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Current practice and innovation in decommissioning, rehabilitation and monitoring on Barrow Island: applications for mine closure

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Abstract

Decommissioning and rehabilitation of a land-based oilfield has many similar challenges to those faced in mine closure. In this paper we describe current practices for decommissioning, rehabilitation, and vegetation monitoring that is applied on Barrow Island, off the west-northwest coast of Western Australia. Barrow Island hosts both oil and gas production facilities and is an internationally significant A Class nature reserve. The island is particularly important for the presence of a diverse fauna, many of which have been lost, or are poorly-represented, on the Australian mainland.

More than 50 years of oil production, and more recently construction of the Gorgon liquefied natural gas facility, has required clearing of vegetation and earthworks for infrastructure, such as well pads, roads, pumping stations, gravel pits and pipeline corridors. Current decommissioning activities for the oilfield are conducted with a 'clean as you go' strategy, focused on the removal of redundant equipment and plant, which in turn opens opportunities for remediation and rehabilitation.

Accurate and cost-effective monitoring of vegetation establishment is an important part of rehabilitation and closure on Barrow Island, as it is for mine closure. Innovative technologies are changing the way environmental monitoring is conducted around the world. In Australia, with an extensive resource sector operating in relatively remote, arid environments there is opportunity to improve the accuracy and scale of environmental monitoring, while reducing health and safety risks, through technologies such as remote sensing.

Combining high-resolution imagery with object-based image analysis (OBIA) allows accurate delineation of vegetation types. This includes the potential to identify key species, over an entire study area, and allows greater insights on rehabilitation performance than standard transect or quadrat-based monitoring of representative areas. The data obtained can remove the potential for on-ground sampling bias, is scientifically repeatable and defensible to regulatory agencies. We applied the OBIA approach to the detection of grasses of the genus Triodia *('spinifex'), which is endemic to Australia and dominate the hummock grasslands that cover around 18% of the continent. Many of Australia's largest mineral resource extraction and oil and gas operations coincide with hummock grassland ecosystems. Therefore, understanding disturbance impacts and restoration outcomes of* Triodia *is critical to successful mine closure in these arid ecosystems.*

The OBIA approach has a wide range of applications in addition to rehabilitation monitoring, such as vegetation condition monitoring or impact assessment, detection of invasive plant species or those of conservation interest and identification of fauna habitats or other features of interest in vast landscapes.

Importantly it has potential to reduce time in the field, thus lowering health and safety risks in our remote and hostile arid environments. We present examples of use of this approach for vegetation impact assessment in natural communities and vegetation monitoring as part of site rehabilitation and closure.

Keywords: *oilfield decommissioning, rehabilitation, remote sensing, object-based image analysis, Triodia, Barrow Island*

1 Introduction

Decommissioning and rehabilitation of a land-based oilfield has many similar challenges to those faced in mine closure. In this paper, we describe current practices for decommissioning, rehabilitation planning and execution, and vegetation monitoring that is applied on Barrow Island, off the west-northwest coast of Western Australia (Figure 1). Barrow Island has been the site of a producing oilfield since 1967 and is currently operated by Chevron Australia for the Western Australia Oil Joint Venture. More recently, the Gorgon Gas Plant has been constructed on the island and is capable of producing 15.6 Mt of liquid natural gas per annum, plus domestic gas, for more than 40 years (Chevron Australia 2016).

