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A preliminary assessment of the standing stock and biomass of trochus in King Sound, north-western Australia.

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NON-TECHNICAL SUMMARY

Trochus shells are fished from intertidal reefs in King Sound, north-western Australia. The fishery currently harvests approximately 50 t annually producing a gross value of approximately A$ 500 000. Most members of the Bardi Aboriginal Community have fished trochus, although an average of 20 fishers operate each month with individual fishers catching between 50 to 100 kg each month. The majority of the catch is exported as raw shell for the production of mother-of-pearl buttons and a portion of the catch is retained by the Bardi Community for local sale as polished shells or jewellery. The biomass of trochus has never been estimated in the 12 year history of the fishery. Estimates of trochus abundance were established from strip transect sampling of reef habitats. The mean density of trochus within legal size limits (65 to 100 mm) on reef edge habitat (4.03 $\pm$ 0.630 se per 156 m^2, n = 35) was significantly greater than on the reef flats (0.39 $\pm$ 0.107 se per 156 m^2, n=56). A Landsat TM satellite image was used to determine to total area of reef edge and reef flat habitat in King Sound. Mean trochus densities were extrapolated to the total areas of reef edge and reef flat habitat. A total biomass of 110 t of trochus was estimated for intertidal reef habitats in King Sound. The total biomass was comprised of 70 t of legal size trochus (65 to 100 mm) and 40 t of under size trochus below 65 mm. These results provide valuable information for management, and a baseline for future stock assessment, of the trochus resource in King Sound.

TECHNICAL SUMMARY

Trochus shell are fished from intertidal reefs in King Sound, north-western Australia. The fishery currently produces approximately 50 t annually, but abundances of trochus have never been estimated in the 12 year history of the fishery. Abundance estimates define the standing stock available for fishing and assist in determining fishing quotas. Estimates of trochus abundance were established from strip transect sampling of reef habitats. The mean density of trochus within legal size limits (65 to 100 mm) on the reef edge (4.03 $\pm$ 0.630 se per 156 m^2, n=35) was significantly greater than on the reef flat (0.39 $\pm$ 0.107 se per 156 m^2, n=56). The total area of trochus habitat in King Sound was determined from a Landsat TM satellite image using 7 spectral signals with a spatial resolution of 30 x 30 m. The predictive success of spectral signals for classifying individual transects into reef edge or reef flat habitats was 96.20%. The satellite image was used to determine to total area of reef edge (9 556 ha.) and reef flat habitat (23 837 ha.) in King Sound. Extrapolation of mean trochus densities and total areas of reef edge and reef flat habitat indicated a total biomass of legal size trochus (65 to 100 mm) of approximately 70 t of trochus in King Sound. The total biomass of under size trochus (below 65 mm) was estimated to be approximately 40 t of trochus in King Sound.

1. INTRODUCTION

BACKGROUND TO THE RESEARCH

A small commercial fishery for trochus (*Trochus niloticus* Linnaeus, 1767) exists in King Sound, north-western Australia. Annual catches of trochus have declined from the 1980 high of 135 t but have been relatively stable around 40 to 70 t between 1985 to 1992. There is no published information concerning this fishery but anecdotal accounts suggest localised depletion of trochus is occurring, especially trochus on reefs closest to access points. Some accounts also suggest the possibility of impact on the fishery by illegal Indonesian fishing and recently further licenses to collect trochus were issued. Although the fishery has been operational since 1979, there have been no surveys of the abundance of trochus in King Sound and the virgin biomass is unknown.

Abundance is a measure of the number of animals in a population. From a biological viewpoint, abundance is likely to influence the rates of growth and mortality and the recruitment of juveniles into the population (Krebs 1985, Begon and Mortimer 1986). Abundance can define the amount available for fishing and assist in the determination of suitable fishing quotas. Estimates of abundance collected over time can be used to monitor changes due to fishing and provide an indication of the success of transplants to re-seed reefs. Consequently, developing and validating methods of measuring abundance is important and requires many considerations. Many countries where trochus is harvested are conducting stock assessment, particularly pre- and post- harvest surveys. There are several ways of expressing population abundance, such as density, standing stock and biomass.

Density estimates provide an estimate of absolute abundance because the total number of animals for a given spatial area is known. Density estimates for trochus can be obtained from strip transects, of variable lengths and widths. This provides an estimate of the number of trochus for a given area of reef habitat. Trochus density estimates range from a mean of 37 trochus per 100 square metres (24 transects) in Kosrae (Molina *et al.* 1991) to a mean of 5 trochus per 400 square metres (20 transects) in Palau (Ngiramolau *et al.* 1991). However, densities are not always uniform within habitats. Molina *et al.* (1991) found a peak trochus density on the upper reef slope at the 3 m contour but density decreases with increasing depth. The number and size of strip transects within the reefs needs to be adjusted according to the trochus density. This will ensure that the variance associated with estimates of mean trochus density within reefs is reduced (Green 1979, Andrew and Mapstone 1987). This increases the likelihood of detecting differences in mean trochus density estimates between reefs if differences exist.

An estimate of the total number of trochus for the total area on which trochus occurs is known as the standing stock. Determination of total standing stock requires extrapolating density estimates across the entire fishing region. This requires estimates of mean trochus density and the total area of trochus habitat. There have been several studies estimating the total area of trochus habitat by planimetry methods using maps and aerial photographs in the Cook Islands (Zoutendyk 1991), Palau (Ngiramolau *et al.* 1991) and Kosrae (Molina *et al.* 1991). The application of remote sensing techniques using satellite imagery has been used most recently to estimate the total area of trochus habitat, including simulated SPOT satellite imagery in New Caledonia (Bour *et al.* 1986); and Landsat TM satellite imagery in the Cook Islands (Nash *et al.* in press), Torres Strait (Long *et al.* 1993) and the Great Barrier Reef (Larkum 1993).

Trochus catches are recorded by the weight of shell collected. Therefore, it is often useful to discuss the amount of trochus available in the population in terms of the total wet weight. The standing stock can be converted to biomass, which is a measurement of the total wet weight of the population, if the size frequency distribution and the size weight relationship of the standing stock are known. Previous surveys indicate the relationship between size and weight for trochus in King Sound can be described by the following relationship (n=1730 r^2 = 0.998; Magro in preparation).

$$\text{Total wet weight (g)} = - 8.39 * \text{Maximum basal diameter (mm)}^{3.12}$$

The values in this relationship can be used to estimate the biomass of trochus, according to the size distribution associated with the density estimates. Additionally, the size frequency distribution of the standing stock can be used to estimate the percentage of the total standing stock that can be exploited. For example, in the Cook Islands the mean maximum basal diameter of 10.1 cm indicated 58% of the population was within the legal size range of 8 to 11 cm (Zoutendyk 1991).

OBJECTIVES OF THE RESEARCH

The objective of the FRDC project was to undertake a final extended field trip in King Sound to complete gathering baseline fishery biology data for the King Sound trochus fishery. The primary aim of this project was to establish estimates of trochus abundance in King Sound. To do this the following questions were raised:

Does trochus density vary between habitats?
Can the satellite image detect spectral groups correlating to trochus habitat?
How much trochus habitat occurs in King Sound?
What is the standing stock and biomass of trochus in King Sound?

