The application of digital aerial photography to shallow water seabed mapping and monitoring – how deep can you see?

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Richard Mount
Marine Research Laboratories, Tasmanian Aquaculture and Fisheries Institute and Centre for Spatial Information Science, University of Tasmania, Hobart, TAS, Australia. <Richard.Mount@utas.edu.au>

Abstract

Aerial imagery is commonly used in conjunction with a GIS for mapping shallow seabed habitats such as seagrass. Typically though, image quality is regularly poor over the water, particularly if originally captured for terrestrial purposes. A large number of interacting factors influence the image quality including environmental conditions such as water clarity, sun angle and water surface state. This paper details one aspect of a broader research effort that aims to further develop techniques for monitoring shallow water vegetation using a combination of high-resolution aerial imagery and boat-based field observations, including benthic (seabed) videography, in a GIS environment. The particular aspect focussed on here is maximising the seagrass "detection depth" of the imagery.

Ideally, aerial imagery needs to be able to detect the deeper boundaries of the seagrass beds if these boundaries are to be tracked through time. The effects of environmental conditions on the detection of these boundaries are examined based on recent surveys conducted in southeastern Tasmania in a temperate estuary with a definite water clarity gradient. The results show that the maximum detection depth is not an absolute measure – rather, it is a relative measure largely determined by the same factors that control seagrass growth. The overall detection depths of the imagery were similar to that of the benthic video, indicating a close match between the deep edges of the seagrass and the maximum detection depths of the aerial photography. The critical components for optimising detection depth are identified. Once light attenuation is minimised, the role of contrast in boundary detection becomes evident. For monitoring, a combination of aerial and boat-based data collection strategies is indicated.

Introduction

Remote sensing of the seabed from the air or space is commonly used for mapping habitats at a wide range of spatial scales (McKenzie et al., 2001; Finkbeiner et al., 2001). Because water effectively absorbs all wavelengths of the electromagnetic spectrum except for the visible, or "optical", wavelengths, optical remote sensing data are most commonly used. This includes imagery from aerial photography, digital videography and the visible bands of satellites such as Landsat, Spot and Ikonos (Lillesand and Kiefer, 1994; Mumby and Edwards, 2002). Dekker et al. (2003) lists current multi-spectral and hyper-spectral sensors suitable for shallow water benthic work and the cost of raw data for each sensor.

Seagrass, for example, is regarded as an important indicator species for measuring the "health" of coastal and estuarine ecosystems, both in terms of biodiversity and water quality (Ward et al., 1998; Saunders et al., 1998). Changes in the deep boundary of a seagrass bed through time are a useful measure for monitoring seagrass condition and impacts (Dennison & Abal, 1999). The depth to which seabed habitat boundaries can be detected is an important issue when assessing the potential use of optical remote sensing for mapping such habitats. Pasqualini et al. (1998) present a list of 18 seabed-mapping studies in which aerial photographic techniques manage to detect seagrass to between 2 and 15 m, which in many cases did not represent the maximum depth of the beds

Norris et al. (1997), Pasqualini et al. (2001) and Sewell et al. (2001), among others, have rejected the use of optical remote sensing in certain circumstances because of its failure to detect the deeper boundaries of seagrass beds. Others, such as Thomas et al. (1999) and McKenzie et al. (2001), identify some of the complications and limitations of optical remote sensing and suggest that it not be used in turbid waters or where access to a combination of "highly developed expertise in remote sensing with equivalent knowledge of the ecology and environmental characteristics of the target site" are not available for the study (Thomas et al., 1999). Some mapping and monitoring efforts have misinterpreted the deeper boundaries of the beds leading to substantial errors in estimating distribution and extent, therefore reducing the value of the resulting maps for monitoring purposes (Edyvane et al., 2000; Rees, 1993). Yet, many programs and researchers continue to make use of remote sensing (Dekker et al., 2003; Hart, 1997; Kendrick et al., 2000; Blake and Ball, 2001; Jordan et al., 2002; Armstrong, 1993; Mumby et al., 1997; Beanish et al., 2002; Cuevas-Jimenez et al., 2002).