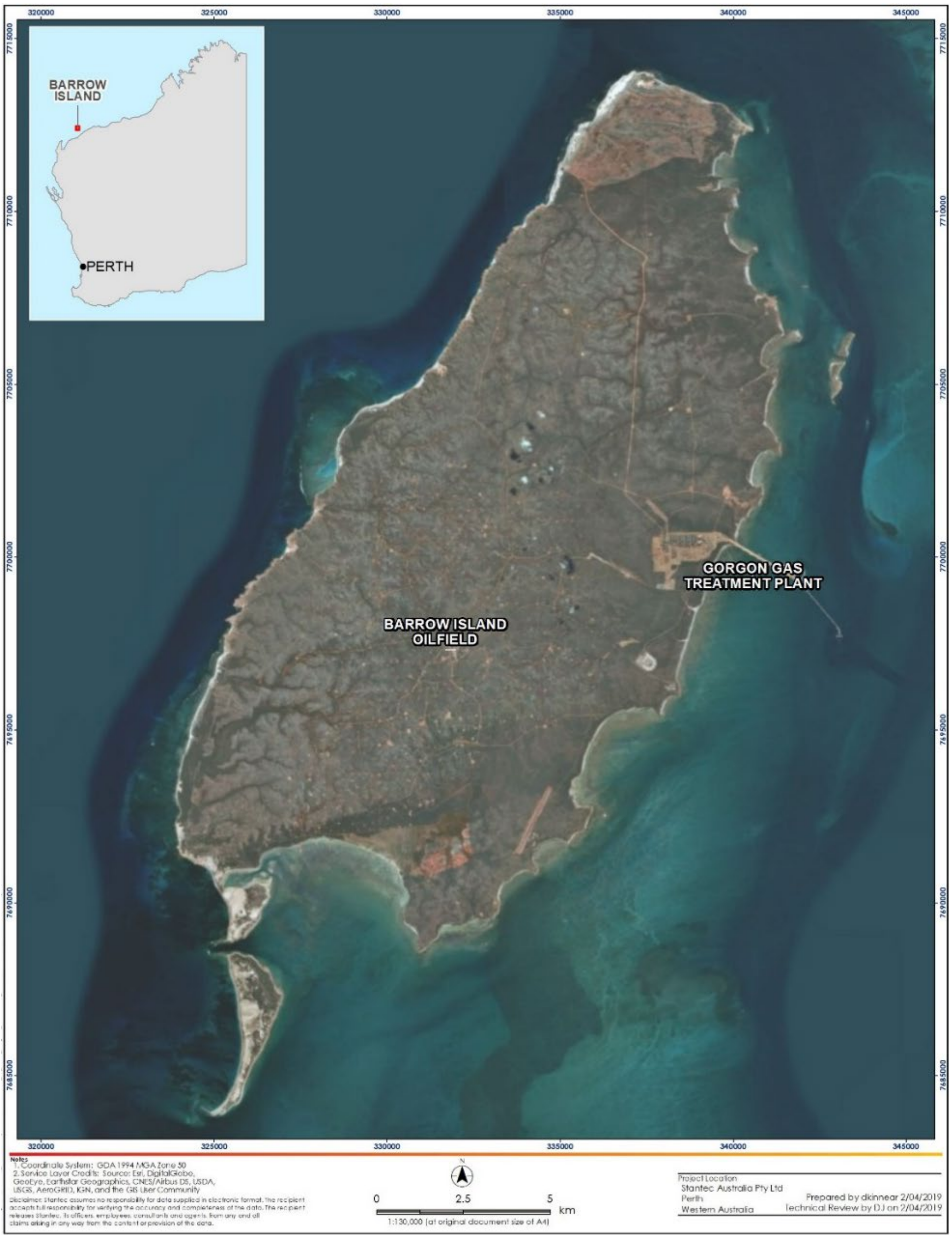


Figure 1 Barrow Island location and features

In addition to hosting substantial energy projects, Barrow Island is an internationally significant A Class nature reserve. The island is particularly important for the presence of a diverse fauna, many of which have been lost, or are poorly-represented, on the Australian mainland (Department of Parks and Wildlife/Conservation Commission of Western Australia 2015).

1.1 Environmental setting

Barrow Island is a geological extension of the Cape Range Peninsula and is composed of Tertiary limestones which outcrop on the central and western uplands, overlain by Quaternary sandy limestones to the east and north and recent calcareous sands on the southern peninsula (Chevron Australia 2005). The island is composed of coastal deposits overlying tectonically-folded limestone. Three broad geomorphic units have been identified:

- Limestone uplands.
- Near coastal lowlands.
- Coastal fringe (Chevron Australia 2005).

Barrow Island is located within the Cape Range subregion of the Carnarvon Biogeographic Region (Department of the Environment and Energy 2017). Barrow Island and adjacent islands are particularly valued for:

- Their diverse and relatively unaltered fauna assemblages.
- Their extensive karst systems and the subterranean fauna they support.
- The important habitat they provide for nesting marine turtles and migratory shorebirds (Department of Parks and Wildlife/Conservation Commission of Western Australia 2015).

Barrow Island supports 377 native plant taxa (Department of Parks and Wildlife 2015), including several species of conservation significance, with only localised occurrences of introduced plant species. The flora is dominated by families such as Poaceae (grasses), Chenopodiaceae (goosefoots), Fabaceae (legumes, peas and wattles), Malvaceae (mallows) and Asteraceae (daisies), and in particular, by the genera *Triodia* (hummock-forming grasses) and *Acacia* (wattles). Three species of *Triodia, T. angusta, T. wiseana,* and *T. epactia*, dominate vegetation cover across a large proportion of Barrow Island.

The island supports 13 species of resident terrestrial mammal species, six of which are considered as rare or likely to become extinct. Other fauna includes 119 bird species, 43 reptiles, and more than 2,000 invertebrates that have been recorded on the island. The presence of the intact suite of mammal fauna, many of which are no longer present on the Australian mainland, together with the subterranean invertebrate populations, is reflected in the classification of Barrow Island as an A Class nature reserve for the purpose of conserving flora and fauna.

2 Current practices in decommissioning and rehabilitation

The Barrow Island Joint Venture (WA Oil) has been extracting oil from Barrow Island since 1967. More recently, the Gorgon Joint Venture (Gorgon) constructed a liquefied natural gas facility on Barrow Island, with first gas exported in 2016. Both operations are managed by Chevron Australia.

More than 50 years of oil production has resulted in clearing of vegetation and earthworks for infrastructure, such as well pads, roads, pumping stations, gravel pits, pipeline corridors and other related infrastructure. As disturbed areas are no longer required, they have been decommissioned and rehabilitated.