2. METHODS

STUDY AREA

Trochus occurs along the Western Australia Kimberley coastline in northern King Sound and off-shore at the Rowley Shoals, Browse Island, Scott reef, Seringapatam reef, Ashmore reef and Cartier Island (Berry 1986, Jones 1986). These trochus stocks have been illegally exploited by Indonesian fishers for many years. Allan (1947) believed early activities of poachers in Western Australia limited the supply of shells through stock depletion. The location of illegal Indonesian fishers collecting trochus in northern Western Australian is a concern to the Bardi Community (Smyth 1993). The commercial Western Australian fishery for trochus is restricted to populations within King Sound (Jones 1986).

King Sound is a large inlet extending 145 km by 60 km in the north-west Kimberley region of Western Australia extending from latitude 16° 00' to 17° 07' S and from longitude 123° 18' to 123° 23' E (Australian Gazetteer 1975). The group of islands at the entrance of King Sound belong to the Buccaneer Archipelago (15° 57' to 16° 12' S and 123° 13' to 123° 26' E). The Buccaneer Archipelago contains an extensive network of over 100 islands, depending on the tidal height. The Bardi Aborigines reside at One Arm Point (16° 26' S and 123° 05' E) on the eastern side of the Dampierland Peninsula and community members collect trochus from intertidal reefs throughout King Sound.

The tidal height and range in King Sound are characteristic of the region. It is a semi-diurnal tide with variations in range between spring and neap tides of up to 11 m (Australian National Tide Tables 1983, 1986). Easton (1970) suggested the many islands in King Sound modify the tides producing variable changes in tidal amplitude and a time difference of several hours compared to standard ports in the Kimberley region. The tides and powerful tidal flow dominate the major water currents within King Sound where there are many narrow straits between the coastline and the numerous islands. The moving tides can produce currents of up to 10 to 30 knots with whirlpools, eddies and vertical walls on the water surface.

Harvesting occurs on exposed reef platforms during low tide periods. The Bardi people would traditionally use reefs around One Arm Point during 2 seasons described by Smith (1987). The Iralboo, or king tide season, occurs between March to May. Winds are usually absent at the start of this season but south east winds develop in April. The Djalalayi, or warming up season, occurs between August and September, when there are strong west winds and unusually low tides. Trochus collecting is more likely to occur during these favourable weather seasons because the low tides provide good reef exposure and the winds are generally favourable for small boats.

Data collection was performed on the exposed inter-tidal reef platforms during low spring tides. Sub-tidal reefs were not surveyed because of the currents associated with the tides and (fear of) saltwater crocodiles which occur in northern Australian waters. Extensive reef areas are exposed at low tide and provide a safe area for survey. Suitable day-time low tides occur during spring tides for approximately 6 to 8 days every fortnight. Low tides occur every 12 hours and it is possible to work on the exposed reef for up to 4 hours (depending on the tidal height and reef height relative to mean sea level). Access to the reefs is gained by small boats. It is possible to complete work on a single reef in 1 day, during a single low tide. This provides 5 to 8 good working days each spring tide, approximately 10 to 16 days each month.

Most of the inter-tidal reefs adjacent to One Arm Point have been main trochus fishing grounds since the fishery began in 1979 and the number of shells in this region have declined following intense fishing pressure. It was necessary to discontinue fishing activity on some reefs to provide an area for trochus populations to regenerate and hopefully reflecting unexploited conditions with increase population levels and larger size distributions. The idea of closing (or resting) reefs is not a new one to the Bardi Community; several reefs were closed in the early 1980s by the Bardi Council to provide a rest from intense fishing activity (Eric Hunter, Bardi Aborigines Association, pers. comm.). Four reefs were closed from fishing activity for research purposes in October 1990 following consultation and discussions with the community members and elders. The reefs chosen were *Niiwardinggoon*, *Mardaj*, *Marloogoon* and *Jooloom* (Figure 1) which are within 10 km of One Arm Point.

Inter-tidal reefs, accessible by small dinghies, occur near One Arm Point; *Bawlon*, *Nambanan* and *Ngoolminjin* within 10 km of One Arm Point (Figure 1). Reefs further away from One Arm Point were also sampled; *Gararr* and *Noonba* are approximately 30 km from One Arm Point across Sunday Strait; *Giirroon*, *Goordoog Goordoog* and *Noomoonj* are approximately 50 km from One Arm Point (Figure 1). Table 1 lists the latitude and longitude of all the reefs surveyed, along with the English name for each island which the reefs are adjacent to. Reference to study sites throughout this report use the Bardi reef names.

TRANSECT SAMPLING

An assessment of the standing stock of trochus in King Sound was made during an extended field trip from April to May 1993. The tides and weather conditions are most suitable during this time of year for this type of work. Trochus density and reef habitat were quantitatively surveyed at a single site on 5 fished reefs and at 2 sites each on the 4 closed reefs (Table 1). Seven randomly placed 4.8 x 32 m strip transects were taken at each of the 13 sites. The reef habitat was recorded at 1 m intervals along the 32 m line transect in the centre of each strip transect. The strip transect was thoroughly searched for trochus, providing an estimate of trochus density (number of trochus per 153.6 m^2} . The maximum basal diameter of all shells collected in each transect was measured using vernier calipers to the nearest 0.05 mm. A reading of the Australian Map Grid co-ordinates was taken at the centre of each line transect using a Magellan™ Global Positioning System (GPS). The longitude and latitudes of each transect are given in the Appendix.

COMPARISON OF TROCHUS SIZE DISTRIBUTIONS BETWEEN REEFS

Size frequency distributions of trochus were plotted for each reef by pooling measurements for trochus collected in the 7 transects on each site and allocating size measurements to 5 mm size class intervals. The total number of trochus measured varied between reef sites: Bawlon (n=6), Gararr (n=25), Nambanan (n=8), Ngoolminjin (n=58), Noonba (n=3), Jooloom edge (n=59), Jooloom flat (n=7), Mardaj edge (n=25), Mardaj flat (n=7), Marloogoon edge (n=30), Marloogoon flat (n=2), Niiwardinggoon edge (n=43) and Niiwardinggoon flat (n=25). The size measurements were useful for selecting size classes for calculating density estimates, especially as density estimates are usually only concerned with estimates of the standing stock of shells that can be legally collected within the set size limits. Consequently, trochus were placed into three groups according to their size: within the legal size range (65 to 100 mm), below the minimum legal size limit of 65 mm and above the maximum legal size limit of 100 mm.

ESTIMATES OF TROCHUS DENSITY

A nested analysis of variance (ANOVA) was used to compare the density of trochus between reef status (closed and fished reefs) for reef flat habitats only. The response variable for the ANOVA were measurements of the number of trochus per 153.6 m^2 from 7 random replicate transects taken from 8 random independent reef flat habitats. A two factor ANOVA was used to compare the density of trochus between reef flat and reef edge habitats for closed reefs only. The response variable for the ANOVA were measurements of the number of trochus per 153.6 m^2 from 7 random replicate transects taken from reef edge and flat habitats from 4 random closed reefs. Cochran's test was used to investigate the assumption of equal variances (Day And Quinn 1989) and a log (x+1) transformation on trochus density data for both ANOVA's gave the best approximation to homoscedascity. The transformed data also gave a closer fit to normality according to the Shapiro-Wilk test using JMP software. ANOVA's were performed using a general linear model with type III sums of squares on SAS software (SAS Institute Inc. 1987). Separate analyses were performed for legal size and under size trochus.

