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Mapping the nesting habitats of saltwater crocodiles (*Crocodylus porosus*) in Melacca Swamp and the Adelaide River wetlands, Northern Territory: an approach using remote sensing and GIS

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Abstract. The utility of integrating remotely sensed data and other spatial information in a geographical information system (GIS) to model habitat suitability for nesting by saltwater crocodiles (*Crocodylus porosus*) was investigated in this study. The study areas, Melacca Swamp and the Adelaide River wetlands, are located 50 km east of Darwin, Northern Territory, and encompass areas of suitable nesting habitat for *C. porosus*. Melacca Swamp is a highly productive nesting area and is managed as a conservation reserve to protect its nesting habitat. Landsat TM, SPOT satellite imagery and large-scale colour aerial photography were evaluated for their utility in mapping habitats preferred for nesting by *C. porosus* within Melacca Swamp. Satellite imagery was capable of identifying generalised habitat classes used for nesting (e.g. open swamp with emergent trees). However, it was only with aerial photography that habitats could be discerned (e.g. sedges with scattered *Melaleuca* trees). Spatial information derived from satellite imagery and other sources was integrated in a GIS to model potentially suitable nesting habitat along the Adelaide River. This methodology effectively identified known preferred nesting areas of *C. porosus* on the basis of the analysis of environmental parameters (i.e. distance to water, vegetation type) that have an influence on selection of nesting habitat. The findings of this research demonstrate the utility of remote sensing and GIS for mapping nesting habitat of *C. porosus* at a range of scales and provide guidelines for application of the approaches used at the regional or State level.

Introduction

The saltwater crocodile (*Crocodylus porosus*) was declared a protected species in the Northern Territory in 1971. The wild population at this time was severely depleted because the species was over-hunted for the skin trade (Messel *et al.* 1979). Since protection, the Parks and Wildlife Commission of the Northern Territory has managed *C. porosus*. Management of the species focuses on sustainable use; the objective of the current plan of management is to facilitate the conservation of *C. porosus* by establishing a commercial value for the species (Anon. 1996). Commercial exploitation of the species for its skin was tested between 1984 and 1989 using animals reared from eggs harvested from wild nests. The development of an export industry based on this method of use proceeded and is now an economically valuable industry to the Northern Territory, with several new crocodile farms establishing in the years since it emerged. In addition, the management authority believes that the management regime has been successful in enhancing the conservation value of *C. porosus* in the eyes of the community.

With the assumption that the market demand for *C. porosus* skins will continue, expansion of the egg-harvesting industry is an objective of the management plan, together with the maintenance of sufficient wild populations to sustain harvest. The industry currently relies heavily on eggs harvested from wild nests annually between November and April (northern Australia’s wet season). Monitoring the impacts of this harvest on wild populations is crucial to ensure the sustainability of the industry. The use of the species to date has proven sustainable, with annual population surveys tracking the increase in the wild *C. porosus* population across the Northern Territory since protection and following the introduction of ranching (Anon. 1996). Expansion of egg-harvesting operations in the wild is a likely progression, which will require a greater ability to identify potential nesting habitats from which eggs can be collected.

Habitats are likely to exist in areas that have not yet been harvested. Furthermore, the coastline of the Northern Territory might contain suitable nesting habitats that are not yet used by *C. porosus* because the population is still

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recovering. Documentation of the spatial distribution of these potentially suitable nesting habitats and the location of important areas for recruitment into the wild population is patchy. Updated information on habitat availability is thus required. This information, as well as contributing to the successful expansion of the egg-ranching industry, will be crucial to future management (Magnusson *et al.* 1978, 1980) as the species, although not currently considered endangered in any Australian State or Territory (Webb and Manolis 1993), could possibly face threats from a combination of ranching and anthropogenic encroachment on wetland nesting habitats.

In Australia, the nesting sites and nest materials used by *C. porosus* reflect the wide variety of wetland habitats that the species occupies in both freshwater and saline environments (Magnusson *et al.* 1978, 1980; Magnusson 1980). Previous research into the nesting ecology of *C. porosus* suggests that, while habitats used for nesting vary across the geographical regions of northern Australia, there are specific environmental variables that influence nest-site selection. Freshwater swamps provide the most productive nesting habitats for *C. porosus*, although the species also uses a broad range of riverine habitats (Magnusson *et al.* 1978; Webb and Manolis 1989; Webb 1991). Nests constructed on riverbanks are usually found where the river meanders through a floodplain (Webb *et al.*1977). Nests constructed further than 100 m from permanent water are rare, and most nests are usually constructed within 20 m of permanent water (Webb *et al.* 1983; Graham 1991). In terms of cover type, mangrove forests are poor nesting habitats (e.g. see Webb *et al.* 1977; Magnusson *et al.* 1978, 1980; Magnusson 1980; FAO 1985), as are open sedge plains and exposed shore communities (Magnusson 1980).