2.1 Decommissioning

WA Oil is executing a ‘clean as you go’ strategy for managing the decommissioning legacy on Barrow Island. In practice, this involves leveraging off current oilfield operations in order to remove redundant equipment, rather than at the end of field life, where resources have typically been redeployed or are unavailable. Current decommissioning activities are focused on the removal of redundant equipment and plant, which has in turn opened opportunities to conduct remediation and active rehabilitation.

2.2 Rehabilitation

Areas disturbed on Barrow Island for production operations and associated infrastructure are progressively rehabilitated when they are no longer required. Rehabilitated areas are predominantly gravel pits, but also include access roads, pipeline corridors, well sites, and former campsites. Current rehabilitation works for WA Oil are conducted according to a regulator-approved Rehabilitation Prescription (Chevron Australia 2015). Similarly, rehabilitation for the Gorgon operations is according to an approved Post-Construction Rehabilitation Plan. Key steps in both current and historical rehabilitation practices include:

- Re-shaping of surface topography to remove abrupt features.
- Spreading topsoil, where available, over disturbed areas.
- Allowing vegetation to re-establish naturally, from soil-stored seed, or seed dispersing from adjacent vegetation.

2.3 Monitoring of rehabilitated areas and completion criteria

Monitoring of rehabilitated areas on Barrow Island has been conducted consistently since 2004. In that 15-year program, sites have been monitored using quadrat-based vegetation assessment, complemented with Landscape Function Analysis. A total of 95 monitoring sites (both rehabilitation and analogue) are now established, with a selection of these monitored annually.

Monitoring data for rehabilitated areas is compared to that from local analogue sites, which are re-assessed to reflect any changes resulting from natural climatic fluctuations. Analogue sites are selected to represent the vegetation types surrounding the rehabilitated areas.

A completion criteria framework for rehabilitated areas in the WA Oil operations has been established as part of the approved Rehabilitation Prescription (Chevron Australia 2015). Key objectives in relation to restoring vegetation and fauna habitat on Barrow Island include:

- Objective 3: The vegetation in rehabilitated areas is compatible with the surrounding undisturbed ecosystem.
- Objective 4: The rehabilitated areas provide appropriate habitat for fauna.

Both objectives are measured against criteria relating to total plant cover and the proportion of *Triodia* that is present (Table 1). The relative adequacy of total plant cover is evaluated with quantitative monitoring of vegetation and compared against cover of natural vegetation at reference sites.

Standard on-ground vegetation monitoring by field ecologists needs to be carefully managed in the hot, arid environment of Barrow Island. In addition, access to remote sites such as Barrow Island can be logistically-difficult. In 2017, we commenced investigating the potential for remote sensing, using object-based image analysis (OBIA) of high-resolution aerial imagery, to provide appropriate quantitative measures of vegetation that were adequate to address completion criteria. Remote sensing techniques such as OBIA, have the potential to reduce health and safety risks and the time and cost associated with mobilisation to remote sites.

Table 1 Excerpt of criteria for restoration of Barrow Island rehabilitation areas, from Phase 3: 'Ecosystem sustainability and rehabilitation completion' (Chevron Australia 2015)

Objectives relating to vegetation and fauna habitat	Criterion	Standard	Measurement/assessment tool
Objective 3: The vegetation in rehabilitated areas is compatible with the surrounding undisturbed ecosystem	Restored vegetation has adequate total plant cover	80% of site has total plant cover greater than 50% of average cover of reference sites, from the same landscape type Maximum dimension of bare patches will not exceed 10 m	Quantitative vegetation monitoring
Objective 4: The rehabilitated areas provide appropriate habitat for fauna	Restored vegetation is dominated by *Triodia*	*Triodia* comprises greater than 50% of total plant cover	Visual inspection and assessment vegetation by Chevron Responsible Person each year, supported by quantitative vegetation monitoring as required

3 Remote sensing and object-based image analysis

3.1 Object-based image analysis

3.1.1 Background

The parameter most frequently measured and recorded for remote sensing is the electromagnetic energy reflected by the object of interest. This includes visible light (red, green and blue (RGB) bands), near infrared (NIR), thermal infrared energy (TIR), and microwaves. The spectral reflectance properties of many earth surface features, such as soil, vegetation and water, can be used to uniquely identify and characterise those features. Exactly how much energy is reflected will vary, and depends upon the nature of the material, and the electromagnetic spectral frequency. The characteristic of the reflected components over a range of wavelengths results in a spectral response pattern, or signature. Finding distinctive spectral response patterns is the key to most procedures for computer-assisted interpretation of remotely sense imagery.

In the visual interpretation of remotely captured images, many characteristics are brought into consideration, including but not limited to; colour (or tone), texture, size, shape, pattern, and context. The development of an OBIA approach in remote sensing arose through the understanding that image objects hold more 'real world value' than pixels alone and was designed to emulate the human mind's cognitive function (Levick and Rogers 2006; Blaschke 2010). Colour (i.e. the spectral response pattern) is an important factor in most computer-assisted interpretation, including OBIA. In that context, the NIR and red bands carry the greatest amount of information about the natural environment. The red band is important because it is the primary region in which chlorophyll absorbs energy for photosynthesis, therefore, this band most readily distinguishes vegetated from non-vegetated surfaces.