APPLICATION OF SATELLITE IMAGERY TO ESTIMATE TROCHUS DENSITY

A Landsat Thematic Mapper (TM) satellite image of King Sound is held at the Remote Sensing Applications Centre of the Department of Land Administration (Figure 2). The image was recorded on 27 August 1986 at 9:40 am during a low spring tide (Australian National Tide Tables 1986). The trochus fishing area within King Sound was isolated. The image was rectified using 17 control points and enlarged to correspond with 1:50 000 navigational charts of regions within King Sound. This produces a geometrically correct image, aligned to the Australian Map Grid (AMG), direct comparison with latitude and longitude bearings or AMG co-ordinates. The mean map error of the image was 22 m, which is less than the dimensions of a single pixel.

Landsat TM images classify ground covers using 7 spectral signals with a spatial resolution of 30 x 30 m (Table 2). Radiance values received by the satellite contains contributions from atmospheric scattering, surface reflectance and substrate upwelled radiance for each spectral signal. Data values correspond to radiance, a measure of reflectance, and values represent digital counts of radiance scaled between 0 to 255. Higher reflectance, usually indicates higher penetration, invokes a higher digital count. The satellite image was analysed using the International Image System (I^2S) software processing system at the Remote Sensing Applications Centre.

ESTIMATING THE TOTAL AREA OF TROCHUS HABITAT IN KING SOUND

The total number of trochus in King Sound can be calculated if the total area of suitable habitat and a reliable estimate of density are known. The transect data provided classification of 91 known reef areas which could be classified according to actual reef site (edge or flat). Each transect corresponds to a single pixel on the satellite image. The location of each transect was placed on the satellite image using the GPS co-ordinates recorded when density estimates were made for each transect. Each pixel was visually inspected to check that it came from dry reef flat or reef edge habitat. Twelve pixels were found to lie positioned either in water or on reef flat edges producing incorrect signals or mixels. These transects were: Gregory (1), Jooloom edge (3), Jooloom flat (2), Mardaj edge (5) and Marloogoon flat (1). Consequently, these 12 pixels could not be used for analysis. Although the image was recorded during a spring low, it was not as big a spring low as when the habitat samples were taken (Australian National Tide Tables 1986; 1993), so the location of the 12 transects were under water when the image was taken. Therefore, 79 transects were used for analysis.

Multiple Discriminant Analysis (MDA) was used to determine the ability of the spectral signals to accurately classify the transects into reef edge and reef flat habitats. Discriminating variables included values for the six bands (blue, green, red, infra-red, mid infra-red and far infra-red). Additionally, ratios of the first three bands (green/red, blue/green and blue/red) were included as ratios high-light subtle differences in the satellite image. Long *et al.* (1993) observed that trochus habitat was best described by a ratio of green to red wavelength, with trochus being most abundant in areas with a high green to red ratio. Jupp *et al.* (1985) attribute high ratios of green to red to submerged coral and rubble shoal habitats.

Accurate determination of ratios required correction for atmospheric scattering. Each band scatters in the atmosphere differently and variations need to be compensated if ratios are going to be calculated. Blue wavelength has the highest contribution from atmospheric scattering. The dark pixel subtraction method was favoured to correct atmospheric back-scattering (Alex Wyllie, Remote Sensing Applications Centre, pers. comm.). The dark pixel gives the lowest reading for all bands, therefore assuming radiance equals zero and the value produced is the contribution from atmospheric back-scattering. The dark pixel for the King Sound image produced radiance values of 49, 14 and 11 for the blue, green and red bands respectively.

Multiple discriminant analysis was performed using DSCRIMINANT on SPSS/PC+. Unstandardised canonical discriminant function coefficients were calculated because variable units were similar. Wilks Lambda, converted into chi square statistics were used to test the significance of discriminant functions. Significant results from this analysis determine whether the satellite image can be classified accurately into suitable trochus habitat. Classification of suitable trochus habitat was determined for 7 regions in King Sound, each corresponding to 1:50 000 maps. The total area of suitable trochus habitat was determined by summing the area of suitable habitat in the 7 regions.

ESTIMATING THE STANDING STOCK AND BIOMASS OF TROCHUS IN KING SOUND

The standing stock for legal size and under size trochus was determined by extrapolating the density estimates to the total area of trochus habitat in each of 7 regions in King Sound. The weight for the average size of legal size and under size trochus was used to convert the standing stock to an estimate of trochus biomass. The total standing stock and biomass of trochus in King Sound were determined by summing the standing stock and biomass of trochus in the 7 regions. The standard error associated with the mean density estimates were used to determine upper and lower limits for standing stock and biomass.

3. RESULTS

COMPARISON OF TROCHUS SIZE DISTRIBUTIONS BETWEEN REEFS

The size frequency distributions from each reef are given in Figure 3. Interpretation of these distributions is hindered by the low abundance on most reefs. Distributions with higher abundances show more readily identified modes. The total abundances are generally higher at reef edge locations (including Ngoolminjin). The 5 fished reefs, except Ngoolminjin, have lower abundances. This is also true of the reef flat samples. Furthermore, the size distribution of fished reef and reef flat samples are dominated by shells below the 65 mm legal limit. The closed reef edge samples have the highest proportions of legal shells (between 65 to 100 mm). Size was variable between reefs, especially the closed and fished reefs. The majority of variation is explained by reef site; larger shells are found on reef edges and reef flats are dominated by smaller shells. However, there were very few trochus above the maximum legal size of 100 mm (Table 3).

ESTIMATES OF TROCHUS DENSITY

Density of trochus was not significantly different between closed and fished reefs on reef flat habitats for both under, and legal size trochus ($F = 0.0157$, $p = 0.9044$ and $F = 0.9169$, $p = 0.3753$ respectively; Table 4). No significant difference in legal size trochus was observed among the 4 reefs ($F = 1.1890$, $p = 0.3282$; Table 4), although there was a significant difference in under size trochus among the 8 reefs ($F = 7.4112$, $p = 0.0001$; Table 4).

There was no significant difference in the density of under size trochus between reef edge and reef flat habitats ($F = 2.3283$, $p = 0.2245$; Table 5). Mean shell density of under size trochus was no greater on the reef edge (2.00 shells per 153.6 m^2) compared with reef flats (1.08 shells per 153.6 m^2; Table 6). However, the reef edge habitats had significantly greater densities of legal size trochus than reef flat habitats ($F = 17.2855$, $p = 0.0253$; Table 5). Mean legal size trochus densities on reef edge and reef flat habitats were 4.03 and 0.39 shells per 153.6 m^2 respectively (Table 6). Additionally, there was no significant difference in the density of under size trochus among the 4 closed reefs ($F = 2.4301$, $p = 0.0766$; Table 5), but a significant difference among the 4 closed reefs was observed for legal size trochus ($F = 3.2880$, $p = 0.0285$; Table 5).

