actual grub damage		
Predicted grub damage	Yes	No	
Yes	10	22	68.7% false positives (22/32)
No	1	41	
	9.1% false negatives (1/11)		

Overall accuracy = 68.9%. The main issues causing false positives were old ratoons, vines, grass weeds and canopy gaps, while lodging/wind and pig/rat/cockatoo damage also contributed. Note that the low number (11) of field observations of canegrub damage is insufficient to accurately determine false positives and negatives.

Table 9 Accuracy assessment of imaged grub damage at the Herbert site, June 2016 based on GeoEye-1 image data.

	Actual grub damage		
Predicted grub damage	Yes	No	
Yes	11	40	78.4% false positives (40/51)
No	0	23	
	0% false negatives (0/11)		

Overall accuracy = 45.9%. The main issues causing false positives were old ratoons, vines, grass weeds and canopy gaps as well as lodging/wind and sprawling, while pig/rat/cockatoo damage also contributed. Note that the low number (11) of field observations of canegrub damage is insufficient to accurately determine false positives and negatives.

As stated above, the overall accuracies were higher when using SPOT-6 imagery compared to GeoEye-1 imagery, despite the higher success rate at detecting canegrub damage using the GeoEye-1 imagery. The main causes of false positives for the Mulgrave site using the GeoEye-1 image were sugarcane lodging due to cane size and wind as well as pig, rat and cockatoo damage. While false positives appeared in the SPOT-6 image map to a similar extent as the GeoEye-1 image with regards to pig, rat and cockatoo damage, false positives were significantly reduced in the SPOT-6 image with regards to lodging due to cane size and wind effects. This was because lodging occurred at a more homogenous level throughout the affected blocks, whereas pig, rat and cockatoo damage was patchy. At the spatial scale of the SPOT-6 image, the lodging appeared homogenous, whereas at the spatial scale of the higher spatial resolution GeoEye-1 images, the lodging produced more distinct textural and spectral differences similar to the appearance of local-scale grub damage. (Figure 8).

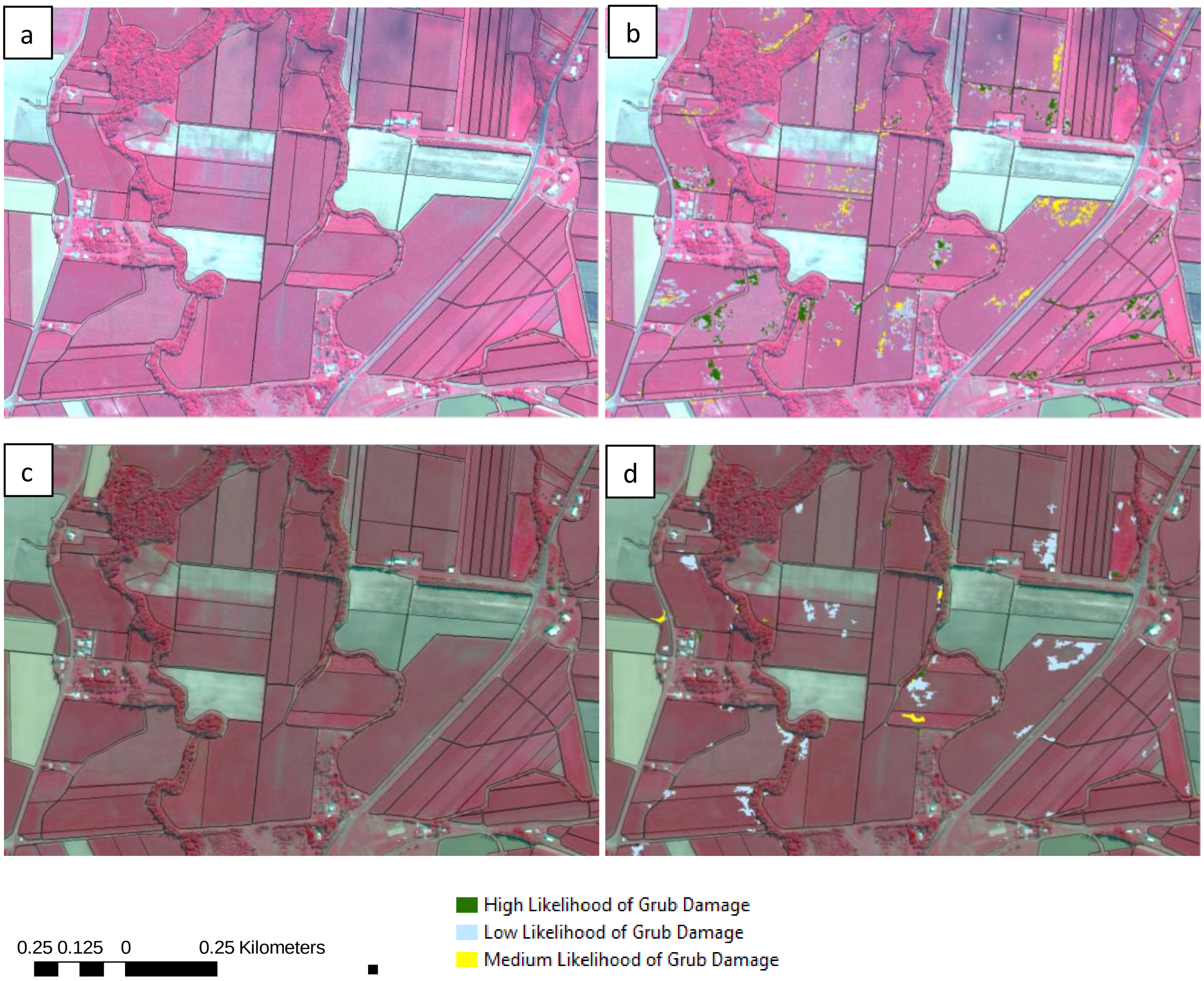

Figure 8. A significant difference in the level of mapped canegrub damage is visible when comparing the GeoEye-1 and SPOT-6 imagery in Mulgrave. (a) Subset of GeoEye-1 image and (b) corresponding image with classification of grub damage. (c) Subset of SPOT-6 image and (d) corresponding image with classification of grub damage.

Figure 7 and Figure 8 display the overestimation of canegrub damage when using the GeoEye-1 imagery compared to the SPOT-6 imagery. Because of the rainfall pattern (late rain and rain during harvest) for the Mulgrave and Herbert regions in 2016, canegrub damage was generally difficult to identify from satellite imagery. Areas with canegrub damage appeared greener and hence with less textural and spectral differences to healthy cane than in previous years. Because of the way grub-affected cane appeared in 2016 (i.e. not as obvious and distinct as previous years) from a satellite image perspective, the thresholds in the rule set had to be reduced to make sure that what appeared to be potential grub damage was included in the final map. This meant that the difference of vegetation index values and texture values between healthy cane and canegrub damage was reduced and hence the likelihood of incorrectly classifying other types of disturbance increased, particularly for the GeoEye-1 image. For the SPOT-6 image, it meant that there was a fine margin between an object being classified as cane with and without damage because of the larger pixel size. That is why most of the grub damage objects for the SPOT-6 image were classified as low likelihood of grub damage rather than moderate or high likelihood of grub damage.