3.1.2 Method development

Aerial imagery of Barrow Island is captured annually for Chevron using fixed-wing aircraft. It is comprised of four bands (RGB and NIR) and is captured at a resolution of 10 cm. All analyses described herein used imagery of this quality, captured in different years. Using on-ground validation data collected from key vegetation species, we initially employed a supervised classification. Each individual Barrow Island object identified within an image had mean spectral reflectance, texture, size, and shape (roundness and linearity) attributes generated. Objects with known cover attributes (from the on-ground validation data) were used to train the OBIA software to identify all similar objects in terms of those key attributes. Five object categories were delineated: *Triodia*, shrubs, litter, bare ground, and developed. The 'developed' category included man-made objects such as pipes and cables, although these were generally rare and highly variable. Using classified object statistics, we established a range of object values for each category.

As a first step, OBIA was tested on imagery of a rehabilitated site for which we already had detailed, on-ground, vegetation cover data. The rehabilitated site was established in 2010 to investigate the impact of herbivore grazing on vegetation establishment and growth. The area consisted of three fenced and three unfenced treatment plot areas. Fences designed to exclude grazing animals had been established immediately after topsoil placement.

Earthworks at the study area had been completed in 2009, and fresh topsoil was spread in June/July 2010. Twelve quadrats (2 m × 2 m) were established in each plot, representing approximately 19% of the area of each plot. Vegetation in the fenced and unfenced plots had been monitored annually from 2011 to 2015. Vegetation parameters monitored included percentage foliage cover, plant density and species diversity. Aerial imagery of the site taken in December 2014 was also classified using OBIA.

Estimates of *Triodia* cover in the study area from on-ground assessment on 1 December 2014, ranged from 60% to 95% (Figure 2). Cover estimates using OBIA extended over a similar range and were very well correlated with on-ground values.

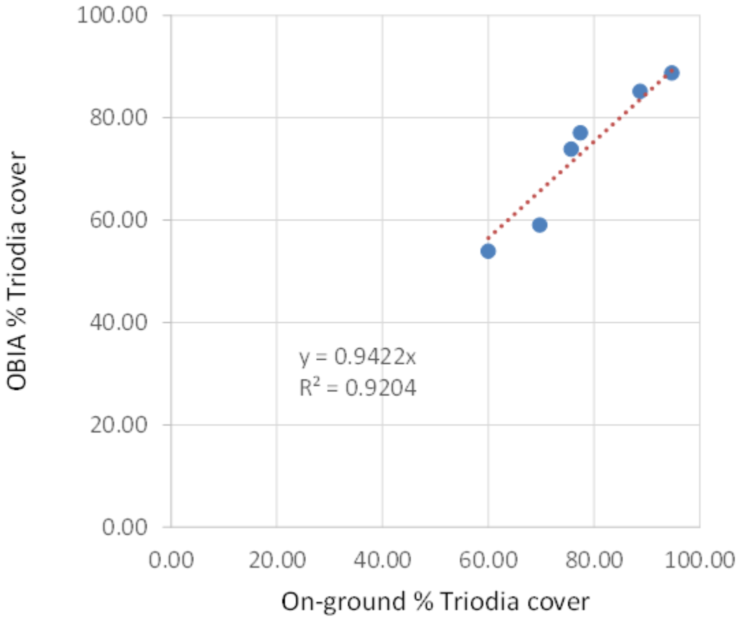


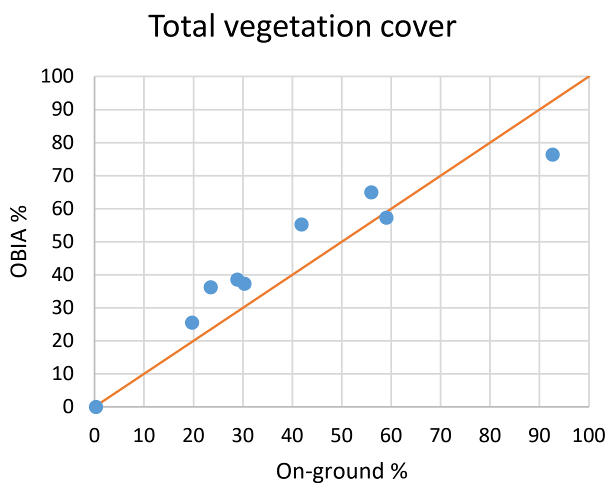
Figure 2 **Triodia cover (%) for six treatment plots in the Herbivore Grazing Trial in 2014 estimated with object-based image analysis, and compared with on-ground estimates of cover from 12 quadrats (2 m × 2 m) per plot**