ESTIMATING THE TOTAL AREA OF TROCHUS HABITAT IN KING SOUND

Discriminant analysis of spectral signals according to reef site was very effective. The spectral signals for the 6 bands and 3 ratios accurately predicted 88.9% and 100% of the 79 transect into reef edge (n=27) and reef flat (n=52) sites respectively. The overall predictive success of spectral signals produced by the satellite image into reef edge or reef flat classification was

96.20%. Only 3 of all 79 transects were inaccurately grouped (transects 2, 31 and 44)

The first discriminant function was highly significant (Chi square = 98.626, $p<0.001$, Table 7). The green/red ratio was found to have the highest unstandardised canonical discriminant function coefficients, therefore contributing the most toward the first discriminant function. Other high ranking variables included (in order): blue/green ratio, green band, blue/red ratio and red band. These results indicate the satellite image was suitable for classification into reef edge and reef flat habitat. Classification was performed for each of the 7 regions in King Sound, producing an image showing the location of reef edge and reef flat habitats (Figure 4) and the total number of pixels in reef edge and reef flat habitats within the 7 regions (Table 8). The total number of pixels was converted to total area (in ha.) and this was highly variable by habitat and region. For example, 7356 ha. of reef flat habitat was determined in the Sunday region while only 1896 ha. on the more suitable reef edge habitat was determined (Table 8). Although the area of reef flat and reef edge habitat in the Caffarelli region was more comparable, 3179 and 3595 ha. respectively, the Cafferelli region had a much larger area of the more suitable reef edge habitat than the Sunday region (Table 8).

ESTIMATING THE STANDING STOCK AND BIOMASS OF TROCHUS IN KING SOUND

The biomass of legal size trochus was variable between the 7 regions, the lowest being 2891 kg in Kimbolton and 23554 kg in Caffarelli (Table 8). The trochus biomass in the Sunday region, which is most accessible to One Arm Point, was estimated to be 15766 kg. The variation in biomass between regions reflects differences in the area of suitable trochus habitat both between regions themselves and between habitat types. Trochus is more abundant in regions with larger proportions of reef edge habitat (Table 8).

The total biomass of legal size trochus for King Sound was calculated to be 71 t of trochus, with a range of 58 to 84 t (Table 9). The total biomass of under size trochus in King Sound was calculated to be 44 t, with a range of 34 to 53 t (Table 9). The total population biomass of trochus is estimated to be 115 t, and 62% of the total population weight was within the legal size limits. The difference between total biomass of under size shells and legal size shells reflects the different average size and corresponding weights of the two groups. Legal size trochus have a larger size which corresponds with a larger weight, compared to under size trochus.

4. DISCUSSION

IMPLICATIONS AND RECOMMENDATIONS

There are a number of limitations associated with a small scale study of this nature. In particular, a large number of assumptions are involved with each analysis. Such as the problems associated with sample size for calculating mean densities of trochus. Additional monitoring of trochus abundance in King Sound would reduce the number of assumptions associated with this research. For example, monitoring the changes in abundance over time can allow determination of the impacts of fishing, if the amount removed in fishing activity is also known.

However, this is the first attempt to obtain an estimate of the standing stock and biomass of trochus in King Sound. This study suggests the total population of commercial trochus in King Sound was approximately 70 t. This biomass is similar to annual production between 1985 to 1992, which ranged from 40 to 70 t, approximately 60 to 100 % of the current biomass estimate. Additionally, the biomass of under size trochus is estimated to be approximately 40 t, which may or may not be able to support a commercial fishery with similar harvest rates under the present management system.

This research has implications for future management of the trochus resource in King Sound. Over size shells are extremely rare, indicating a reduced broodstock to reseed populations. The maximum basal diameters of trochus from all transects were low, possibly indicating growth over fishing of the trochus resource. Furthermore, the average sizes were close to the size where trochus in King Sound become sexually mature (approximately 65 mm). The problem of over-fishing may be increased if abundances are declining in addition to decreases in the average sizes collected. This causes particular concern because a reduction in sexually mature shells will reduce the spawning stock biomass, resulting in recruitment over fishing.

The application of satellite imagery for assisting the estimation of standing stock and biomass of trochus in King Sound was successful. Discriminant analysis of satellite data indicated significant differences between reef edge and flat habitats. An artificial channel created by a ratio of the green to red bands contributed the most toward significantly discriminating between reef edges and flats, supporting earlier research by Long *et al.* (1993). The area mapped as trochus habitat can affect both the accuracy and precision of the final biomass estimate (Hill and Ahmad 1992). Multiple images over time are required to remove errors associated with interpolation and extrapolation of a single image. However, satellite image processing allows mapping of extensive areas quickly, accurately and inexpensively, particularly when suitable classification has been discriminated (Bour *et al.* 1986, Long *et al.* 1993). There is some possible application for selecting areas to reseed wild populations with hatchery reared trochus juveniles based on the findings of this research.

INTELLECTUAL PROPERTY

There is no apparent intellectual property associated with this research. Provision and analysis of the satellite image data was facilitated by Andrew Buchanan from the Remote Sensing Applications Centre, Department of Land Administration, Western Australia.

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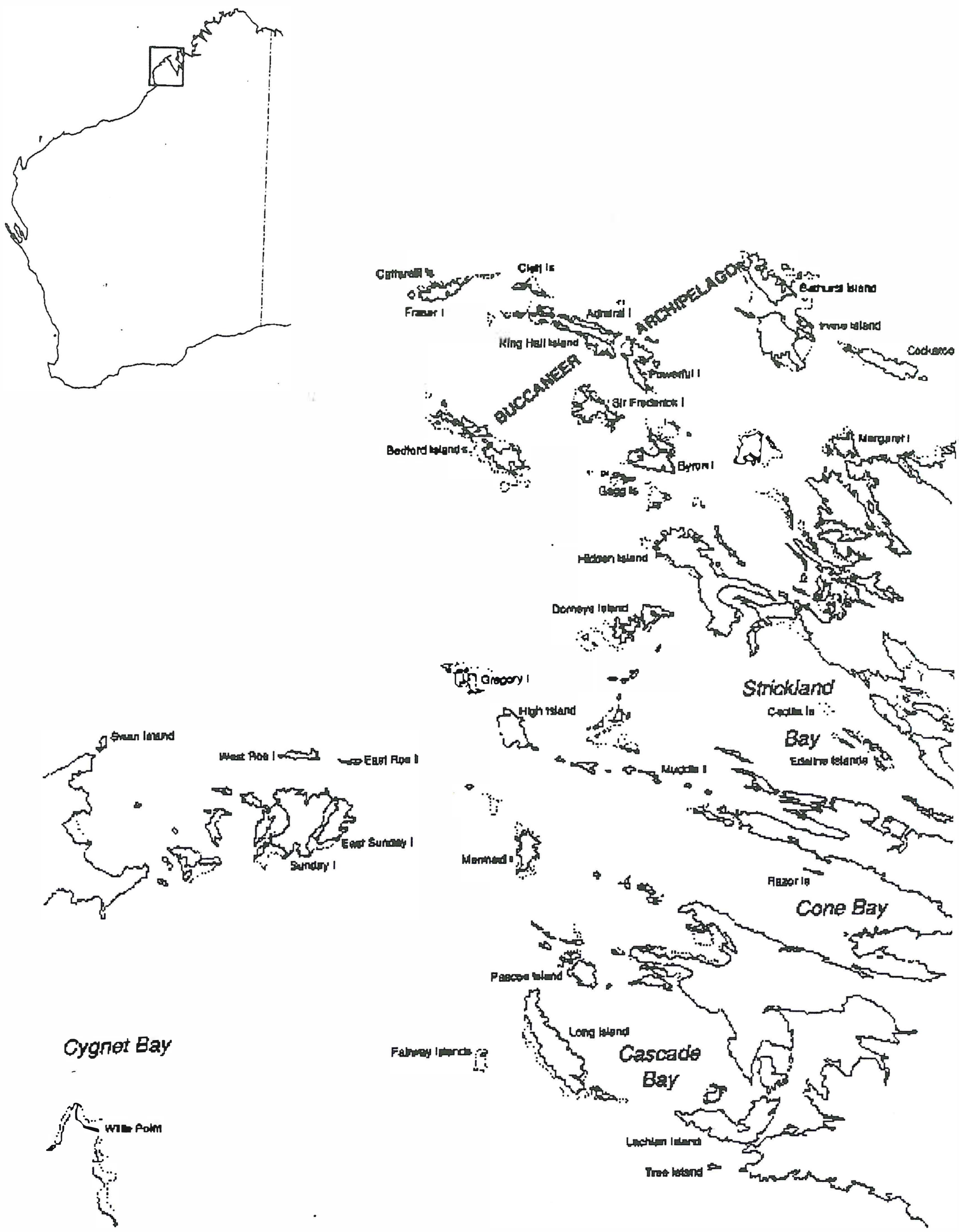