Information is not available in a spatial context and therefore at present is of limited relevance to management. Research into the nesting ecology of *C. porosus* in northern Australia has been limited to a few river systems, and most surveys were conducted in the late 1970s and early 1980s. Furthermore, current survey methods are not capable of providing spatial data. At present, annual spotlight and helicopter counts over selected river systems are the standard method of population monitoring (Anon. 1996). In the past, documentation of available nesting habitats in selected areas has been conducted through a combination of aerial surveys, boat surveys and searches on foot (e.g. Webb *et al.*1977; Magnusson *et al.* 1978, 1980; Magnusson 1980). Helicopter surveys are a cost-effective method of finding nests when only small areas are surveyed; however, this approach is not satisfactory for larger areas or for comprehensive mapping of habitat.

Remote sensing therefore appears to be the only feasible technique for mapping the nesting habitats of *C. porosus* across the extensive Northern Territory coastline. This technology has been used to map the habitats of the Yangtze alligator (*Alligator sinensis*) in China (Zhujian *et al.* 1986), but its utility for mapping the nesting habitats of *C. porosus* has not been investigated. Remote sensing has provided a cost-effective means of documenting wildlife habitat in coastal and wetland areas in the region (e.g. Ahmad and Hill 1994; Menges *et al.* 1998). The advantages of using remote sensing for collecting data in wetland environments where ground surveys are restricted by access and economic constraints are widely accepted (e.g. see Catt and Thirarongnarong 1992; Jennings *et al.* 1992; Johnston and Barson 1993; Rutchey and Vilcheck 1994; Lee and Lunetta 1995). In mapping the nesting habitats of *C. porosus*, other elements, such as the danger to the researcher during ground surveys, must also be taken into account when considering the value of remote sensing as a management tool for this species.

This paper presents the results of a study that assessed the utility of remote sensing and associated geographical information system (GIS) approaches for mapping the nesting habitats of *C. porosus* in the Melacca Swamp and Adelaide River wetlands. These wetlands were selected to provide a representation of both the freshwater swamp and riverbank nesting habitats of *C. porosus* in the Northern Territory. Furthermore, the area is an important nesting site for *C. porosus*, and eggs are collected from the area annually for local crocodile farms. Nesting data collected over the past 20 years provided a substantial base of information to assist in the development and assessment of remote-sensing and GIS techniques. The research reported is the first phase of a larger project that aims to develop effective methodologies for mapping nesting habitats in more remote areas of the Northern Territory, where knowledge of *C. porosus* nesting is less comprehensive. Ultimately, an extensive database of nesting habitats along the entire coastline of the Northern Territory will be established.

Methods

Study area

The Adelaide River and Melacca Swamp wetlands are located approximately 50 km north-east of Darwin (Fig. 1).

Adelaide River

The floodplain system of the Adelaide River covers an area of 136 800 ha including several swamps, lakes, lagoons and dams (Jaensch 1993; Whitehead and Chatto 1995). The floodplain is dominated by several grass and sedge communities and is fringed by open woodland (*Eucalyptus*, *Melaleuca*, *Acacia* spp.). Mangrove species, including *Rhizophora stylosa*, *Campostemon schultzii* and *Avicennia marina*, dominate the riverbanks (Messel *et al.* 1979). Other species present include the climber *Derris trifoliata*, the parasite *Amtema mackayense*, the annual *Tecticornia australasica* and the rare wetland plant *Goodenia quadrifida* (Jaensch 1993; Whitehead and Chatto 1995).

The downstream limit of *C. porosus* nesting along the Adelaide River occurs at approximately 15 km from the sea. The upstream limit is ~85 km by river from the sea, or just below the mouth of Marrakai Creek (Fig. 1). The most-intensive bank nesting occurs in the downstream meandering sections of the river. Nesting in these areas occurs on the concave under-cut banks abutting the meander point bars,