3.1.3 Monitoring of rehabilitated sites

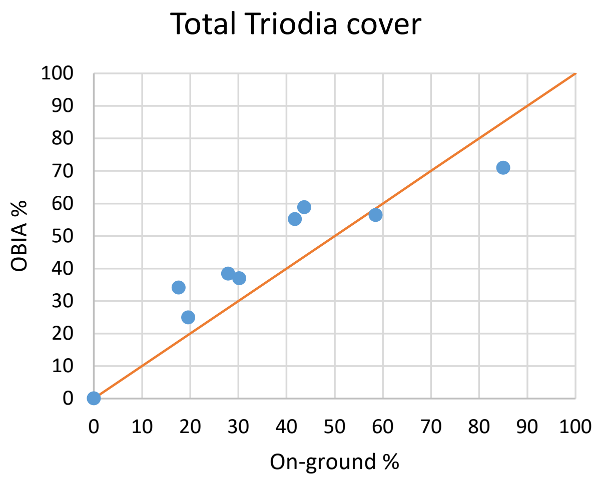
In 2017, nine rehabilitated WA Oil sites on Barrow Island were monitored using quadrat-based, on-ground assessments. The sites ranged in age from less than a year, to 42 years since rehabilitation. The boundary of the rehabilitated area to be monitored was defined manually from the aerial image. Aerial imagery of these sites was then classified using OBIA, and cover estimates for total vegetation ('*Triodia*' plus 'shrubs'*)* and *Triodia* only, were derived.

Estimates for total vegetation cover using OBIA ranged from near zero up to 76%, averaging 44%. By comparison, on-ground estimates ranged from near zero to 93%, with an average of 39% total cover (Figure 3). Cover estimates from on-ground assessment were derived from between five and eight quadrats (4 m × 4 m), representing between 0.8% and 6% of the area of each of the rehabilitated sites, whereas assessment using OBIA applied to 100% of the area in each case. The relatively small sampling area for the on-ground assessments is likely to have been an important factor in comparison of assessment methods.

As for total cover, estimates of *Triodia* cover on rehabilitated sites using OBIA were slightly higher than quadrat-based assessments, averaging 16% more cover attributed to *Triodia* species (Figure 3). *Triodia* species were also estimated by OBIA to make up a greater proportion (97%) of total cover, compared to 82% from on-ground assessment.



(a)



(b)

Figure 3 Relationship between on-ground assessments of: (a) total vegetation cover (%); and (b) Triodia cover (%) for rehabilitated sites (n = 9) monitored in October 2017, and object-based image analysis estimates from high-resolution aerial imagery, also captured in October 2017. The 1:1 ratio line is also shown

Shrub and litter cover were low on the WA Oil rehabilitated sites. In contrast to total cover and *Triodia* cover, estimates of shrub cover and litter using OBIA tended to be slightly lower than from on-ground assessment.

3.1.4 Differentiating between Triodia species

We investigated the capacity of OBIA to distinguish between the three species of *Triodia, T. angusta, T. wiseana* and *T. epactia* where they were present in various combinations. Three control sites where two *Triodia* species were known to be present, were selected for the investigation.

After training OBIA on specific examples of each of the three *Triodia* species identified on-ground, differences in spectral characteristics were able to be used in image classification and the relative distribution of each species was demonstrated at each site (Figure 4). The differences in spectral characteristics were principally in foliage colour, foliage texture and plant size. The relative proportion of total *Triodia* cover estimated by OBIA to be contributed by each species was consistent with previous on-ground monitoring data (Figure 5). While not required by current completion criteria, the capacity to quantify the presence of each *Triodia* species will be useful in assessing undisturbed areas, and in providing a better understanding of the re-establishment of each species in rehabilitated areas.