Figure 1: Map of King Sound and the Buccaneer Archipelago where trochus are harvested from intertidal reefs.

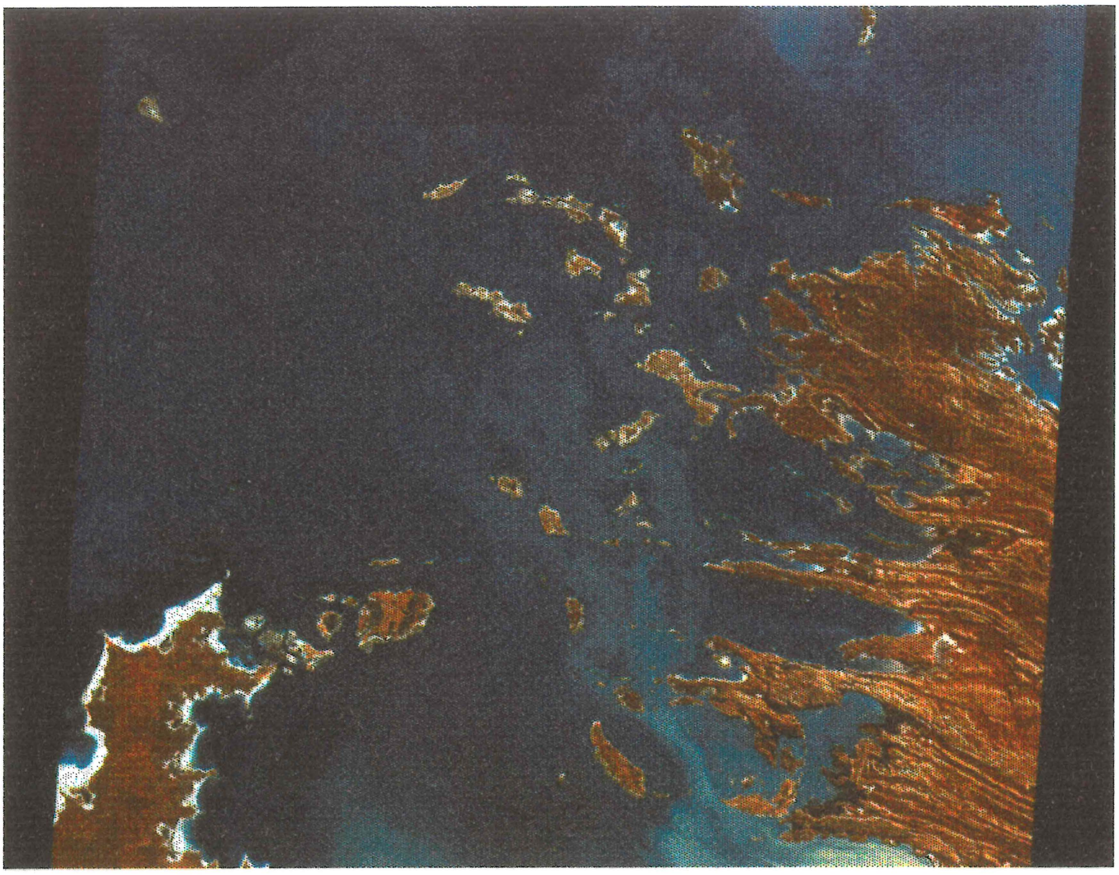


Figure 2: Landsat Thematic Mapper (TM) satellite image of King Sound trochus fishing area extending 145 km by 60 km in the north-west Kimberley region of Western Australia extending from latitude 16° 00' to 17° 07' S and from longitude 123° 18' to 123° 23' E.