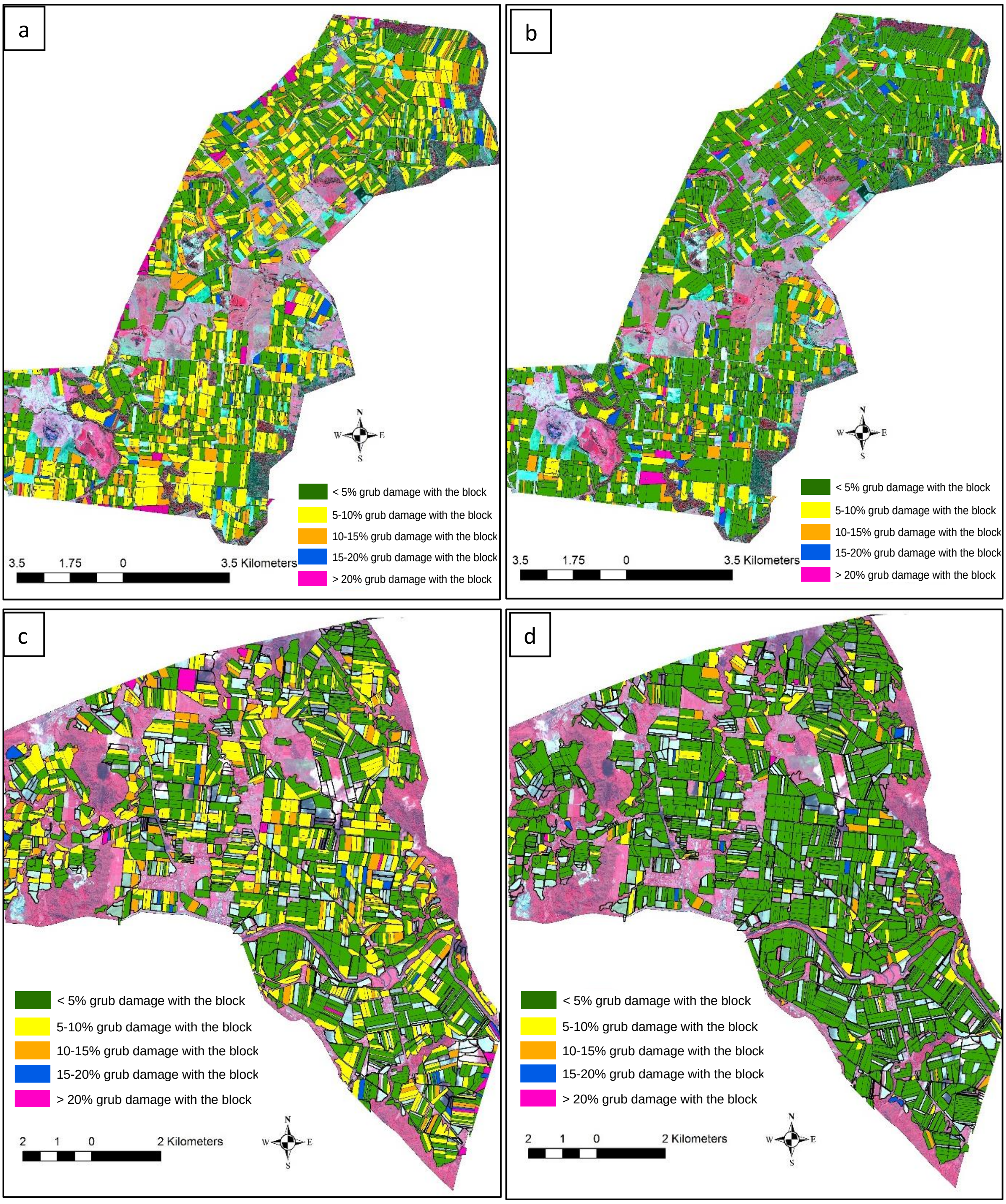

Figure 9. Distribution of blocks with different levels of grub damage based on the mapping results of the GeoEye-1. (a+c) and SPOT-6 (b+d) image data for the Herbert (a+b) and Mulgrave (c+d) sites.

Using the SPOT-6 imagery from the Mulgrave region, 999 out of 3633 blocks were mapped with some likelihood of canegrub damage, contrasting strongly with the GeoEye-1 imagery where 1731 out of 1827 blocks were mapped with some likelihood of canegrub damage. Similar observations were identified for the Herbert imagery, with 5257 out of 10328 blocks identified with some likelihood of grub damage in the SPOT-6 imagery and 2518 out of 2672 blocks with possible grub damage in the GeoEye-1 imagery. Hence, based on these results, SPOT-6 imagery appears to have good potential to be used as a cheaper alternative to the higher spatial resolution and costly GeoEye-1 imagery.

Table 10-13 provide details of which field-based categories were either correctly or incorrectly classified in the SPOT-6 and GeoEye-1 imagery. For the Mulgrave site, lodging due to cane size and wind as well as pig, rat and cockatoo damage were the main contributors to incorrect classification of grub damage when using the SPOT-6 imagery (Table 10). The majority of sites incorrectly classified were in areas of low likelihood of grub damage. Similar characteristics, but to a larger extent, were identified for the GeoEye-1 image although blocks with old ratoons, vines and canopy gaps sparse cane were also misclassified using the GeoEye-1 imagery (Table 11). Most blocks with healthy cane were correctly classified using both types of imagery. For the Herbert site, sprawling and lodging caused more overestimation of canegrub damage in the GeoEye-1 imagery than the SPOT-6 imagery (Table 12-13).

Table 10 Field-based observations in relation to the SPOT-6 derived mapping results for the Mulgrave site.

Land-Cover classes identified in the field	No Grub Damage	Low Likelihood of Grub Damage	Medium Likelihood of Grub Damage	High Likelihood of Grub Damage
Light grub damage	7	19	8	5
Moderate grub damage	1		6	
Heavy grub damage	1			
Old ratoon/vines/grasses /canopy gaps/sparse	5		2	1
Lodging/size/wind	58	10		1
Healthy cane	27	1		
Pig/Rat/Cockatoo damage	4	11		
Sprawling	6	1		
Wet/inundated	2	2		

Table 11 **Field-based observations in relation to the GeoEye-1 derived mapping results for the Mulgrave site.**

Land-Cover classes identified in the field	**No Grub Damage**	**Low Likelihood of Grub Damage**	**Medium Likelihood of Grub Damage**	**High Likelihood of Grub Damage**
Light grub damage	1	5	8	21
Moderate grub damage		1	1	6
Heavy grub damage			1	
Old ratoon/vines/grasses /canopy gaps/sparse	1		5	2
Lodging/size/wind	20	3	11	25
Healthy cane	15	1		
Pig/Rat/Cockatoo damage	4	2	3	6
Sprawling	2		1	
Wet/inundated			1	2

Note: Not all field observations were within the extent of the GeoEye-1 image; hence, more observations are included in Table 10 for the SPOT-6 imagery than in Table 11.