This pattern of use indicates that optical remote sensing is being used at its limits and that there are a large number of variables influencing successful image acquisition through water. These variables include the characteristics of the target habitats, the range of water and atmospheric environmental conditions and the type of methods used to acquire the imagery (Phinn et al., 2000). Some of the difficulties arise because the available spectrum is limited to the visible wavelengths when imaging through the water column. Further complications are created by the variability and high level of light absorption and scattering in coastal marine water compared to air, and the impact of the air/water interface interactions such as refraction and surface glint (Finkbeiner et al., 2001; McKenzie et al., 2001). All of these characteristics reduce the capacity to observe the seabed, particularly as water clarity reduces and depth increases. There are also regional differences as these factors impact differently depending on latitude, lithography, rainfall, water temperature, biota and coastal geomorphology, among other variables. For instance, there are considerable differences in sun angle, tidal range and general turbidity levels between estuaries in tropical and temperate Australia.

Improved detection of the deep edges of seagrass beds can increase the precision of monitoring the extent and patchiness of seagrass beds through time, through more accurate delineation of patch boundaries (McKenzie et al., 2001). Short-term events, such as severe flooding, can impact on local seagrass distribution patterns, as can a range of other abiotic and biotic factors (Moore and Wetzel, 2000; Dennison and Abal, 1999). However, the position of the deeper edges of most aquatic macrophytes is primarily a response to the average light conditions, as light is a limiting factor for seagrass growth (Carruthers et al., 2001). Therefore, chronic decreases in water quality are likely to result in a loss of habitat on the deeper boundary. The average light conditions are determined by the average annual water clarity conditions (Dennison and Abal, 1999). This means that the deeper edges of the seagrass beds are most likely to be detected in remotely sensed imagery when water clarity is near the average maximum.

The current study is designed to test this notion in temperate shallow marine waters using practical, readily available technologies such as Secchi disks and digital cameras. The primary aim of this study is to determine whether it is possible to detect the deeper edge of seagrass beds using digital aerial photography when water clarity was near its average annual maximum.

This paper describes the preliminary findings of one component of a broader research effort that aims to further develop techniques for monitoring shallow water vegetation using a combination of purpose-flown high-resolution aerial imagery and boat-based field observations.

Study Area

The study area in North West Bay, an estuary in southeastern Tasmania, Australia (43°S, 147.25°E) (Figure 1) is approximately 7 km^2. It was selected to cover seagrass beds growing under a range of typical estuarine water clarity conditions. Secchi depth values grade from 2-4 m in the north of the bay near the main river delta to 4-9 m in the south with occasional very clear values of 12-14 m (Jordan et al., 2002). Tidal range is low at approximately 1 m. The dominant species of seagrass is *Heterozostera tasmanica* with *Halophila australis* found fringing on both the inner and outer edges of the beds.

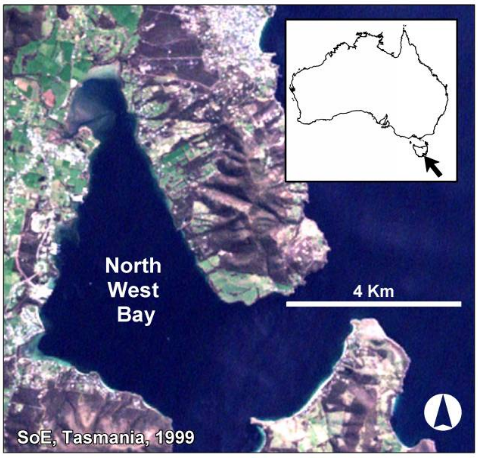

Figure 1. Location map and Landsat image of North West Bay, Tasmania.