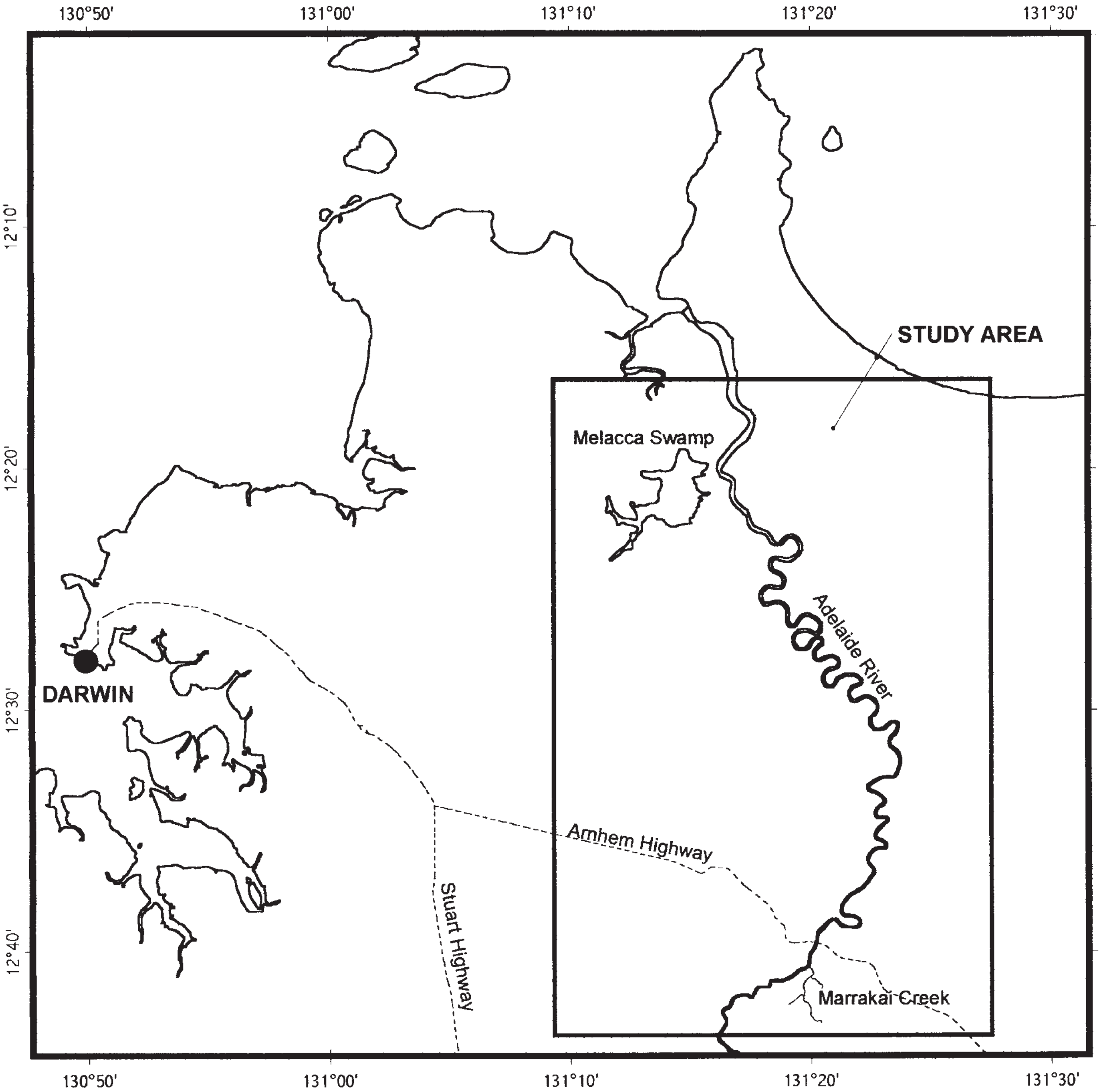

Fig. 1. The location of the study areas in the Northern Territory.

or in the shrub layer behind the mangroves that fringe the floodplain (Fig. 2*a*). The vegetation constituents of nest sites vary, with grass/sedge species, *Mimosa pigra*, *Derris trifoliata* vine, mud and sticks often used. Outer floodplain areas that can be accessed via permanent creeks adjoining the river also contain suitable nesting habitats.

Melacca Swamp

Melacca Swamp is an elevated freshwater wetland adjacent to the Adelaide River (Webb *et al.* 1983). Unlike many of the swamps in northern Australia, Melacca Swamp is permanently inundated, with a spring-fed creek traversing the southern section. This year-round water supply makes the swamp one of the most important areas for off-bank crocodile nesting in the Northern Territory (Jaensch 1993; Whitehead and Chatto 1995). A resident population of 440–530 saltwater crocodiles is maintained in Melacca Swamp year-round, and 12–30 nests are harvested annually (Webb and Manolis 1993). The importance of Melacca Swamp as a nesting area for saltwater crocodiles has been recognised, with the Parks and Wildlife Commission of the Northern Territory managing the 23-km^2 area as a reserve, specifically for the conservation of *C. porosus* nesting habitat (Anon. 1996).

The area used for nesting is dominated by large discrete beds of *Thoracostachyum sumatranum* (saw grass) under a canopy of *Melaleuca* spp. This vegetation association is the preferred habitat for nesting (Fig. 2*b*). *Melaleuca* trees provide a stable base to support a nest, as well as protection from the elements for the eggs and the female while she guards the nest. Saw grass is used in nest construction. Nests are also common in open beds of *T. sumatranum* sedge.

(*a*)

(*b*)

Fig. 2. Typical nest site of *C. porosus* (*a*) on the Adelaide River and (*b*) at Melacca Swamp.