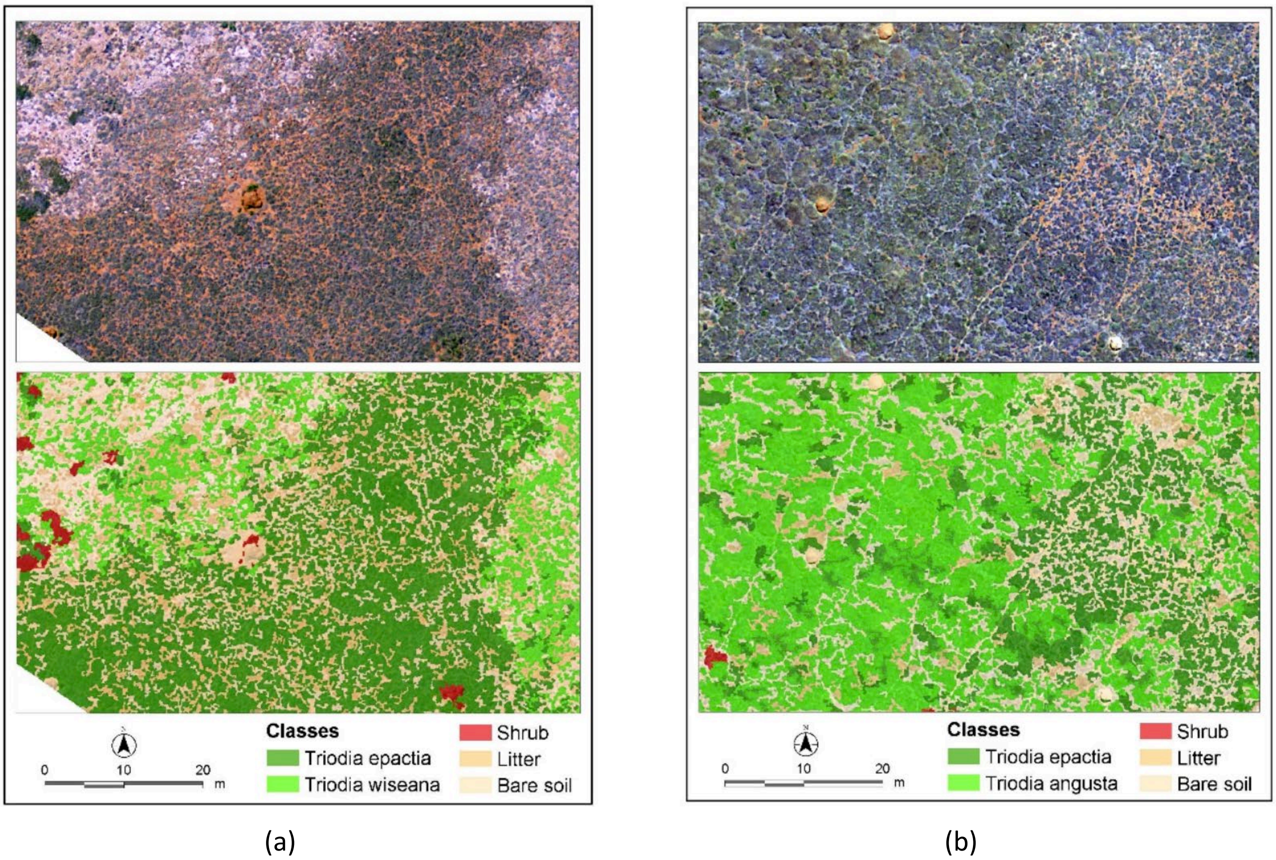


Figure 4 (a) Original aerial image of site Control 1 (top) compared with its object-based image analysis classification (bottom), demonstrating differentiation between Triodia epactia and T. wiseana; (b) Original aerial image of Site Control 20 (top) compared with its object-based image analysis classification (bottom), demonstrating differentiation between Triodia angusta and T. epactia

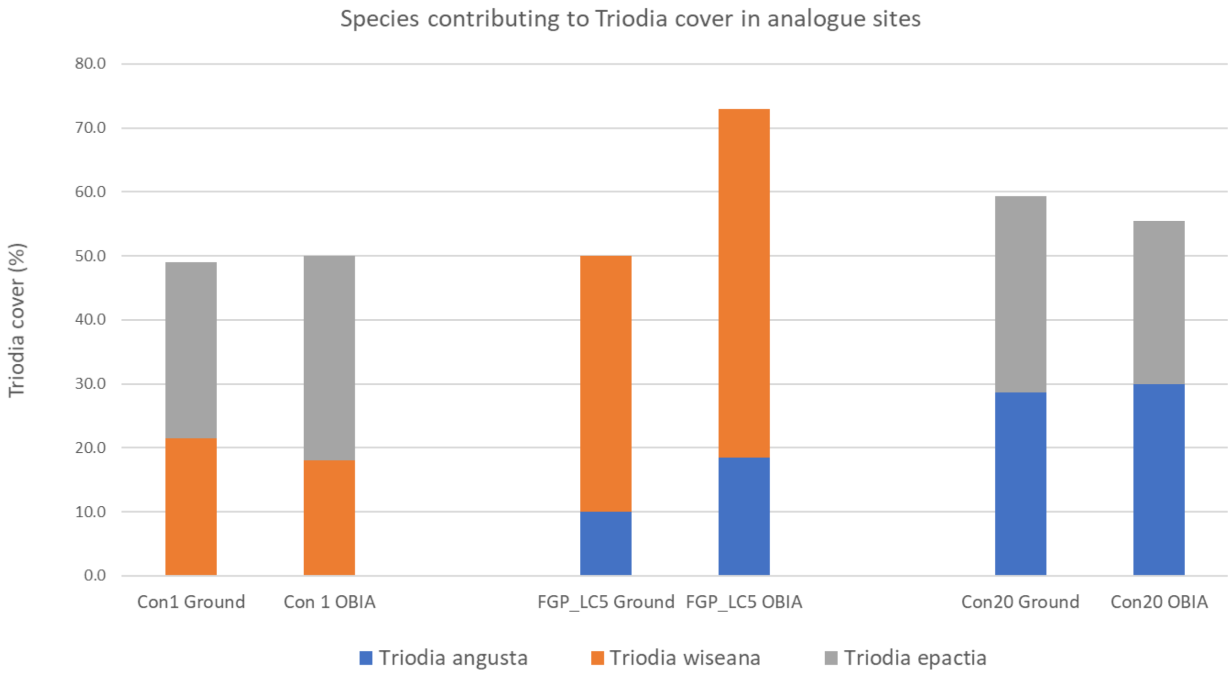


Figure 5 Comparison of estimates (on-ground or object-based image analysis) of foliar cover for individual Triodia species at three sites where two species were present

3.1.5 Assessing vegetation status on legacy sites

In 2018, we extended the use of OBIA to assess the status of vegetation at two areas on Barrow Island where there had been historic disturbance. The primary objective was to identify if remedial rehabilitation was required, in the context of vegetation-related standards identified in completion criteria for Barrow Island (Table 1).