Table 12 Field-based observations in relation to the SPOT-6 derived mapping results for the Herbert site.

Land-Cover classes identified in the field	**No Grub Damage**	**Low Likelihood of Grub Damage**	**Medium Likelihood of Grub Damage**	**High Likelihood of Grub Damage**
Light grub damage	1	7		1
Moderate grub damage		2		
Old ratoon/vines/grass weeds/canopy gaps/sparse	5	5	4	1
Lodging/size/wind	15	2	1	1
Healthy cane	6			
Pig/Rat/Cockatoo/Bandicoot damage		3		
Sprawling	13	3	1	
Waterlogged/Inundated	2	1		

Table 13 Field-based observations in relation to the GeoEye-1 derived mapping results for the Herbert site.

Land-Cover classes identified in the field	No Grub Damage	Low Likelihood of Grub Damage	Medium Likelihood of Grub Damage	High Likelihood of Grub Damage
Light grub damage			2	7
Moderate grub damage			1	1
Old ratoon/vines/grass weeds/canopy gaps/sparse	2		6	7
Lodging/size/wind	7	1	1	10
Healthy cane	5			1
Pig/Rat/Cockatoo/Bandicoot damage				3
Sprawling	8	2	3	4
Waterlogged / Inundated			1	2

6.3. Assessment of Mackay Region Based on 2018 Imagery

The image processing for the whole Mackay region (2,650 km^2) based on the image acquired on 31 May 2018 (Figure 10) took a single computer 38 hours and 39 min to process, and produced a total of 8055 polygons classified as high likelihood of canegrub damage, 4261 polygons classified as medium likelihood of canegrub damage, and 31407 polygons classified as low likelihood of canegrub damage.

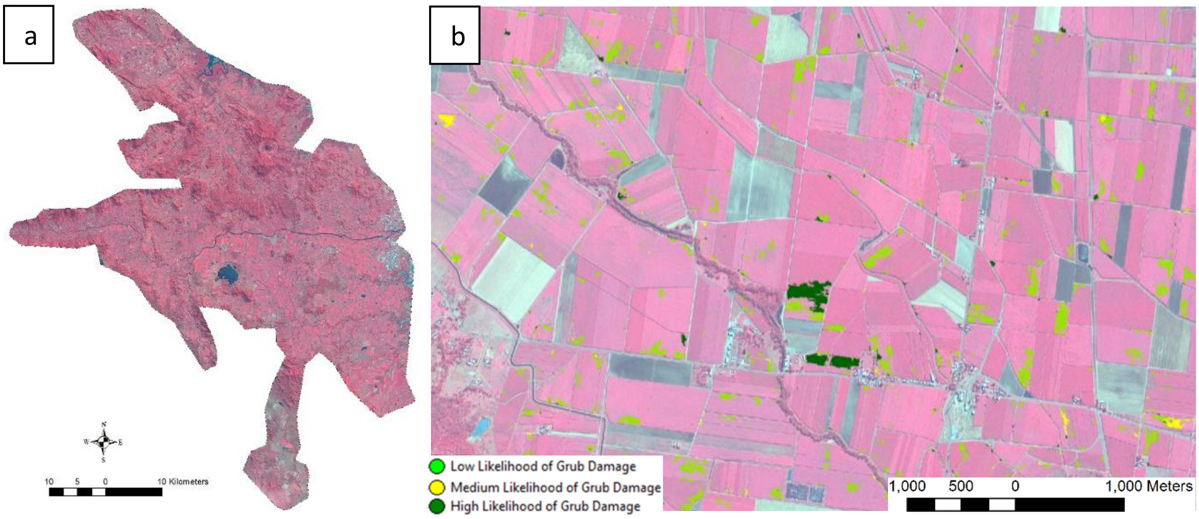

Figure 10. (a) Pan-sharpened SPOT-6 image of the whole Mackay Region collected on 31 May 2018 and (b) selected subset showing mapped canegrub damage.

Fieldwork was undertaken to acquire information on the location and representation of canegrub damage within the Mackay region. A helicopter flight was also taken to identify further potential canegrub damage sites for validation purposes. Selected sites suspected of potential cane grub damage from both satellite acquired imagery and helicopter acquired photographs were ground truthed. The ground-truth data were integrated with the mapping results of the SPOT-6 image to produce an error matrix (Table 14 and 15) to get an understanding of false positives and negatives.

Table 14 Ground-truthing data: Error matrix showing correctly classified canegrub damage as well as errors of omission and commission.

Land-Cover classes Field observations	Mapped as no canegrub damage	Mapped as low likelihood	Mapped as medium likelihood	Mapped as high likelihood
Heavy grub damage				1
Medium grub damage			1	1
Possible grub damage	14	21	9	14
Old grub damage		1		
Lodging/Snapping	23	6		
Weedy/Dry/Canopy gaps/Stunted	13	23	2	12
Rat damage	4	4		
Flooded/Water damage		1		2
Thin cane		2	1	
Old standover cane	3	1		1
Healthy cane	33	10	1	
Total	**90**	**69**	**14**	**31**

From Table 14, it can be seen that the few sites confirmed in the field as heavy and medium grub damage were also mapped as grub damage. Of those sites identified as possible grub damage, 44 out of 58 locations were mapped as canegrub damage. However, the low likelihood category represented 21 of the 44 mapped grub damage sites. The low likelihood category, if included, caused a significant amount of false positives due mainly to lodging, weeds, gaps and stunted cane, rat damage and even some healthy cane. Some of the healthy cane that was mapped as low likelihood of canegrub damage occurred with damage caused by herbicides or was planted with wider spacing and hence produced lower vegetation index values and high texture values. The main contributor causing false positives was blocks with lots of weeds and gaps and stunted cane.

As the “low likelihood of grub damage” category used for the classification was the cause of significant error of commission (false positives), this category should be disregarded in this case. It is difficult to say what effect that would have on the detection of canegrub damage sites, because of the very low number of sites detected in the field. For the helicopter sites assessed, there were only four ‘positive’ grub sites, while for the other ground-truthed locations identified based on the imagery, only three sites were identified (Table 15). Of those sites identified as possible grub damage, 21 out of 57 locations were mapped as canegrub damage. However, the low likelihood category represented 10 of the 21 mapped grub damage sites. Because of the very low number of canegrub damage sites, there were not enough data for “calibration” of the rule set thresholds used to classify sites into the three categories of low, medium or high likelihood of canegrub damage. Hence, existing thresholds from previous years were used. This may have affected the results and the ability to discriminate other disturbance factors from grub damage, especially in the low likelihood of canegrub damage category. Using generic thresholds for classifying the three categories of likelihood of grub damage may cause either over- or underestimation of canegrub damage, but without enough field data for calibration or to validate the results based on the generic thresholds, this becomes difficult to determine.