Moving northwards through the swamp, *Melaleuca* spp. become more scattered, and *Phragmites karka* sedges are intermixed with *T. sumatranum*. These sedges are used for nesting, as is a small patch of *Melaleuca* spp. and monsoon forest species on the western edge of the swamp. A small area dominated by *Melaleuca* spp. with an understorey of *P. karka*, *Typha* sp. and *Flagellaria indica* contains nests every season (B. Ottley, personal communication). An arm of open *Typha* spp. bordering the floodplain is also used for nesting, although not extensively. Isolated stands of sedges and rushes (e.g. *Hymenochaeta grossa*, *Eleocharis* sp. and *Typha* sp.) occur within the swamp but are not used for nesting because they drain in the dry season.

Field reconnaissance

In the 1997–98 nesting season, reconnaissance of Melacca Swamp was undertaken during ranching operations conducted by Wildlife Management International (WMI). The suitability of cover types comprising the swamp as nesting habitat for *C. porosus* was assessed.

Nest sites were accessed with a Jet Ranger helicopter. Teams of three people navigated from drop-off points within the swamp (treeless areas) to nest sites, which were flagged with tape dropped onto the site as it was spotted from the air. Boat oars carried by two people (front and rear) provided protection used in the event of confrontations with aggressive crocodiles. The third (middle) person carried a receptacle for the eggs. The oars were used to 'explore' deeper channels and areas surrounding nests for crocodiles, especially females, which usually remain close to their nests. The oars were also used to beat the vegetation and water along the access path to the nest, providing an incentive for crocodiles to leave the area.

Traversing the heavily vegetated swamp is difficult, with a 50-m walk to a nest site often taking up to 45 min. Once at the nest, various observations were recorded (e.g. temperature in nest mound, number of eggs, vegetation type and materials used in the nest). This information is important for research purposes and also must be recorded and produced to the management authority as a condition of the ranching licence. The eggs were loaded into the receptacle for the trip back to the helicopter. Care was taken to keep the eggs as stable as possible, because too much movement can damage the embryos.

During the reconnaissance, habitats suitable for nesting were identified and annotated on an aerial photo mosaic of the swamp. In addition, historical nesting data were plotted on the aerial photography in order to identify relationships between vegetation associations and nest-site distribution. The knowledge of cover types at Melacca Swamp, acquired during the reconnaissance, was used in subsequent analyses to define the classes derived from computer-aided classification of satellite images and aerial photographs. Class definition was also aided by the extensive expert knowledge available from WMI, who organised all fieldwork and was a partner in the research project.

Reconnaissance of the Adelaide River nesting habitats was completed as part of the 1997 dry-season census of crocodile numbers. Helicopter surveys with WMI personnel provided the opportunity to view riverbank nesting areas and to assess the relationship between landscape features and preferred nesting habitats.

Mapping suitable riverine nesting habitats

Analyses used to delineate potentially suitable riverbank nesting habitats of *C. porosus* are outlined in Fig. 3. Environmental variables known to influence selection of nesting habitat, as found in previous studies, were incorporated into a habitat model. The criteria were:

(1) nesting does not occur in mangrove forest, coastal flats or fringing woodland areas, but is restricted to floodplain habitats adjacent to rivers (Magnusson *et al.* 1978); and
(2) nesting usually occurs within 20 m of, and not more than 100 m from, deep permanent water (Graham 1981; Webb *et al.* 1983).

Remote sensing and GIS methods were investigated to determine whether they could be used to derive a spatial representation of those areas that satisfy both components of the above model.

A Landsat TM satellite image, acquired on 27 October 1999, was used to produce a map of all cover types in the study area. The satellite image was georeferenced to topographic maps at a scale of 1:50 000, and the study area and spectral bands relevant to this study were extracted from the data to reduce storage space and processing time. The classification of cover types adhered to a subset of the scheme used by Magnusson *et al.* (1978) in their study of *C. porosus* nesting habitats on the Liverpool–Tompkinson river system. These cover types were considered by Magnusson *et al.* (1978) as 'specific enough to reflect crocodilian preferences, whilst remaining sufficiently broad to include the diversity of habitats encountered across coastal Northern Territory'. Certain cover types that could not be delineated from the satellite imagery were not included in the classification scheme developed for the current study. The resulting classification scheme consisted of the following six land-cover classes:

(1) open water,
(2) mangrove forest,
(3) open swamp,
(4) swamp with tree canopy,
(5) exposed shore, and
(6) open sedge or grassland.