Methods

The general approach was to capture airborne digital imagery and water clarity measures over the study sites and determine seagrass detection depths. An independent measure of the location of the deep edges of the seagrass beds was also collected via benthic videography. The two data sets were then compared taking into account depth, water clarity, habitat type, boundary contrast and boundary gradient.

Data capture

Existing water turbidity and clarity measures for North West Bay were assessed to obtain approximate average water clarity conditions (Jordan et al., 2002). Secchi disk readings are a simple, though effective, visual index of water clarity. Secchi depths were collected pre-flight to determine when water clarity was close to the average annual maximum and during the flight to obtain measures of image water clarity. Turbidity readings were also taken during the flight at 1 m depth with a Hach 2100P turbidity meter, with three replicates at each site. Each water sample site was located where it was both definitely visible in an image and in waters deeper than the Secchi depth yet as close as possible to the deep edge of a seagrass bed.

Imagery was acquired from a light plane with a port in the floor using a fixed Canon EOS D30 digital camera with a high quality 24 mm lens. Image size is 2160 x 1440, which at 2,360’ gives a ground resolution of 0.315 m per pixel and an extent of 681 x 453 m. This means that the minimum discernible object is, depending on its shape and contrast, about 1 m across. The imagery has standard red, green and blue bands with 8 bits in each. Imagery was captured under a clear sky and a sun elevation between 25° and 30°. This sun angle, combined with the windless conditions, ensured no surface glint and, due to the effects of refraction, gave an effective sun elevation underwater of 48° to 50°, thus limiting the effects of shadowing. Ground control was provided by a mix of stable geographic features and temporary floating tarpaulins that were 2.4 x 1.8 m in size and anchored securely in 3 directions.

Benthic video footage was collected using a submersible MorphCam single CCD digital video camera with images recorded on a Sony TRV900 digital handycam. The MorphCam was attached to a weighted tow frame at a 45° angle to the horizontal. The frame was suspended approximately 1 m from the sea floor, and maintained at this height by a winch operator on deck by viewing the live video footage, giving a field of view (FOV) that varied between 0.5 to 2 m wide. Tow speed was kept to less than 1 knot to maintain the camera position below the GPS antenna. A single frequency Garmin Map 135 GPS sounder was used with a Landstar differential unit providing real-time corrections. Estimated horizontal positional error is 3-5 m under kinematic operation. Differential GPS location, time, date and water depth were overlayed onto the video from the GPS sounder using a genlock device and logged in a file for use in the analysis.

The sampling paths of the video transects were targeted at the deeper edges of seagrass beds. The general locations were selected by using pre-existing seagrass maps of the study area and, in the field, a path was taken which zigzagged across the mapped boundary. The interaction of winds and currents and navigational imprecision meant that the exact location of each path was randomised to some extent along any one edge. The procedure adopted was to continue a run into deeper water until a combination of the live video footage and knowledge of the maximum depth to which seagrass grows in the area clearly indicated that the deep edge of the seagrass beds had been passed.

Digital aerial photography was collected on 12th January 2003 along with *in situ* measurements of water quality. Videographic data of the deep boundaries of seagrass beds were collected on the 7th February and 5th March 2003.

Data analysis

Five sites distributed across the study area where chosen for analysis. The aerial imagery was geo-referenced in ArcGIS 8.1 (ESRI, 2001) using available ground control points and then contrast enhanced using a simple stretch (Pasqualini et al., 1998). Apparent boundaries of the seagrass beds were digitised. Detailed image processing, as proposed for a later stage of this study, is not covered here. Estimated positional error potentially present in the imagery is around 5 to 8 m – mainly due to DGPS error in locating ground control and image capture geometry, including lens distortion.