Figure 11 shows the distribution of objects classified as moderate and high likelihood of canegrub damage for the Mackay region in 2018. Please note that the mapped grub damage areas are enlarged in Figure 11 for visualisation purposes. There seem to be no distinct canegrub damage ‘hotspots’, but a more even distribution of mapped grub damage. This may simply be because most of these objects actually represent other types of disturbance as little grub damage was reported from field observations. Hence, a conclusion for the developed method is that for years with low levels of canegrub damage, and hence insufficient calibration and validation field data, it is very difficult to determine how successful the mapping method is.

Table 15 Helicopter ground-truthing data: Error matrix showing correctly classified canegrub damage as well as errors of omission and commission.

Mapped canegrub damage was divided into three classes, i.e. low, medium and high likelihood of grub damage, based on their vegetation index and texture image values. Bold font indicates 'Positive' grub damage and grub presence confirmed by ground-truthing of helicopter-acquired imagery.

Land-Cover classes **Field observations**	**Classified as low likelihood**	**Classified as medium likelihood**	**Classified as high likelihood**	**Not classified as grub damage***
Drought stressed	0	0	1	2
Grub damage and insects present	0	**1**	**3**	0
Healthy cane confirmed	4	0	0	11
Natural lodging	2	0	0	11
Old damage/large gaps	0	0	1	9
Other agronomic issues	0	1	0	1
Vines/Other weeds	4	0	2	2
Water related damage	0	0	2	0
Total	**10**	**2**	**9**	**36**

***** "not mapped" = ground truthed sites that were not mapped as low, medium or high likelihood of grub damage by SPOT-6 imagery but were observed as 'damaged' by ground surveys and helicopter-acquired imagery. NB. Harvested sites were excluded from the dataset.

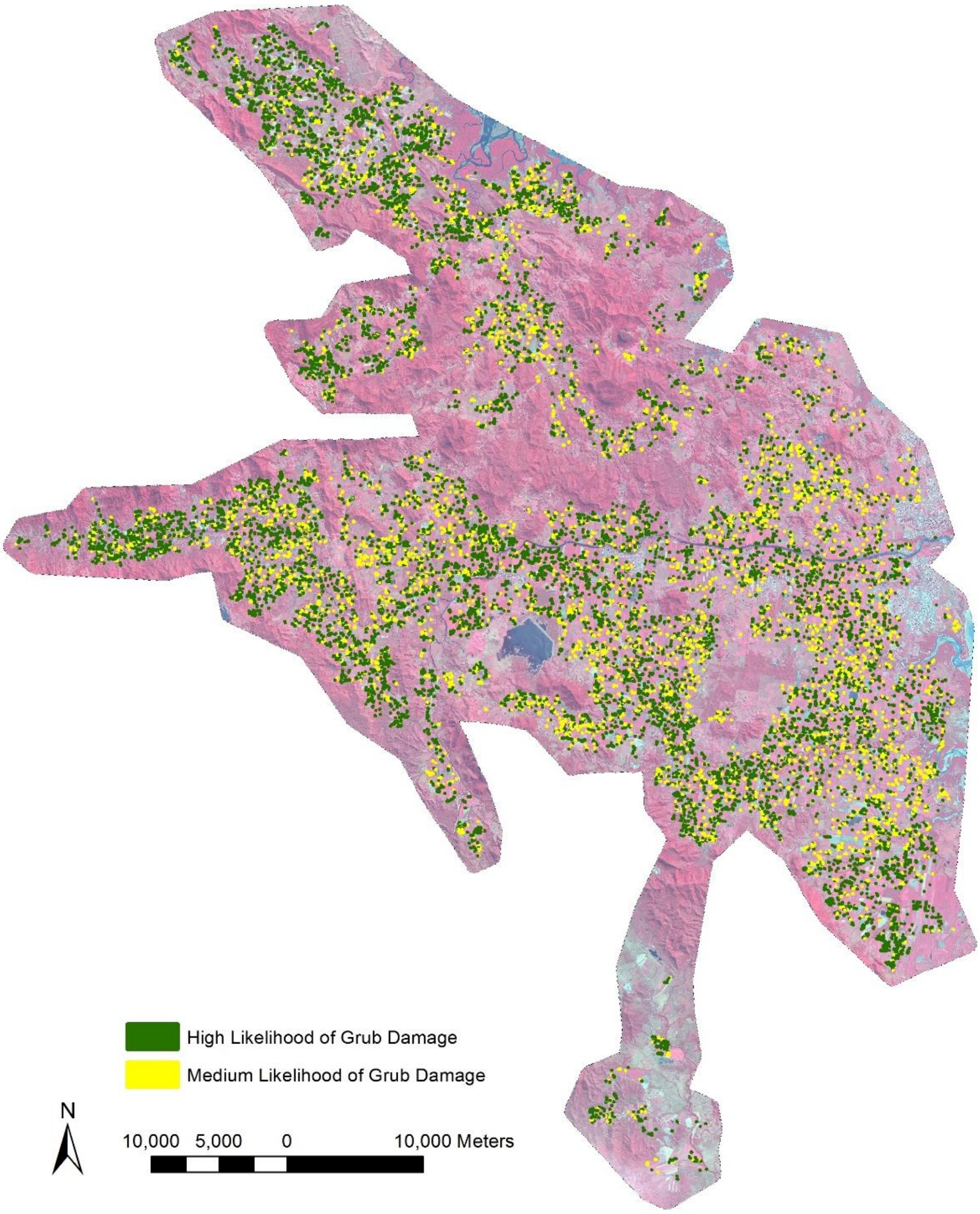

Figure 11. Distribution of objects mapped as medium and high likelihood of canegrub damage.

Please note that the objects have been enlarged for visual appearance and hence do not represent the actual size of mapped grub damage patches. Objects classified as low likelihood of grub damage were omitted, as a large proportion of these represented false positives (based on the comparison with field data).

A multi-spectral SPOT-6 image was acquired by Andrew Robson (UNE) for yield estimation of the Mackay region on 29 April 2018 (Figure 11) and provided as an in-kind contribution to the project. Unfortunately, this image data set did not include a panchromatic band. As the costs of the panchromatic was approximately $18,000 and as cloud cover and shadows occupied a large part of the image, the panchromatic band was not purchased. With a pixel size of 6 m, the multi-spectral image was not useable because of the lack of spatial detail, i.e. image texture, which is a main characteristic used in the GEOBIA algorithm for automatically identifying canegrub damage. Hence, the SPOT-6 image collected on 29 April 2018 was deemed unfeasible for the analysis.