The satellite image was classified into spectrally similar classes using a computer-aided unsupervised classification technique (ISODATA). Spectral similarity and spatial relationships between the

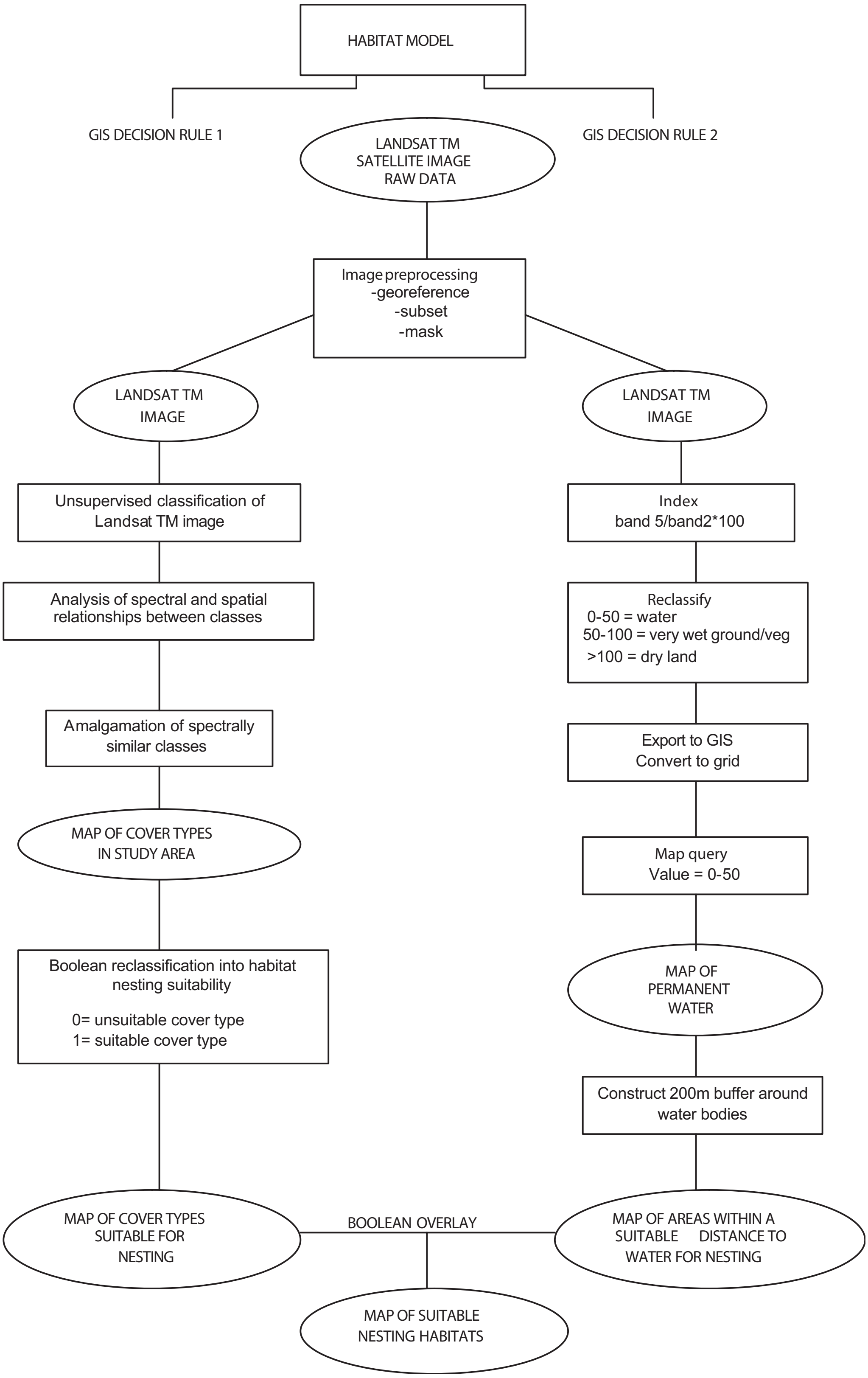

Fig. 3. Integrated remote sensing and GIS method used to map nesting habitats of *C. porosus* on the Adelaide River.

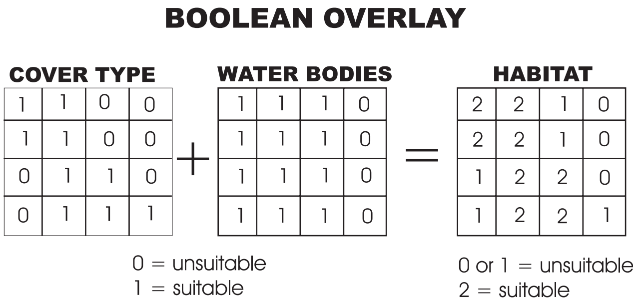

Fig. 4. Illustration of a Boolean overlay operation. Each grid cell is a conceptual representation of a pixel from a satellite image classification.

derived classes were assessed. Each spectral class was assigned to one of the predefined cover types to produce a map of the spatial distribution of these cover types in the study area. The land-cover map was subject to a Boolean reclassification to assign all unsuitable cover types (mangrove, coastal flats and woodland) a value of 0 and all suitable habitats a value of 1 (Fig. 4).