The benthic video footage was viewed and as each habitat boundary was crossed, the new habitat type was characterised using classes “sand”, “*H. tasmanica*” and “*H. australis*”, (adapted from Barrett et al., 2001). A further class of “epiphyte” was added. These classes were modified with subjective estimates of “substrate brightness” on a scale of 1 to 5, “vegetation density” (1 to 4) and “epiphytic loading” (1 to 5). Two variables were developed to characterise the boundary itself – "gradient" and "contrast". Gradient is a subjective measure of the rate of change between habitat classes with categories consisting of "abrupt", "well defined", "patchy" and "gradual". Contrast is a subjective measure of the difference in overall brightness between the old habitat and the new, with categories consisting of "none, "low", "moderate" and "high".

All of the resulting video footage codes, the sounder depths and the DGPS position of the video camera were loaded into a GIS as a point layer. Estimated positional error potentially present in the boundary point locations is around 4 to 6 m – mainly due to DGPS error and differences in the video camera location relative to the GPS antenna. When overlaying layers in a GIS, the positional error propagates (Burrough and McDonnell, 1998) and so, the overall potential positional error of the combined GIS point layer and the geo-referenced imagery was calculated to be 6 to 10 m.

To determine whether the video boundary was matched by a boundary visible in the imagery, the position and depth of the GIS point boundary markers were visually compared to the position of the digitised seagrass bed boundaries visible in the imagery, particularly noting the deepest edges. Any potential matches were evaluated and the optimal match identified. Potential matches were identified as those digitised bed boundaries closer than the overall potential positional error. The optimal match was usually the closest boundary. Attributes relating to the best match were recorded against each boundary defined in the video footage, including the presence or absence of a matching boundary in the polygon layer digitised from the imagery, the distance and direction to that boundary and the classes either side of the edge.

Finally, a comparison of the maximum seagrass detection depths obtained in the video footage with those from the aerial imagery was conducted in each of the 5 study sites. Whereas the previous methods rely on the video footage as the standard, this method compares the two sets of data against each other. Firstly, the imagery was placed over a pre-existing high-resolution digital elevation model (DEM) in the GIS. The DEM was generated from previous single beam sounder surveys (Jordan et al., 2002) At each of the 5 sites, an average of four or five depths at which seagrass was clearly discernable in the imagery was obtained from the DEM and compared with the average of the deep edge boundary point depths obtained directly from the sounder readings recorded in the video log file. A limitation of this method is that the video footage was not necessarily captured over the deepest part of any one seagrass bed.

Results

In total, 105 boundaries were identified in the video footage – 71 inter-class boundaries and 34 intra-class boundaries. Of the inter-class boundaries, 58 were sand/seagrass boundaries – 27 of which were matched in the imagery and 31 missed. *H. tasmanica* to sand boundaries are relatively easy to match, whereas any boundary involving *H. australis* is missed more often than matched. Of the 15 deep edge boundaries, 9 were picked in the imagery, 4 were missed and 2 were uncertain (Table 1).

Table 1. Summary of deep edge boundary match results between video footage and digitised boundaries from aerial imagery, North West Bay, Tasmania, Jan-Mar, 2003. Note: Ha = *H. australis* and Hz = *H. tasmanica.*

Boundary grouping	Match	Miss	Uncertain	Total
All	39	64	2	105
Intra-class	9	23	2	34
Inter-class	30	41	0	71
Sand/seagrass	27	31	0	58
Ha/all	6	19	2	27
Hz/sand	13	8	0	21
Deep edge	9	4	2	15

The results for match rate by contrast for the sand/seagrass boundary points show that boundaries are missed in the aerial imagery much more often as boundary contrast reduces and vice versa for matched points (Figure 2a). A chi-squared test for independence between the matches and the misses confirmed that there is an extremely low probability (2.6×10^{-15}) that the results are due to the chance effects of random sampling and are, therefore, highly likely to come from different populations. For depth, there is a similarly strong relationship (Figure 2b). There is a dependency between perceived contrast and depth as illustrated in Figure 2c and supported by a chi-squared value of 1.4×10^{-4}. Conversely, there is no apparent relationship between match rate and the gradient variable, with a chi-squared value of 0.52 (Figure 2d).