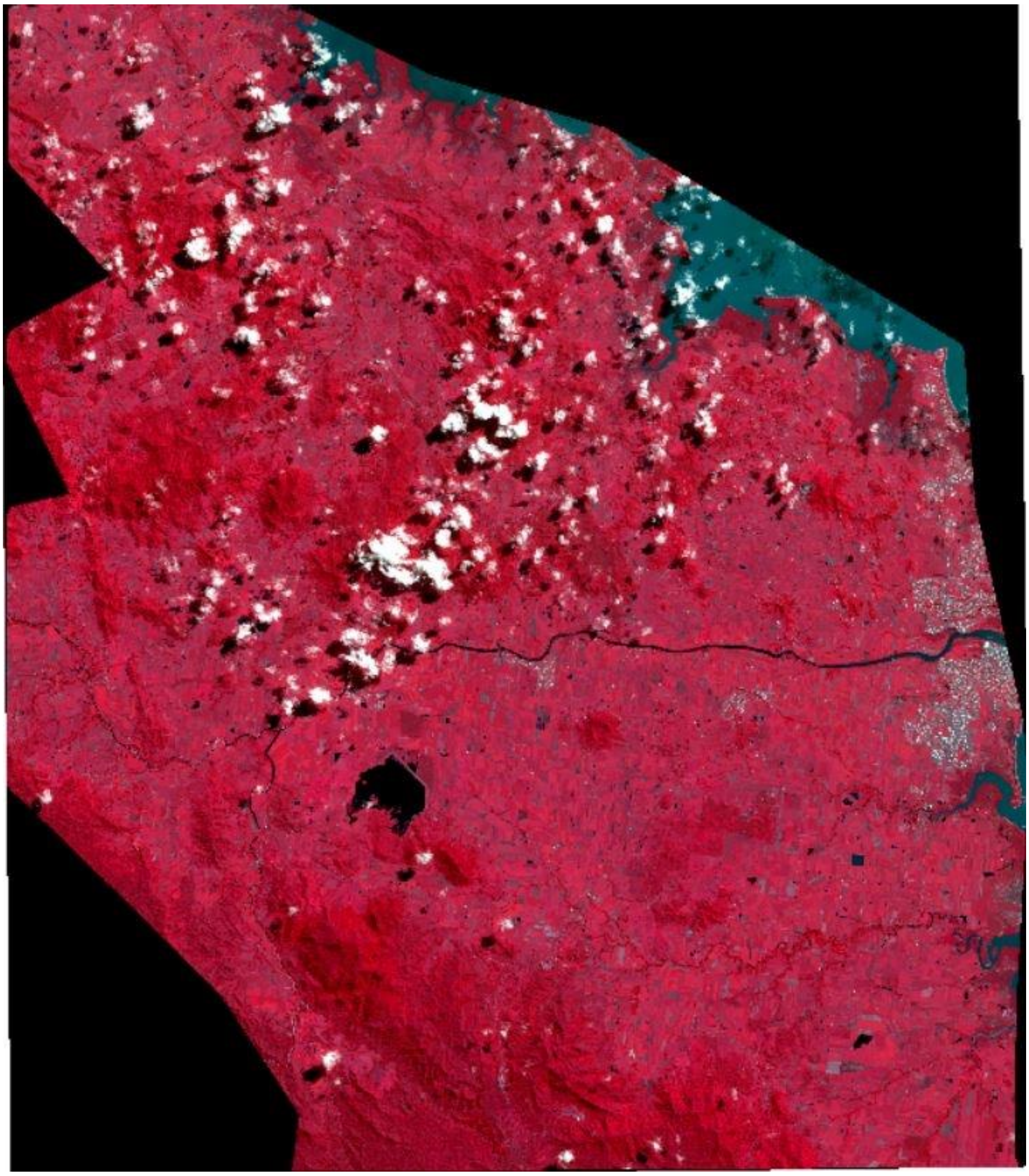

Figure 12. Multi-spectral SPOT-6 image collected on 29 April 2018 for the Mackay region showing distinct cloud cover areas.

As an alternative to SPOT-6 imagery, Planet image data with a blue, green, red and near infrared band with a pixel of 3 m acquired on the 31 May 2018 (same date is the SPOT-6 image) was downloaded for testing (Figure 11). The developed GEOBIA algorithm was used for the Planet image data for mapping of canegrub damage.

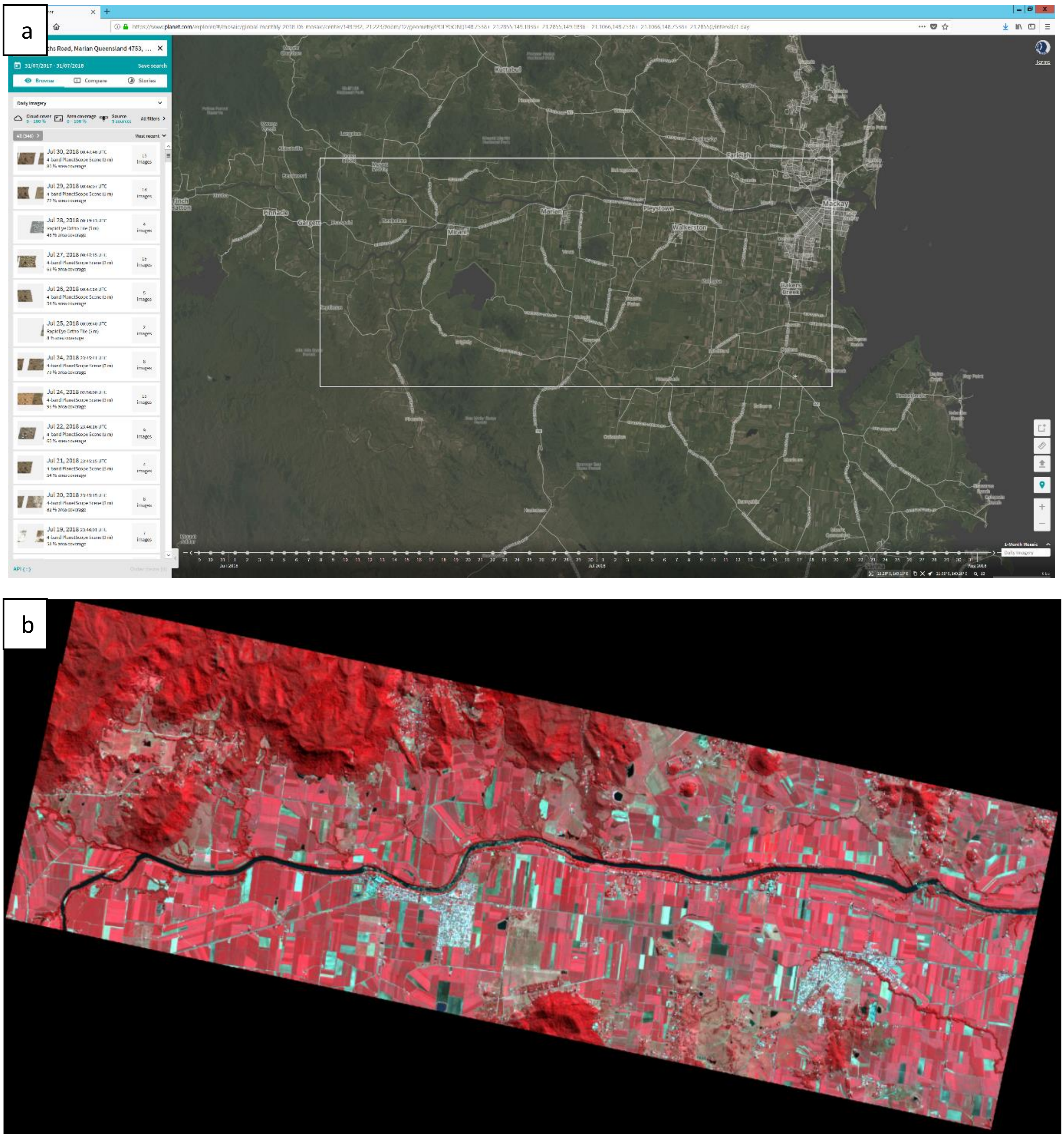

Figure 13. (a) Planet Labs portal and (b) the download CubeSat image data displayed as a false colour composite acquired on 31 May 2018.