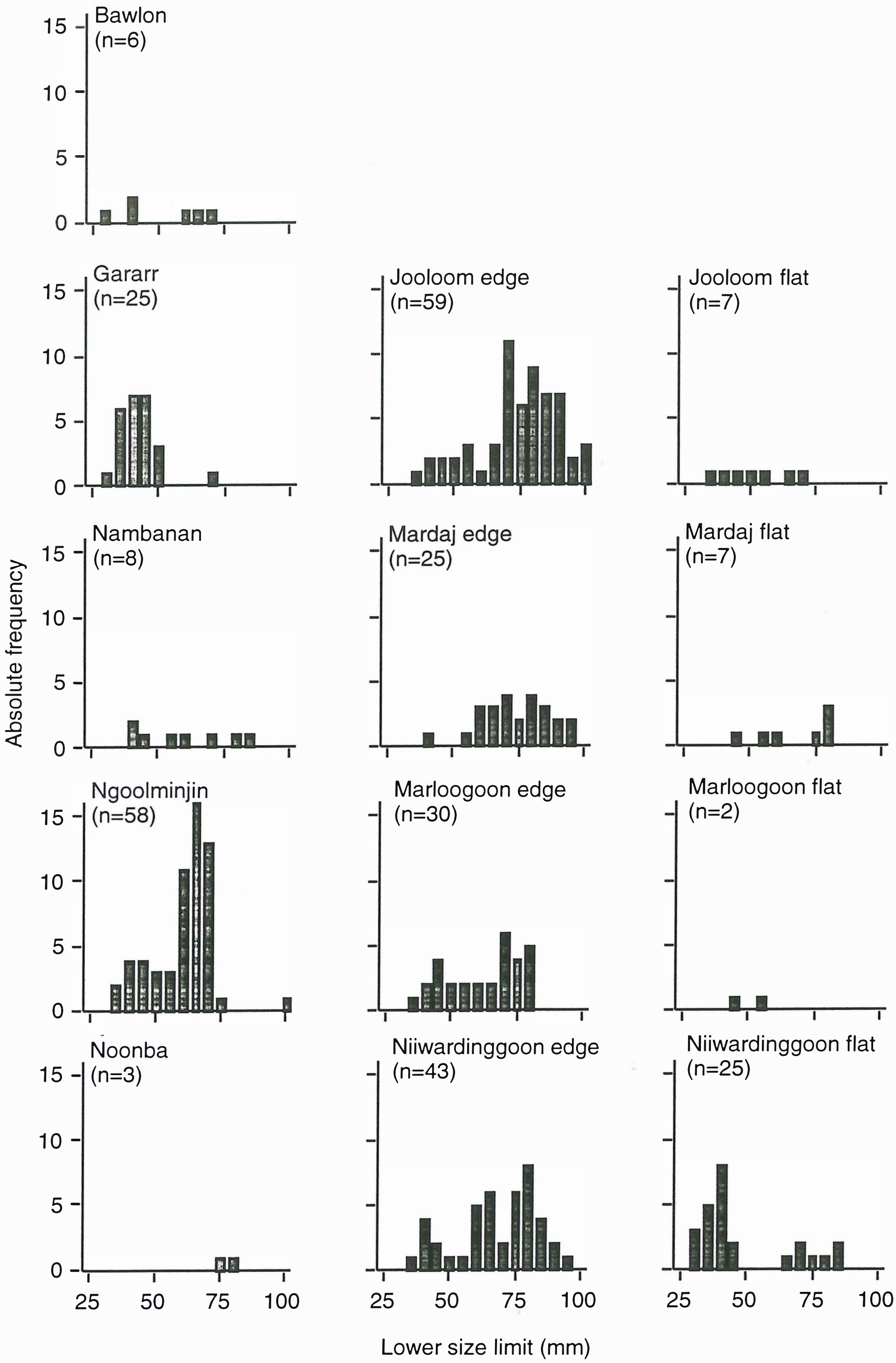


Figure 3: Size frequency distributions at 13 locations in King Sound in April and May 1993. Size classes are 5 mm intervals.

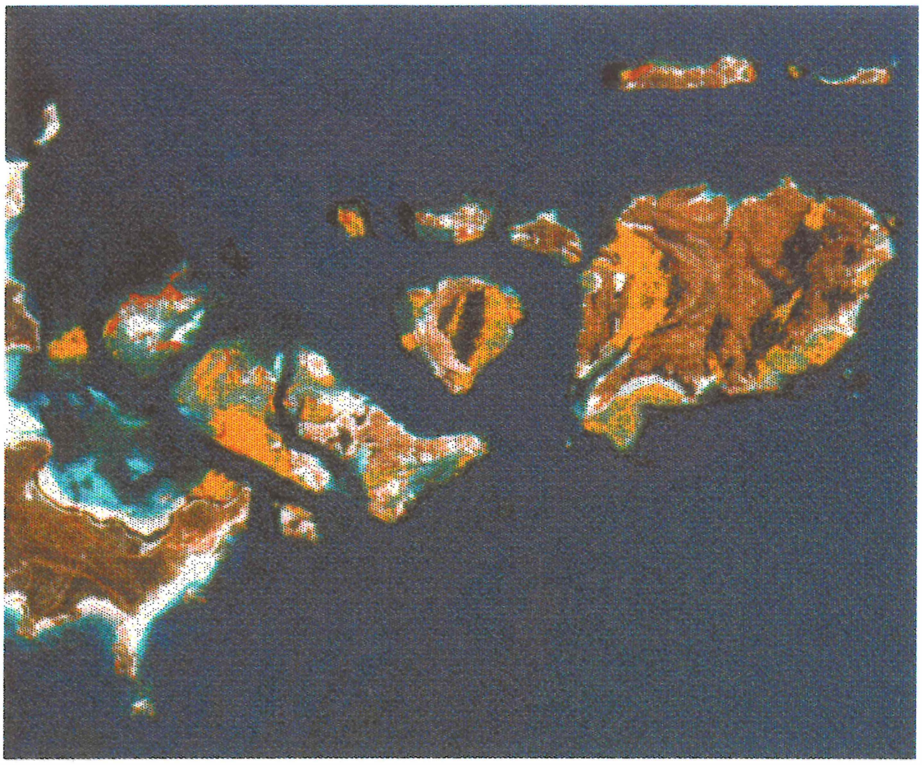
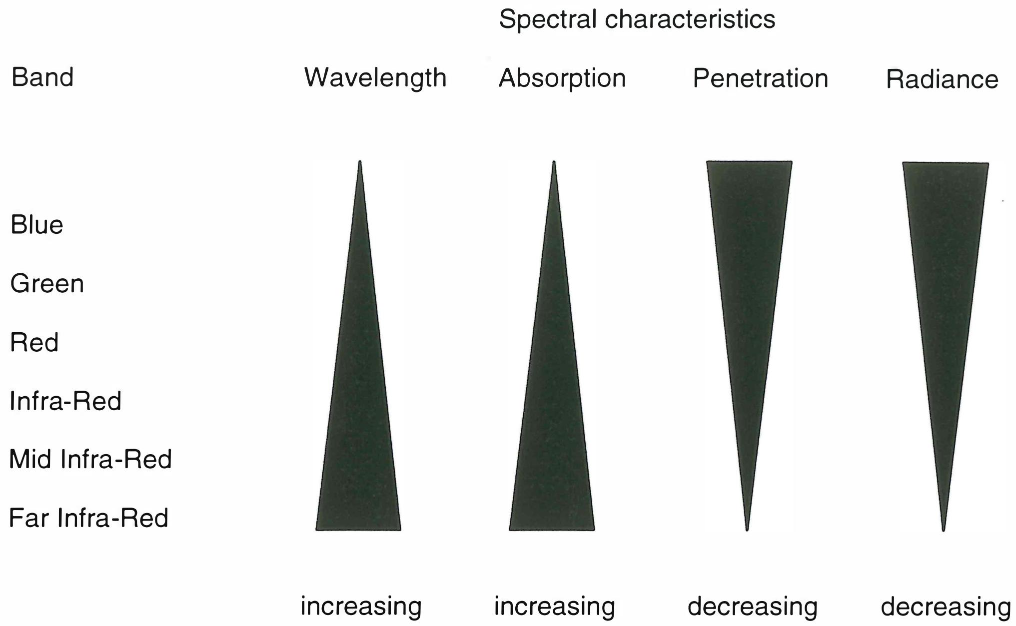


Figure 4: Landsat Thematic Mapper (TM) satellite image of the Sunday Island region in King Sound following classification of reef edge (red) and reef flat (yellow) habitats.

Table 1: Summary of names and locations of the 13 reefs researched in King Sound. Longitude and latitudes were calculated from 1:50 000 maps of King Sound.