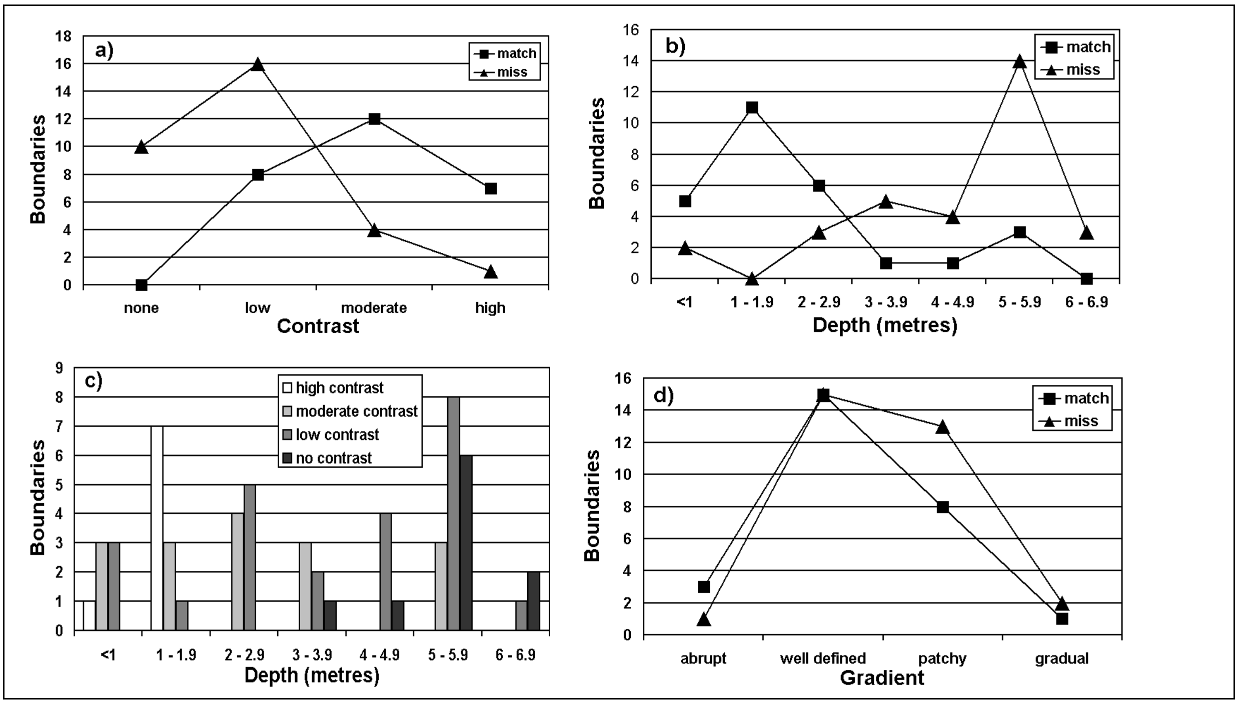

Figure 2. Results of match rates by contrast, depth and gradient for seagrass/sand boundaries in North West Bay, Tasmania, Jan-Mar 2003: a) Number of matched boundaries in each "contrast" category. b) Number of matched boundaries in each "depth" category. c) Number of boundaries in each "depth" category subdivided into "contrast" categories. d) Number of matched boundaries in each "depth" category. Note: squares = matches, triangles = misses.

Finally, for each of the 5 study sites, the mean maximum depth at which seagrass was positively visible in the aerial imagery was compared with the mean maximum seagrass detection depth of the video footage (Figure 3a). Please note that the depths were derived from a pre-existing high resolution DEM and are independent of the benthic video depth data. The results show the depths at which seagrass are visible over broader areas in the imagery are very similar to the detection depths of the video. They are also clearly related to Secchi depth, though are, on average, are about 60% shallower (Figure 3b). There was no apparent relationship of detection depth with turbidity.