In Figure 12, the field-validated canegrub damage was mapped with both the SPOT-6 and the Planet image data. In the SPOT-6 image, both spectral and textural differences are visible for the canegrub-damaged area, while the Planet image data mainly display a spectral difference with little variation in texture. As the canegrub damage in this case exhibited both spectral and textural characteristics that the GEOBIA algorithm could detect, the canegrub damage was detected in both image data sets. Figure 13 shows an example where the Planet image data did not work due to the lack of textural information. While the area with canegrub damage did not exhibit spectral characteristics suitable for mapping damage, the textural information from the SPOT-6 image was enough for the GEOBIA algorithm to detect the canegrub damage. In fact, most of the canegrub damage identified in the field was not mapped with the Planet image data because of the larger pixel size. Hence, the use of a single Planet image was deemed unfeasible for use.

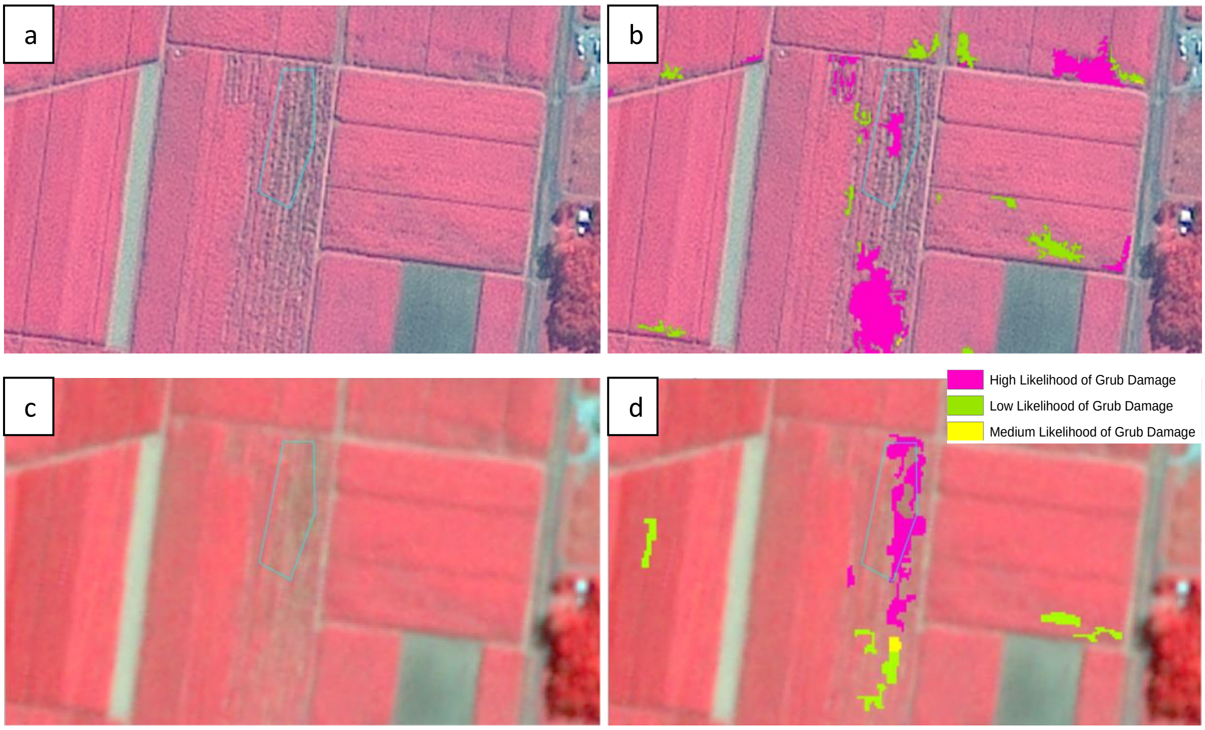

Figure 14. (a) SPOT-6 image and (b) corresponding SPOT-6 image with mapped canegrub damage; (c) Planet image and (d) corresponding Planet image with mapped canegrub damage.

The outlines indicate an area with canegrub damage identified in the field.