Status	Habitat	Bardi reef name	English name	Latitude	Longitude
Closed	Edge	Jooloom	Middle Island	16° 27' S	123° 05' E
Closed	Flat	Jooloom			
Closed	Edge	Mardaj	One Arm Point	16° 26' S	123° 04' E
Closed	Flat	Mardaj			
Closed	Edge	Marloogoon	Tallon Island	16° 25' S	123° 07' E
Closed	Flat	Marloogoon			
Closed	Edge	Niiwardinggoon	Rees Island	16° 23' S	123° 06' E
Closed	Flat	Niiwardinggoon			
Fished	Flat	Bawlon	Waterlow Island	16° 26' S	123° 05' E
Fished	Flat	Gararr	Mermaid Island	16° 25' S	123° 21' E
Fished	Flat	Nambanan	Sunday Island	16° 26' S	123° 10' E
Fished	Flat	Noonba	Gregory Island	16° 18' S	123° 19' E
Fished	Edge	Ngoolminjin	Apex Island	16° 24' S	123° 03' E

Table 2: Summary of spectral bands classified by Landsat TM.



Spectral band	Band number	Wavelength (μm)	Spatial resolution (m)
Blue	1	0.45 to 0.52	30 x 30
Green	2	0.52 to 0.60	30 x 30
Red	3	0.63 to 0.69	30 x 30
Infra Red	4	0.76 to 0.90	30 x 30
Mid Infra Red	5	1.55 to 1.75	30 x 30
Far Infra Red	7	2.08 to 2.34	30 x 30
Thermal	6	10.40 to 12.50	120 x 120

Table 3: Summary of the total numbers of under, legal and over size trochus at each reef.

Reef	Under size < 65 mm	Legal size 65 to 100 mm	Over size > 100 mm	TOTAL
REEF FLAT				
Bawlon	4	2	0	6
Gararr	24	1	0	25
Nambanan	5	3	0	8
Noonba	0	3	0	3
Jooloom	5	2	0	7
Mardaj	3	4	0	7
Marloogoon	2	0	0	2
Niiwardinggoon	18	7	0	25
REEF EDGE				
Ngoolminjin	27	30	1	58
Jooloom	11	45	3	59
Mardaj	5	20	0	25
Marloogoon	13	17	0	30
Niiwardinggoon	14	29	0	43

Table 4: A nested ANOVA on density (number of trochus per 156 m^2) by status (fished and closed) for reef flat habitats only. A log (x+1) transformation was used to provide the closest approximation to homoscedascity; *** = highly significant and ns = non-significant.

a. ANOVA for under size trochus (below 65 mm).

Source	df	MS	F	p	
Status	1	0.0050	0.0157	0.9044	ns
Reef (Status)	6	0.3177	7.4112	0.0001	***
Residual	48	0.0429			

b. ANOVA for legal size trochus (65 to 100 mm).

Source	df	MS	F	p	
Status	1	0.0366	0.9169	0.3753	ns
Reef (Status)	6	0.0399	1.1890	0.3282	ns
Residual	48	0.0366			

Table 5: A two factor ANOVA on density (number of trochus per 156 m^2) comparing reef edge and flat habitats for closed reefs only. A log (x+1) transformation was used to provide the closest approximation to homoscedascity; * = significant ($p<0.05$) and ns = not significant.

a. ANOVA for under size trochus (below 65 mm).

Source	df	MS	F	p	
Reef	3	0.1395	2.4301	0.0766	ns
Habitat	1	0.2040	2.3283	0.2245	ns
Reef * Habitat	3	0.0876	1.5260	0.2198	ns
Residual	48	0.0574			

b. ANOVA for legal size trochus (65 to 100 mm).

Source	df	MS	F	p	
Reef	3	0.2312	3.2880	0.0285	*
Habitat	1	2.7233	17.2855	0.0253	*
Reef * Habitat	3	0.1575	2.2403	0.0956	ns
Residual	48	0.0703			

Table 6: Summary of the mean density of under and legal size trochus on reef edge and reef flat habitats.

Source	n	Mean density of under size trochus (Number of shells / 156 m² ± se)	Mean density of legal size trochus (Number of shells / 156 m² ± se)
REEF FLAT	56	1.1 ± 0.2283	2.0 ± 0.4140
Bawlon	7	0.6 ± 0.2973	0.3 ± 0.2857
Gararr	7	3.4 ± 0.6851	0.1 ± 0.1428
Nambanan	7	0.7 ± 0.4205	0.4 ± 0.4285
Noonba	7	0.0 ± 0.0000	0.4 ± 0.4285
Jooloom	7	0.7 ± 0.1844	0.3 ± 0.1844
Mardaj	7	0.4 ± 0.2020	0.6 ± 0.2973
Marloogoon	7	0.3 ± 0.1844	0.0 ± 0.0000
Niiwardinggoon	7	2.6 ± 1.1096	1.0 ± 0.3779
REEF EDGE	35	0.4 ± 0.1071	4.0 ± 0.6304
Ngoolminjin	7	3.9 ± 1.6822	4.3 ± 1.2670
Jooloom	7	1.6 ± 0.5714	6.4 ± 1.5865
Mardaj	7	0.7 ± 0.2857	2.9 ± 1.7515
Marloogoon	7	1.9 ± 0.4040	2.4 ± 1.3067
Niiwardinggoon	7	2.0 ± 0.7559	4.1 ± 0.8571

Table 7: Summary of Multiple Discriminant Analysis of spectral bands into reef site groups: edge (n=27) and flat (n=52) where a. shows the unstandardised canonical discriminant function coefficients with the level of significance for univariate F-tests of each variable (df=1x77) and the ranking of variables; b. shows statistics for the significance test and c. shows a summary of correct classification.

a.

Band	DF1	Ranking	p
Blue	-0.5351	7	0.0553
Green	1.841	3	0.2565
Red	-1.0732	5	0.0553
Infra Red	0.0204	10	0.0022
Mid Infra Red	-0.0023	9	<0.0001
Far Infra Red	0.3380	8	<0.0001
Ratio Green/Red	-17.9612	1	0.0147
Ratio Blue/Green	9.2616	2	0.0270
Ratio Blue/Red	1.5483	4	0.9782
Ratio Blue/Green/Red	-1.0644	6	0.7134
Constant	12.1033		

b.

Statistic	Value
Wilks Lambda	0.257
Chi square	97.946
df	10
Significance	<0.0001

c.

Actual Group	Predicted reef edge	Predicted reef flat
Reef edge	88.9%	11.1%
Reef flat	nil	100.0%

Overall correct classification = 96.20%

Table 8: Estimates of the total area of trochus habitat and trochus biomass estimates in 7 regions within King Sound. Area estimates were calculated from the number of pixels classifed in the ground-truthed satellite image (1 pixel = 30 x 30 m). Standing stock was determined by extrapolating density estimates from transect sampling to total areas. Biomass was determined using a size-weight relationship for trochus (Total wet weight (g) = - 8.39 x Maximum basal diameter (mm) $^{3.12}$; n = 1730, r^2 = 0.998).