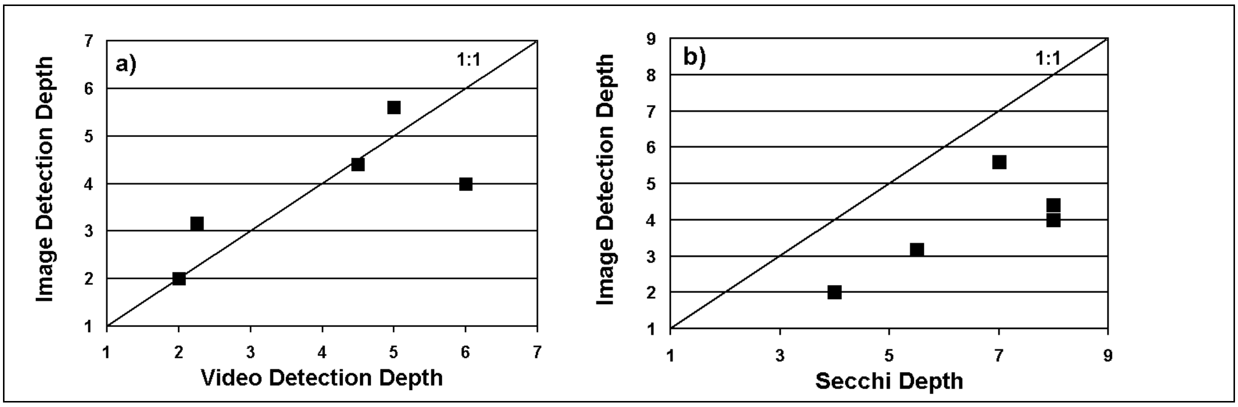

Figure 3. Comparison of the maximum perceived seagrass detection depths in the aerial imagery at 5 sites in North West Bay, Tasmania, Jan – Mar 2003 with a) the maximum measured seagrass detection depths in the benthic video footage, and b) Secchi depths (depths in metres). 1 to 1 ratio lines are also shown.

An example of the resulting imagery with the video transect overlaid can be seen in Figure 4.

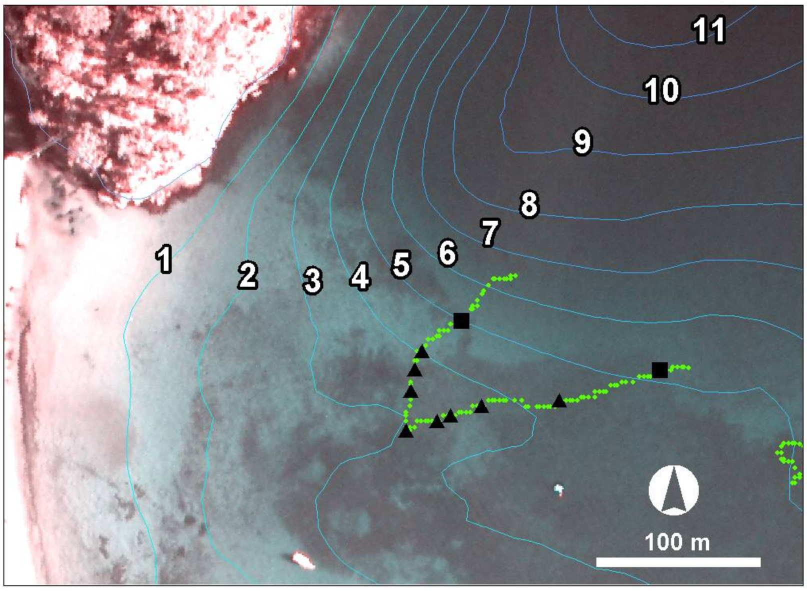

Figure 4. Boundary locations from benthic video transect and depth contours in metres, Snug Beach, North West Bay, Tasmania. Numbers = depths in metres, small circles = video transect, squares = deep edge boundaries, triangles = other boundaries.