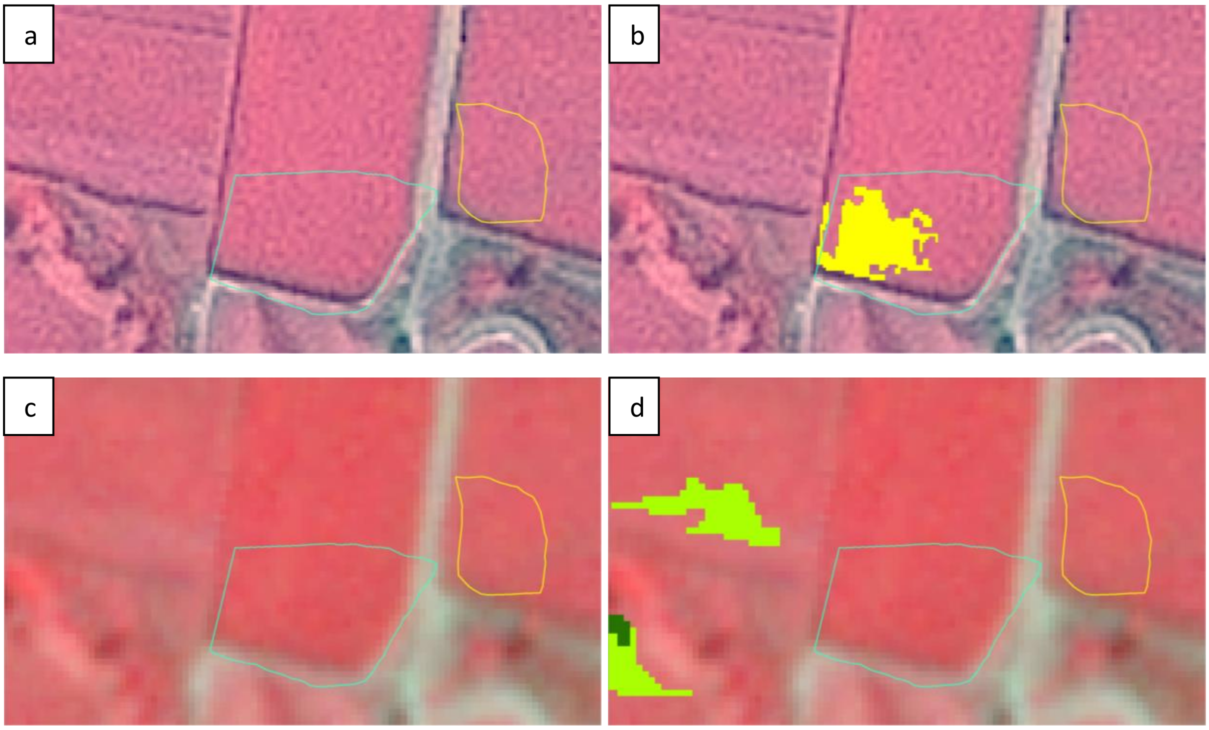

Figure 15. (a) SPOT-6 image and (b) corresponding SPOT-6 image with mapped canegrub damage; (c) Planet image and (d) corresponding Planet image with mapped canegrub damage.

The cyan outline indicate an area with canegrub damage identified from the helicopter flight, whereas the yellow outline represents healthy cane.

6.4. Summary of Overall Accuracy

One of the more difficult factors in developing and interpreting maps for canegrub damage is that the relative accuracy is dependent not only on the spatial resolution of the imagery analysed (e.g. from either GeoEye-1 or SPOT-6) but also on the extent of actual grub damage that occurs in each geographical region and each season. One simplistic method to determine the "overall accuracy" of this approach is *to quantify the number of correctly mapped observations for all land-cover classes (in this case sites with and without canegrub damage) and divide by the total number of observations*. In general mapping healthy cane is easier than mapping unhealthy cane so the extent of healthy cane versus grub damage cane influences the overall accuracy. In a previous study (SRA1011342; Sallam 2015) the overall level of accuracy of using GeoEye-1 was relatively high up to 98.7% but still varied between regions so ranged from 75-98.7% (Johansen *et al.*, 2018).

In the current study, when analysing the 2013 data the GeoEye-1 had a higher overall accuracy (92.8%) than SPOT-6 imagery (78.57%). In contrast in 2016, despite having a lower spatial resolution, SPOT-6 imagery seemed to outperform GeoEye-1 in terms of overall accuracy in both the Mulgrave and Herbert but again the accuracy levels differed between regions and were generally lower (Table 16). In the case of the Herbert, only 11 canegrub positive field sites could be detected by ground truthing and this is reflected in the lower overall accuracy than in the previous study. Disappointingly in 2018 in Mackay despite ground truthing over 200 sites on only three of those sites were grubs detected, suggesting a poor grub damage season overall. Whilst these three sites were correctly identified as grub damage sites and a further 77 sites were correctly classified as not grub damage sites, this means that 81 sites were incorrectly classified as canegrub damage. This results in an overall accuracy figure of 80/204 or 39.2% (Table 16).

Table 16 Overall accuracy in predicting canegrub damage for three cane-growing regions using GeoEye-1 and SPOT-6 imagery.

Imagery Source	Region	Year	% Overall Accuracy
SPOT-6	Mackay	2013	78.57
GeoEye-1	Mackay	2013	92.80
SPOT-6	Mulgrave	2016	79.10
GeoEye-1	Mulgrave	2016	58.00
SPOT-6	Herbert	2016	68.92
GeoEye-1	Herbert	2016	45.95
SPOT-6	Mackay	2018	39.2

7. CONCLUSIONS

Objective 1: Examine the feasibility of using Spot 6/7 imagery to produce reliable canegrub damage risk maps.

Spot 6 satellite-acquired imagery was used to map canegrub damage in several cane-growing regions of Queensland. However, the reliability of this mapping approach varied both between sites and between growing seasons. Mapping high- and medium-likelihood damage areas was generally more successful than mapping low damage areas. Initial results comparing SPOT-6 and GeoEye-1 imagery from 2013 for a selected area of Mackay showed great potential for SPOT-6 imagery as an alternative source of image data suitable for detecting canegrub damage and reducing overestimation compared to GeoEye-1 imagery. Significant levels of canegrub damage occurred in Mackay in 2013, which facilitated the image analysis and ensured sufficient field data for algorithm calibration and mapping result validation. However, the results for the Mulgrave and Herbert regions in 2016 and the Mackay region in 2018 were far less conclusive. The Mulgrave and Herbert regions experienced above-average rainfall in the months prior to and during harvest, resulting in regrowth and greening of cane affected by grub damage and thus potentially masking effects of grub damage, whereas the level of canegrub damage in the Mackay region in 2018 was very low. This also caused the number of field observations with positive canegrub damage to be too low for undertaking proper algorithm calibration and validation of the mapping results. In conclusion, the findings of this research shows that the developed mapping algorithm is suitable for SPOT-6/7 imagery, but the overall approach and associated results are only suited for regions and years with significant levels of canegrub damage, allowing sufficient field data of canegrub damage location to be collected. Hence, for future periods with significant canegrub damage, it would be worth applying the developed mapping approach for detection of areas requiring targeted treatment.

Objective 2: If feasibility is demonstrated, work with at least two productivity services to develop a commercialisation plan.

In response to the high costs (approximately A$64/km^2) of Digital Globe imagery, including GeoEye-1 and WorldView-2, -3 and -4 imagery, one of the objectives of this project was to assess if cheaper SPOT-6/7 satellite imagery could provide a suitable means and alternative for canegrub damage detection. However, due to restructuring in the pricing of SPOT-6/7 imagery, the costs of these image data have increased during the course of this project from approximately A$6/km^2 to a current A$17.5/km^2. The Spot6/7 satellites are also shortly to be decommissioned. Following a review meeting with Mackay Area Productivity Services it was decided that at this stage it would be inadvisable to develop a commercialisation plan.

8. RECOMMENDATIONS FOR FURTHER RD&A

8.1. Satellite-based imagery

While cost of imagery is likely to remain an issue for the sugarcane industry in the future, new free image data provided by Planet Labs have come on the market in the last couple of years. Planet Labs currently has > 250 CubeSat's in orbit providing blue, green, red and near infrared image data at 3 m pixels on a daily basis anywhere on Earth. Currently, imagery covering up to 10,000 km^2 can be downloaded per month at no cost. While the spatial resolution of 3 m pixels is likely to be insufficient for the mapping approach used in this project, the dense time-series of imagery, i.e. daily coverage, may provide additional multi-temporal information for mapping canegrub damage. In addition, Planet Labs currently has 13 SkySat satellites, providing coverage up to four times per week anywhere on Earth at 0.72 m pixels. If the SkySat imagery were to be provided at no cost in the future, these data sets would be ideal for mapping canegrub damage. If the focus remains on using satellite imagery for canegrub prediction then future work might focus on using time-series of free Planet Labs imagery to assess if increased temporal resolution can compensate for the slightly lower spatial resolution.