Various times of image acquisition and processing techniques were investigated for the delineation of permanent water bodies. Imagery acquired late in the dry season (27 October 1999) was used to ensure that only permanent water bodies, rather than residual water remaining after the wet season, were mapped. Water could not be easily delineated from non-water areas. To achieve this an index (BAND5/BAND2 × 100) was used to derive a new image that enhanced the differentiation between these cover types.

Ecological studies indicate that nests are rarely found further than 100 m from permanent water. To incoporate this, a 200-m buffer was constructed around all of the delineated water bodies within a GIS. A 200-m buffer was used rather than a 100-m buffer to allow for the inherent inaccuracies in the data available for modelling purposes, and because we wanted to avoid unwarranted exclusion of suitable habitats at the outer edge of the buffer zone. The resulting layer defined all areas within 200 m from water, and potentially suitable for nesting.

Each of the cover-type maps was integrated with the 200-m buffer around waterbodies by a Boolean overlay operation (Fig. 4). The derived habitat maps were then validated with archived nest and field data.

Mapping suitable freshwater swamp habitats

The resolution of data required to map habitats suitable for nesting within a freshwater swamp is unknown. In this study, satellite images (Landsat TM, SPOT XS, SPOT PAN) and true colour aerial photographs (1 : 15 000 scale) were acquired to determine which data provide the best combination of spectral and spatial resolution for this purpose. Preprocessing of the satellite-image data sets followed the same format as outlined in the previous section. Computer-aided classifications of the satellite data were undertaken with the ERDAS Imagine image-processing system. The aim of these classifications was to delineate vegetation types, which could then be reclassified on the basis of suitability as nesting habitat for *C. porosus*.

The aerial photos were scanned, georeferenced and overlaid as a mosaic to form a continuous photo base-map. The base-map was enlarged on screen to a scale of 1 : 5000. Boundaries between cover types were most easily interpreted at this scale than at other scales that were assessed. Cover types interpreted from the aerial photos were manually digitised in ArcView GIS. The resulting map was then reclassified into suitability classes on the basis of the use of each cover type for nesting by *C. porosus*. The land-cover classes interpreted from both the satellite images and aerial photos were labelled with data obtained during field reconnaissance and the expert knowledge of WMI personnel.

A helicopter-sampling technique was used to collect ground-truth data in order to validate the habitat map. A Kawasaki KH4 helicopter was used to collect cover-type information along four east–west transects. Five sample points were defined along each transect at 1-km intervals. At each point, photo records of cover types were collected in the north, south, east and west directions. Written descriptions of cover type were also recorded. The ground-truth data were compared with the classifications produced from satellite images and aerial photographs to calculate the accuracy at which habitats were mapped from each of the data sources.