Discussion

Airborne optical remote sensing is an established technique for mapping and monitoring seagrass beds (Thomas et al., 1999). This work seeks to extend these techniques by specifically evaluating the detection of the deeper edge boundaries of seagrass in a temperate estuary. The water clarity measures collected on the day of image capture show that conditions were at the higher end of the average conditions, but not exceptionally clear.

Boundary match rates and contrast

The video/image match rate results contain a number of useful insights. The intra-class match rates are much lower than inter-class match rates, indicating that changes in density within classes are difficult to ascertain. There is a clear difference in the value of the "contrast" and "gradient" boundary characterisation variables for this study. Contrast performed well and, while it could be improved by using a ratio of measurements based on the net greyscale values of the video images before and after a boundary, it has proved to be useful for characterising sand/seagrass boundaries. The variable could be used in the future to assess specific areas to determine whether aerial photography would be a suitable method for mapping and monitoring.

"Contrast" also has a relationship with depth, where perceived contrast decreases as depth increases. This is possibly because there is less water turbulence at depth and thus both the organic and inorganic particle composition is different and the particle size range smaller, leading to reduced reflectance values. Clearly, the absorption properties of the water itself will eventually make even high contrast boundaries undetectable at greater depths. This observation is relevant to the deeper growing species of seagrass such as *Posidonia oceanic,* with a maximum depth limit of 35 m (Carruthers et al,. 2001), though *Heterozostera tasmanica* has been recorded at 18 m (Barrett et al. 2001). While "gradient" is not useful for identifying boundaries in imagery, it may still be useful for other forms of boundary work including landscape ecology patchiness metrics (see below).

Within the classes, *Halophila australis* was the most difficult boundary to match, which may be partially explained by the large amount of substrate left revealed by its very short, sparse growth habit. It also tends to occur on the deeper, darker fringes of the *H. tasmanica* beds. This means it is difficult for optical remote sensing to clearly identify the deep edge boundaries when *H. australis* is present. A more promising result was evident for the *H. tasmanica* boundaries, which were matched more often than not, particularly at a sand boundary.

Video versus imagery detection depths

The results of the more general comparison between benthic video and imagery show similar seagrass detection depths were derived from the two data sources at all 5 sites (Figure 3). Also, the deeper edges of the seagrass beds were located at greater depth as the Secchi depths increased. Imagery seagrass detection depths for *H. tasmanica* were about 60% of *in situ* Secchi depths. These findings support the findings of others that the seagrass is limited by average light conditions (Carruthers et al., 2001). They also show that aerial photography is able to detect the deeper edges of seagrass beds when the water clarity is higher than average. That the imagery and videography have similar seagrass detection depths probably means that, at these depths and for these species, water column attenuation is not as much a limiting factor on boundary detection as the contrast between the habitat classes. The fact that the relatively clear turbidity readings were not related to detection depths suggests that absorption and scattering factors other than turbidity – such as tannins – may be more influential in this case. The Secchi depth usefully integrates these other factors and the turbidity into a single apparent optical measure (Preisendorfer, 1986). Carruthers et al. (2001) provide a detailed discussion of the relationship between the Secchi disk, average annual light and maximum seagrass depth limits.

Complementarity of video and aerial imagery

The imagery offers the benefit of a much greater spatial coverage of the deeper boundary than the video transect. The latter has the drawbacks of a very limited field of view and a much smaller chance of capturing the spatial variation in the deep edge position at any one time. The imagery has the drawback of increased uncertainty at the deeper edges. The two data sources compliment each other well, as the imagery can provide a much more detailed view of the deeper edge than that provided by the video, and the video greatly increases the confidence of locating the deeper edge in the imagery as well as improving habitat identification generally (Figure 4). Pasqualini et al. (1998) argues that aerial photography also compliments side scan sonar when mapping the deeper edges of seagrass habitats that grow to depths of 30 m, such as *Posidonia oceanica* in the Mediterranean Sea. Estimates of seagrass areas by Rees (1993) and Edyvane et al. (2000) – that were largely based on pre-existing optical remote sensing alone – both suffered from an inaccurate location of the deeper boundaries. For example, Edyvane et al. (2002) estimated only 15% of the seagrass mapped by a later, more accurate, study of the Bruny Bioregion of southeastern Tasmania (Barrett et al., 2001).