Two areas of historical disturbance were selected, both within the vegetation community type: Hummock Grassland of *Triodia wiseana* with mixed emergent shrub species on valley slopes (Mattiske Consulting Pty Ltd 1997). These sites can be more broadly described as 'runoff' areas in the Barrow Island landscape.

The RGB, NIR 10 cm resolution aerial imagery captured in 2017 was analysed using OBIA, and average foliar cover attributed to '*Triodia*' and 'shrubs' was defined. Average foliar cover in a fixed radius around each pixel was calculated and used to depict the overall distribution of vegetation cover that had become established. This averaged cover was then depicted in relation to the standard defined in the completion criteria for the WA Oil operations (Figure 6).

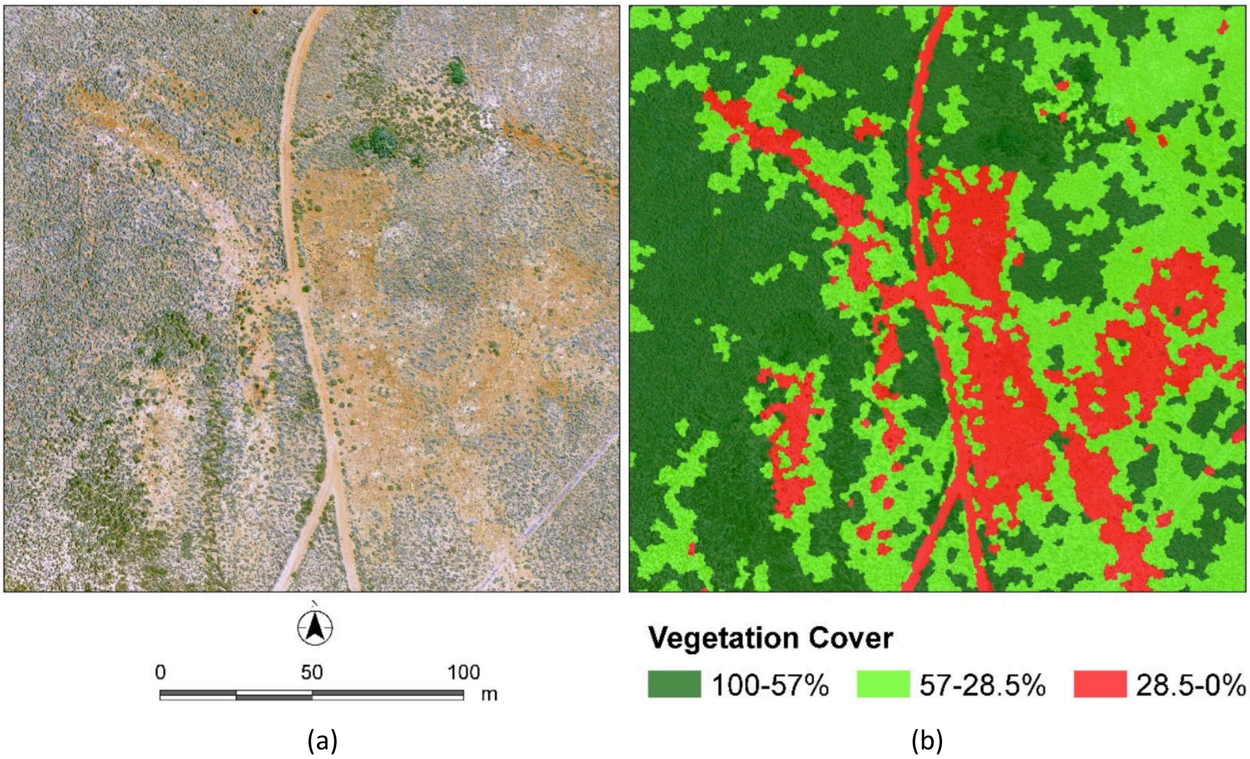


Figure 6 **(a) Original image of an area of historic disturbance; (b) a depiction of vegetation cover on that area, depicted in terms of the relevant numeric standard for vegetation cover as defined in completion criteria, and derived from object-based image analysis**

The graphical depiction of foliar cover was used to draw boundaries around areas recommended for remedial rehabilitation works, based on a visual assessment that considered factors such as size of the area, proximity to other areas of low cover, and the practical requirements of access and minimum working area for machinery. Key vegetation parameters such as *Triodia*, shrub and total cover percentages were generated through OBIA together with the exact spatial area recommended for remedial rehabilitation. When established as a routine procedure, this OBIA-based assessment of legacy sites will be complemented with a prior inspection to ensure that completion criteria for surface topography has been met. Identification of areas where surface topography and drainage do not meet the required standard, and therefore will require remedial earthworks, will be an important consideration in the process of defining the overall areas recommended for rehabilitation.