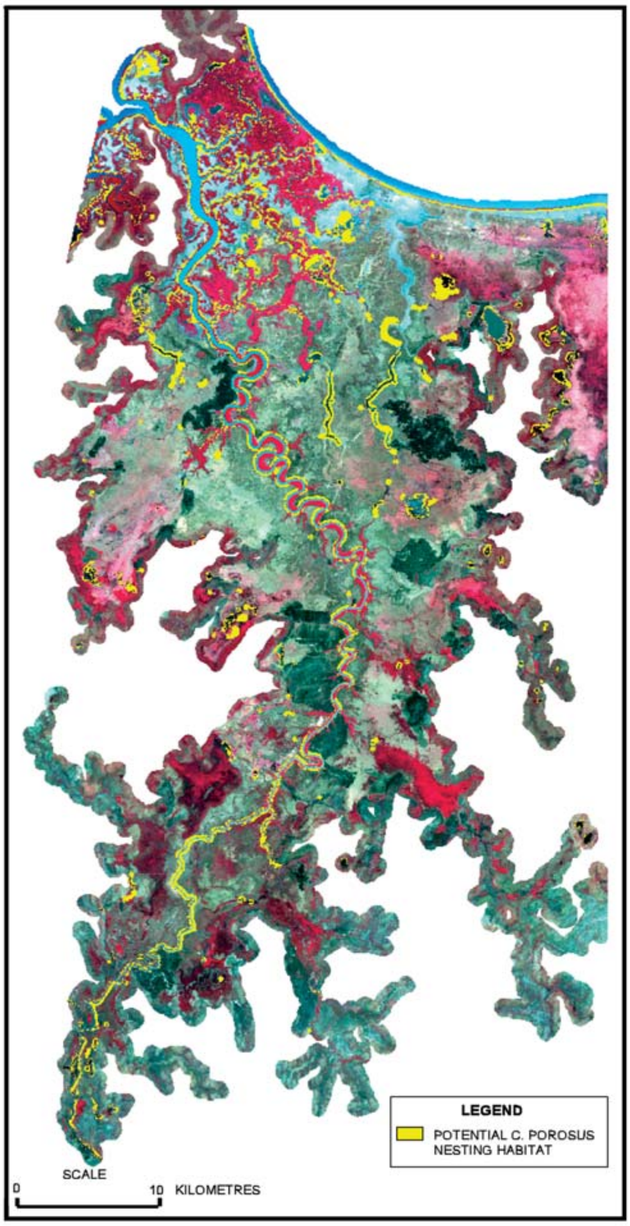

Fig. 5. Potential nesting habitats of *C. porosus* on the Adelaide River derived from the integration of remote sensing and GIS technologies. The background is a Landsat TM false-colour composite of the Adelaide River floodplain.

Results

Riverine nesting habitats – Adelaide River

Areas along the Adelaide River that were identified as suitable nesting habitat are shown in Fig. 5. Visual assessment of the suitable habitats in conjunction with archived nest data and field data indicated that 41% of the archived nesting data fell within areas classified as containing suitable nesting habitat. Owing to the spatial inaccuracies in these data, this gives only an approximate indication of the success of the modelling. Some areas that have contained nests each year were not identified as suitable nesting habitats. This appears to be a function of the insufficient spatial resolution (30 m) of the satellite imagery to detect narrow creek lines that are used by *C. porosus* to access nesting habitats in the outer floodplains. Freshwater swamp areas that fringe the floodplain were identified as suitable nesting habitats by the modelling but are not used for nesting because they do not hold enough water in the dry season to support populations of *C. porosus*. Melacca Swamp is currently the only swamp in the area where *C. porosus* are known to nest.

Some areas identified as suitable habitat have not produced nests, according to the recorded nesting data. These misclassifications may have resulted from spectral confusion between cover types. Alternatively, the absence of recorded nests does not necessarily indicate that the habitat is unsuitable for nesting. Habitats may not have been used for several reasons. For example, the population of *C. porosus* is still expanding, so some habitats are yet to be taken up because there is not yet the demand from the population. Also, as the population has been expanding in the Adelaide River area, there has also been an increase in nesting in Melacca Swamp. This indicates that some breeding females may be moving into Melacca Swamp, which perhaps leaves suitable nesting habitats along the river unused.

Freshwater swamp nesting habitats – Melacca Swamp

Fourteen land-cover classes comprising Melacca Swamp were derived from interpretation of large-scale colour aerial photographs (Fig. 6). Eleven of these classes represent vegetation communities used for nesting by *C. porosus* (Fig. 6). Most nests are found in the open *Melaleuca* forest with an understorey of *T. sumatranum* sedge. All vegetation communities used for nesting were successfully delineated on the aerial photographs with an overall mapping accuracy of 89 ± 5% (mean ± 95% confidence interval). Accuracy attained for classes representing nesting habitats of *C. porosus* ranged between 93% and 100%, while the lowest accuracy of all mapped classes was 81%. Errors of commission and omission were low for all classes, with the exception of open sedge and grassland classes, where there was substantial overlap. Amalgamation of the 14 classes into the three more generalised cover categories identified by satellite imagery produced no significant change in overall mapping accuracy.

Unsupervised classifications of satellite imagery produced final land-cover maps consisting of three classes (Fig. 7). The specific vegetation communities mapped by aerial photography were not duplicated by any of the satellite-imagery classifications; however, open sedge, mixed grass and sedge and forested areas were successfully delineated with a high level of mapping accuracy. Of the satellite-image classifications, Landsat TM imagery produced the most accurate results with associated overall mapping accuracy of 86 ± 5%. Classification of the SPOT XS image produced a map with 82 ± 3% overall mapping accuracy, while analysis of the SPOT PAN image resulted in a mapping accuracy of 71 ± 6%. There were significant differences in mapping accuracy achieved for each imagery type ($P < 0.05$).

Archived nest data show that most of the sedge and forested areas within Melacca Swamp are used for nesting by *C. porosus* (Fig. 7). The exception to this is the *Melaleuca*, *Acacia* and *Eucalyptus* forest that borders the swamp. This vegetation community was classified in the forested class along with communities extensively used for nesting. The inability to distinguish between these cover types may have implications where the aim is to map specific vegetation communities used for nesting; however, satellite imagery is clearly not capable of this. Therefore, the potential use of satellite imagery in this project will be as an initial reconnaissance tool to identify freshwater swamp areas that potentially contain nesting habitats, a purpose for which the inability to distinguish between the mentioned classes will not be an issue. Areas of open grassland that occur in the south-eastern section and on the western edge of the swamp were successfully delineated on the satellite image classifications (Fig. 7).

Discussion

The nesting habitat of *C. porosus* in Melacca Swamp and the Adelaide River wetlands reflects the broader habitat mosaic across the Northern Territory and tropical northern Australia. The results of the current study are therefore of relevance to the mapping and monitoring of *C. porosus* nesting habitats within the broader region.