Landscape ecology metrics

Improved detection of deep edge boundaries with imagery should have benefits for analyses of spatial pattern and structure using methods such as landscape ecology metrics. Fonseca and Bell (1998) extracted perimeter/area ratios for seagrass beds from 50 x 50 m field-sampled study sites and related them to the physical variables of wave exposure, current speed and depth. There is considerable scope for image-based landscape ecology work as the raster structure of the imagery and broad spatial coverage suit this type of analysis. It should be noted, though, that many landscape ecology metrics rely on ratios of perimeter to area of mapped polygons (McGarigal and Marks, 1995). The trimming of polygons to a particular depth when the deep boundary is unknown significantly reduces the value of such measures, particularly when seeking to understand the patch dynamics of the deep boundary.

Limitations

With regard to limitations, there is a scaling problem between the field data and the aerial image data when attempting to match the boundaries perceived in the benthic videography with those in the imagery. This is because the video field of view is about the size of the smallest discernible object in the imagery, that is, about 1-2 m. This means that, if the video camera was crossing sand and entered a narrow sand channel about a metre wide between two seagrass beds, no boundary would be apparent. In the imagery, however, a sand/seagrass boundary is likely to be drawn across the start of the channel as the narrow sand channel itself may be blurred by the resolution of the pixels (Figure 4).

Finally, the study area represents only one set of environmental conditions and results may not hold for different seagrass species, substrates, water clarity conditions and wave exposure levels.

Conclusions

The results indicate that purpose-flown digital aerial photography coupled with boat-based benthic videography offer good opportunities for monitoring and mapping the deeper edges of seagrass beds. The two technologies compliment each other well – video for its precise boundary detection and more accurate classification of habitat types and aerial photos for its extensive spatial coverage.

The maximum detection depth is not an absolute measure – rather, it is a relative measure largely determined by the same factors that control seagrass growth. It was found that the deeper edges of the seagrass were located at greater depth as the Secchi depth increased. The seagrass detection depth of the imagery also increased with

Secchi depth and at a similar rate. Imagery seagrass detection depths for *H. tasmanica* were about 60% of *in situ* Secchi depths. The overall detection depths of the imagery were similar to that of the benthic video, indicating a close match between the deep edges of the seagrass and the maximum detection depths of the aerial photography. Once water attenuation factors were optimised, the contrast of the boundaries was found to be an important factor in boundary detection. Given that the imagery was acquired when water clarity was good but not exceptionally high, these results are promising.

This study indicates that critical components for optimising detection of the deep boundaries of seagrass beds are to:

1. Evaluate the contrast of the deep boundaries of the target habitat
2. Purpose-fly the image acquisition to optimise environmental conditions (eg sun angle and water clarity)
3. Obtain pre-flight water clarity readings with a Secchi disk to:
    - Predict detection depths in the imagery, and
    - Fly when water clarity is higher than the annual average
4. Maximise the field of view when using benthic videography, yet retain enough detail to classify the bottom accurately, and
5. Combine aerial imagery and in-water data to greatly enhance the results**.**

Anticipated future work directions include:

1. Develop more objective measures of the “contrast” and “gradient” boundary characterisation variables
2. Compare simple contrast stretching and hand digitising with more sophisticated image processing including classification and segmentation
3. Increase the positional accuracy of data collection through improved GPS methods such as post processing
4. Apply the boundary detection methods to the broader research goals of improving estimates of extent, patchiness and biomass – including using landscape ecology metrics – and monitoring, using change detection.

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