Region	Reef site	Number of pixels classified	Area (ha.)	Standing stock	Biomass (kg)	Total region biomass
Yampi	Edge	1185	1067	27972	6434	
	Flat	5012	4511	11537	2654	9087
Strickland	Edge	490	441	11566	2660	
	Flat	573	516	1319	303	2964
Kimbolton	Edge	371	334	8757	2014	
	Flat	1657	1491	3814	877	2891
Cascade	Edge	536	482	12652	2910	
	Flat	3312	2981	7624	1753	4664
Mermaid	Edge	1934	1741	45652	10500	
	Flat	4226	3803	9728	2237	12737
Caffarelli	Edge	3994	3595	94278	21684	
	Flat	3532	3179	8130	1870	23554
Sunday	Edge	2107	1896	49736	11439	
	Flat	8173	7356	18813	4327	15766
TOTAL						71663

Table 9: Summary of King Sound trochus biomass estimates (kg total wet weight).

KING SOUND	Lower biomass	Estimated biomass	Upper biomass
Legal size shells	58641	71663	84522
Under size shells	34856	44019	53215
TOTAL	93497	115682	137737

APPENDIX Location of strip transects according to Australian Map Grid co-ordinates

Reef site	Transect	Easting	Northing
Bawlon	1	5 - 08 - 508 E	51 81 83 - 079 N
	2	5 - 08 - 580 E	51 81 83 - 051 N
	3	5 - 08 - 561 E	51 81 83 - 048 N
	4	5 - 08 - 613 E	51 81 83 - 012 N
	5	5 - 08 - 703 E	51 81 82 - 979 N
	6	5 - 08 - 668 E	51 81 82 - 913 N
	7	5 - 08 - 705 E	51 81 82 - 970 N
Gararr	1	5 - 36 - 867 E	51 81 85 - 087 N
	2	5 - 36 - 820 E	51 81 85 - 057 N
	3	5 - 36 - 833 E	51 81 85 - 090 N
	4	5 - 36 - 763 E	51 81 85 - 024 N
	5	5 - 36 - 741 E	51 81 85 - 065 N
	6	5 - 36 - 713 E	51 81 85 - 068 N
	7	5 - 36 - 689 E	51 81 85 - 041 N
Jooloom edge	1	5 - 09 - 190 E	51 81 81 - 796 N
	2	5 - 09 - 268 E	51 81 81 - 832 N
	3	5 - 09 - 249 E	51 81 81 - 778 N
	4	5 - 09 - 181 E	51 81 81 - 801 N
	5	5 - 09 - 178 E	51 81 81 - 809 N
	6	5 - 09 - 318 E	51 81 81 - 866 N
	7	5 - 09 - 169 E	51 81 81 - 809 N
Jooloom flat	1	5 - 08 - 815 E	51 81 81 - 978 N
	2	5 - 08 - 849 E	51 81 81 - 965 N
	3	5 - 08 - 890 E	51 81 81 - 951 N
	4	5 - 08 - 937 E	51 81 81 - 917 N
	5	5 - 08 - 990 E	51 81 81 - 879 N
	6	5 - 08 - 965 E	51 81 81 - 907 N
	7	5 - 09 - 028 E	51 81 81 - 846 N
Mardaj edge	1	5 - 07 - 739 E	51 81 82 - 741 N
	2	5 - 07 - 735 E	51 81 82 - 753 N
	3	5 - 07 - 723 E	51 81 82 - 754 N
	4	5 - 07 - 666 E	51 81 82 - 755 N
	5	5 - 07 - 666 E	51 81 82 - 734 N
	6	5 - 07 - 678 E	51 81 82 - 697 N
	7	5 - 07 - 649 E	51 81 82 - 712 N
Mardaj flat	1	5 - 07 - 114 E	51 81 82 - 997 N
	2	5 - 07 - 149 E	51 81 82 - 924 N
	3	5 - 07 - 224 E	51 81 82 - 903 N
	4	5 - 07 - 287 E	51 81 82 - 901 N
	5	5 - 07 - 346 E	51 81 82 - 856 N
	6	5 - 07 - 336 E	51 81 82 - 869 N
	7	5 - 07 - 404 E	51 81 82 - 808 N

Reef site	Transect	Easting	Northing
Marloogoon edge	1	5 - 12 - 403 E	51 81 85 - 436 N
	2	5 - 12 - 455 E	51 81 85 - 466 N
	3	5 - 12 - 458 E	51 81 85 - 518 N
	4	5 - 12 - 417 E	51 81 85 - 538 N
	5	5 - 12 - 395 E	51 81 85 - 551 N
	6	5 - 12 - 393 E	51 81 85 - 648 N
	7	5 - 12 - 399 E	51 81 85 - 627 N
Marloogoon flat	1	5 - 12 - 075 E	51 81 85 - 515 N
	2	5 - 12 - 075 E	51 81 85 - 515 N
	3	5 - 12 - 225 E	51 81 85 - 427 N
	4	5 - 12 - 269 E	51 81 85 - 501 N
	5	5 - 12 - 274 E	51 81 85 - 480 N
	6	5 - 12 - 273 E	51 81 85 - 624 N
	7	5 - 12 - 294 E	51 81 85 - 654 N
Nambanan	1	5 - 16 - 876 E	51 81 82 - 230 N
	2	5 - 16 - 893 E	51 81 82 - 243 N
	3	5 - 16 - 843 E	51 81 82 - 219 N
	4	5 - 16 - 932 E	51 81 82 - 196 N
	5	5 - 16 - 994 E	51 81 82 - 165 N
	6	5 - 16 - 944 E	51 81 82 - 148 N
	7	5 - 16 - 988 E	51 81 82 - 112 N
Ngoolminjin	1	5 - 05 - 538 E	51 81 87 - 074 N
	2	5 - 05 - 545 E	51 81 87 - 070 N
	3	5 - 05 - 560 E	51 81 87 - 079 N
	4	5 - 05 - 489 E	51 81 87 - 111 N
	5	5 - 05 - 484 E	51 81 87 - 102 N
	6	5 - 05 - 465 E	51 81 87 - 121 N
	7	5 - 05 - 452 E	51 81 87 - 126 N
Niiwardinggoon	1	5 - 11 - 160 E	51 81 88 - 858 N
	2	5 - 11 - 204 E	51 81 88 - 848 N
	3	5 - 11 - 208 E	51 81 88 - 835 N
	4	5 - 11 - 256 E	51 81 88 - 831 N
	5	5 - 11 - 309 E	51 81 88 - 829 N
	6	5 - 11 - 475 E	51 81 88 - 730 N
	7	5 - 11 - 419 E	51 81 88 - 771 N
Niiwardinggoon flat	1	5 - 11 - 293 E	51 81 88 - 514 N
	2	5 - 11 - 257 E	51 81 88 - 742 N
	3	5 - 11 - 234 E	51 81 88 - 726 N
	4	5 - 11 - 255 E	51 81 88 - 691 N
	5	5 - 11 - 276 E	51 81 88 - 716 N
	6	5 - 11 - 337 E	51 81 88 - 641 N
	7	5 - 11 - 450 E	51 81 88 - 648 N

Reef site	Transect	Easting	Northing
Noonba	1	5 - 33 - 610 E	51 81 97 - 510 N
	2	5 - 33 - 602 E	51 81 97 - 419 N
	3	5 - 33 - 629 E	51 81 97 - 427 N
	4	5 - 33 - 680 E	51 81 97 - 390 N
	5	5 - 33 - 751 E	51 81 97 - 383 N
	6	5 - 33 - 804 E	51 81 97 - 296 N
	7	5 - 33 - 869 E	51 81 97 - 309 N