8.2. Alternative Damage Mapping Approaches

A recent review has highlighted the complexities and different potential approaches when using remote sensing to detect insect pests and their associated damage (Jansen *et al.,* 2016). There are other remote-sensing approaches that could also be considered including (i) combining and overlaying imagery data sets as part of an integrated mapping system (ii) use of proximal soil sensors (such as EM38) or other soil mapping data sets (iii) use of other types of platforms for imagery collection (such as unmanned aerial vehicles (UAVs) and (iv) use of other imagery types (such as hyperspectral sensors - which can be used both from either satellites or UAVs).In other industries, including horticulture, forestry, arable, pasture and viticulture (Barbedo, 2019; Cosby *et al*., 2016), recent advances in remote-sensed imagery and geospatial image processing have enabled the creation of rapid and ongoing monitoring tools for the detection/surveillance and risk mapping of soil-borne insect pests.

8.2.1. Proximal Soil Remote Sensing

Overlaying layers of vegetation imagery spectral data with soil mapping data (such as soil type and/or soil electrical conductivity) could improve the efficiency of the damage mapping approach for canegrubs. This should be explored further as there is already some evidence to suggest that soil characteristics influence the establishment and population abundance of root-feeding pests. Cockchafer grubs cause substantial economic damage by attacking the roots of perennial ryegrass. These scarab grubs are known to be associated with higher altitude regions within a paddock and well-drained soils with a low ECa (apparent electrical conductivity) value. A combined approach (utilising the use of NDVI, EM38 and elevation maps) for their early detection has been developed for the dairy industry (Cosby *et al.,* 2016) with 88% accuracy in detection. Canegrubs are known to be associated with some soil characteristics (Ward, 2003; Sallam, 2015) so combining data sets is likely to increase the accuracy of detecting damage and 'hot spots' for canegrub presence. In the Burdekin region, sandy delta-type soils are preferred compared to high clay content soils by greyback canegrubs (Ward, 2003). Preliminary studies in SRA project 2011/342 indicated that, at least in the Mulgrave region, specific soil types (e.g. well drained granitics and red/brown schists and volcanic soils) were more prone to grub damage (Sallam, 2015).

8.2.2. Hyperspectral Imagery

This study primarily focused on the use of multispectral imagery, focusing on NDVI, to map canegrub damage areas as this type of imagery is more widely available, and cheaper to obtain, from satellite platforms. However, it is very limited in its spectral resolution with only 4-7 relatively wide spectral bands, making it very difficult to actually detect and discriminate damage caused by a specific pests or group of pests. More pest-specific spectral signatures can be developed using hyperspectral imagery that enables the examination of up to 200 narrow spectral bands in the same electromagnetic region as multispectral data. Use and validation of hyperspectral imagery to define a more 'canegrub-specific' spectral signature is required to improve the level and specificity of detection and thereby reduce the risk of false positives/negatives. This approach has already been developed for the root-feeding pest grapevine phylloxera (Renzullo *et al.*, 2006) where the spectral signature was found to be associated with changes in ratios of particular photosynthetic pigments (Blanchfield *et al.*, 2006). This type of approach could be conducted first using a 'bottom-up' approach to detection rather than a top-down approach (using satellite imagery). For example, obtaining spectral signatures of sugarcane varieties under different levels of canegrub damage under controlled conditions and then upscale in a field-testing scenario using unique spectral signatures on modified spectral sensors. This approach has been successfully validated recently using hyperspectral cameras on UAVs (Vanegas *et al.*, 2018). Whilst currently there are limited opportunities currently to obtain hyperspectral imagery from satellites, they will become available in 2-3 years with the launch of new satellites.

8.2.3. Unmanned Aerial Vehicles (UAVs)

The potential use of UAVs on a farm scale, rather than area-wide, could also be explored for damage mapping of canegrubs. UAVs and their providers are gradually becoming more accessible to the sugarcane industry and there is keen interest in this type of technology from some growers. UAVs do have a limited payload, limited flight period and cannot cover large areas. However, they have some distinct advantages over the use of satellite imagery including lower flight altitude, better spatial resolution, fewer problems with cloud cover impacting on imagery collected and can carry different types of image sensors, such as narrow band spectral band filters, which may be required if a unique spectral signature can be characterised for canegrubs in the future. Some researchers have also combined the use of UAVs with satellite imagery by gathering ground truth data using UAVs to improve satellite-acquired data calibration (Otsu *et al.*, 2018). The use of spectral sensors carried on UAVs is already being explored by other industries for the detection of beetles, thrips, moths and aphids (Hunt & Rondon, 2017; Nebiker *et al*., 2016; Stanton *et al*., 2017; Zhang *et al*., 2018).

8.2.4. Ground-based Canegrub Detection

One of the main requirements of any remote sensing approach is for ground validation to verify presence or absence and relative abundance of a pest. In the case of canegrubs this is usually a laborious process which requires substantially digging, root examination and 'on the spot' assessment and quantification (Samson and Eaton, 2012; Sallam and Lowe, 2012). This type of approach could be improved by the development of a DNA probe system, which could provide a more accurate assessment of grub presence and abundance and could also increase the number of samples to improve validation. Although probes have not yet been developed for canegrubs specifically they have been developed and field validated for other root-feeding insect pests (Herbert *et al.*, 2008). Another approach, which could be taken, is to determine if, due to the extent of root damage caused by canegrub feeding, the chemical profile in sugarcane leaves is modified due to upward or downward regulation of secondary metabolites. If this were to be the case, then there would be potential to characterise a chemical fingerprint associated with canegrub presence. This chemical fingerprinting approach, which could ultimately lead to another type of sampling approach (e.g. leaf samples), has been investigated for both foliar and root feeding pests (Benheim *et al.*, 2016; War *et al*., 2016) but not yet for sugarcane pests.

9. PUBLICATIONS

A paper summarising the mapping approach using GeoEye-1 Imagery in SRA project 2011/342 and highlighting the use of GEOBIA and eCognition software also used in this project was published as follows:

Johansen, K., Sallam, N., Robson, A., Samson, P., Chandler, K., Derby, L., Eaton, A., Jennings, J. (2018). Using GeoEye-1 imagery for multi-temporal object-based detection of canegrub damage in sugarcane fields in Queensland, Australia. *GIScience and Remote Sensing*, 55(2), 285-305.

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12.APPENDIX

12.1.Appendix 1 METADATA DISCLOSURE

Table 17 Metadata disclosure 1

Data	SPOT-6 satellite imagery GeoEye-1 satellite imagery
Stored Location	University of Queensland / Kasper Johansen
Access	Restricted license allocated to the University of Queensland for research purposes. An additional payment will be required for extending the license of the imagery, in case the image data were to be distributed to and used by other parties.
Contact	For further information, see attached license agreement and/or contact: Simon Greig from GeoImage on 07-33194990/0449722386 and simon@geoimage.com.au