3.1.6 Remote sensing of potential impacts on vegetation cover and condition

As an extension of the application of OBIA on Barrow Island, we investigated the potential for it to provide an automated, timely and cost-effective method that will ultimately enable island-wide monitoring for changes to vegetation cover and condition. This may be beneficial in the ongoing requirement to monitor impacts such as those from potential non-indigenous species introductions.

Two areas of Barrow Island were selected for a change detection analysis, using aerial imagery from 2008 and 2017. The image of each study area was segmented into objects using OBIA, based on properties of each pixel within the image. Ground-truthing to identify vegetation species types allowed a database to be developed to train the OBIA software. Living vegetation was then identified in imagery for both study areas and at both dates of capture, and a change detection analysis allowed the vegetation cover difference between 2017 and 2008 to be calculated.

Triodia species made up almost all of the vegetation cover in the study areas, reaching a maximum cover of 72.5% in 2017. In general, live vegetation cover was greater in 2017 than in 2008, presumably reflecting more favourable conditions in prior years, although rainfall in the 12 months prior to image capture in 2008 was approximately 35% more than that in the same period for 2017.

Localised losses in vegetation cover since 2008 were able to be detected and were due primarily to vegetation clearing associated with construction, roads or drainage. Some areas of natural change were also identified and, when applied as a routine procedure, these would be recommended for a field inspection to better understand potential causes.

4 Conclusion

As a result of this study, we have established that with appropriate on-ground identification of vegetation types, OBIA of high-resolution aerial imagery can provide accurate estimates of total vegetation cover, and cover attributed to *Triodia* species. This approach offers great potential for detailed quantitative vegetation assessment over much larger spatial scales than possible with on-ground transect or quadrat-based approaches, and is applicable to rehabilitation and closure of energy and mining projects. If OBIA and aerial imagery can be used to reduce on-ground field work in remote areas that have inherently higher health and safety risks, such as for many resource projects in Australia, then the benefits would be substantial.

As part of our collaborative study we have demonstrated that an OBIA-based approach for vegetation assessment can be useful for monitoring vegetation performance in rehabilitated areas, screening rehabilitated legacy areas in terms of their vegetation status, and for change detection in vegetation cover, as part of environmental impact assessment.

In this study, we related OBIA cover estimates with those obtained from on-ground, quadrat-based assessment. Using quadrat assessments as a 'benchmark' for OBIA estimates has inherent limitations, due to low on-ground sampling intensity and the natural spatial heterogeneity or 'patchiness' of some analogue and rehabilitated areas. If further validation of the accuracy of OBIA estimates in relation to those from field monitoring was required, then a targeted investigation could be conducted. This could involve increasing levels of on-ground sampling intensity, through increasing numbers of quadrats in a defined area. This would be even more definitive if the study area was accurately defined in captured imagery via on-ground survey. An accurate survey would overcome inherent limitations of using hand-held GPS coordinates to locate monitoring sites on aerial images. A study of this type would also be valuable for refining sampling intensity for future on-ground monitoring.

Species differentiation within the *Triodia* genus was shown to be possible after specific ground-truthing to inform OBIA settings. It is worth noting that the current performance criteria for WA Oil's operations do not stipulate particular species of *Triodia* to be re-established, but refer simply to total *Triodia* cover. Distinguishing between *Triodia* species would likely be useful for future assessments of undisturbed vegetation, and in improving understanding of re-establishment of each species in rehabilitated areas.

Differentiation between live *Triodia* foliage (included in % cover) and senescent *Triodia* foliage ('litter') is difficult and somewhat subjective for on-ground assessors, and may be a factor affecting the correlation of quadrat-based estimates with those from OBIA. Undisturbed natural vegetation on Barrow Island can have substantial amounts of *Triodia* litter, because fire is infrequent. More intensive studies of mature, high-litter areas, including targeted ground-truthing is likely to enhance OBIA outcomes in vegetation with a substantial litter component.

The species mix in young rehabilitation on Barrow Island is known to be relatively dynamic, with many of the early-colonising species being short-lived. These short lifecycles mean that the colour and condition of foliage can change markedly between monitoring events. If OBIA was to be used to monitor newly-restored areas, then it is likely that ground-truthing would be required at each monitoring event. In addition, higher resolution imagery, such as from unmanned aerial vehicle platforms, may be useful in detecting juveniles of slower-growing species such as *Triodia*. If achievable, then this would be useful to assess density of *Triodia* seedlings in young rehabilitation, a critical indicator of eventual rehabilitation outcomes.

Acknowledgement

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