Mapping the riverine nesting habitats – Adelaide River

The utility of integrating remotely sensed data classifications with ancillary data in a GIS for mapping potentially suitable nesting habitats of *C. porosus* was illustrated in this study. Furthermore, the incorporation of additional environmental parameters known to influence nesting habitat selection into the decision criteria may effectively increase the predictive capabilities of this method. Crerar *et al.* (1998) used elevation as a criterion, which proved useful for distinguishing between those

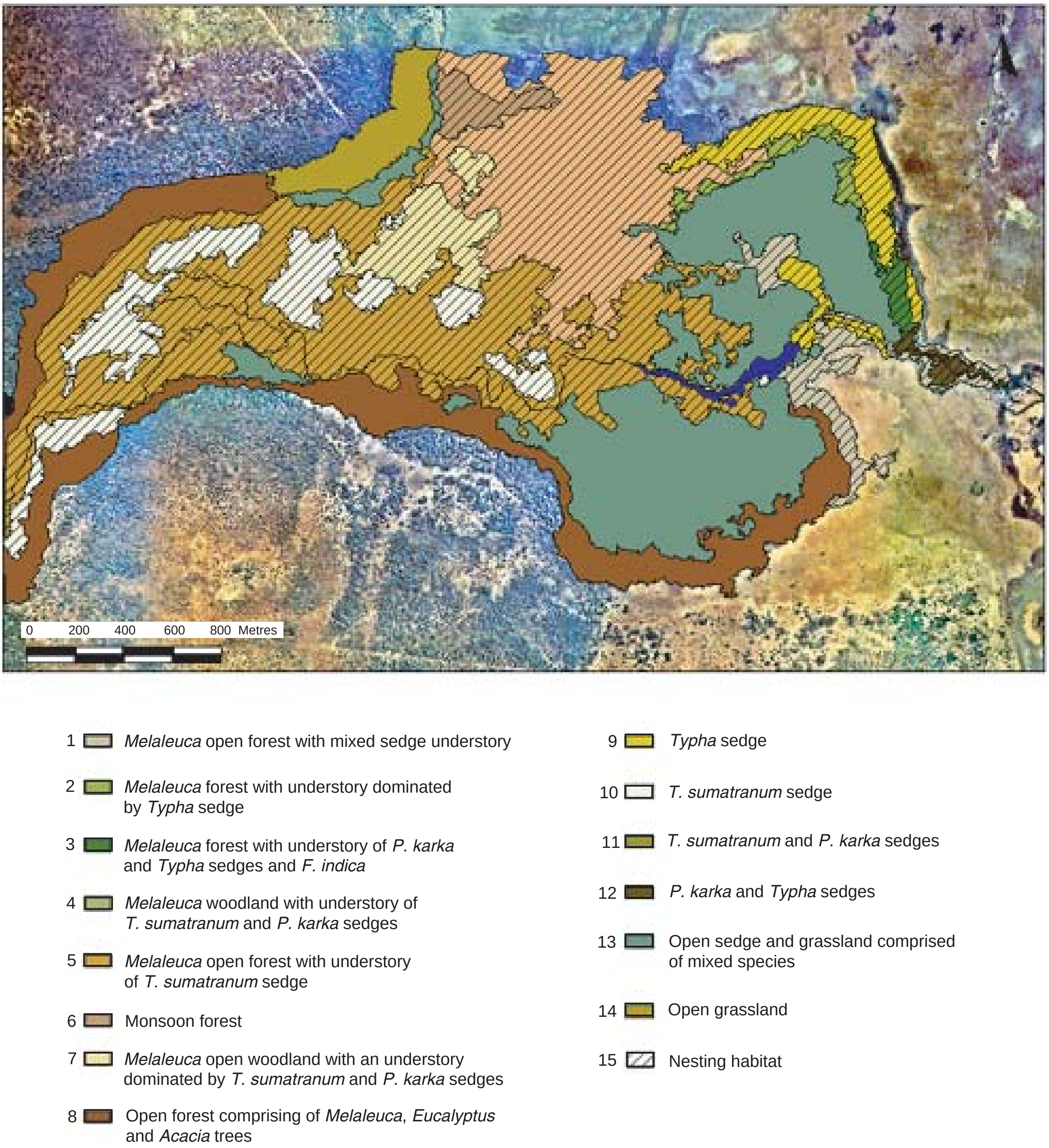

Fig. 6. Cover-type map of Melacca Swamp derived from interpretation of aerial photographs. Habitats used for nesting by *C. porosus* are hatched, as shown in the legend.

habitats used for nesting by *C. porosus* and *C. johnstonii* (the freshwater crocodile) in the Liverpool River area. Other data, such as river salinity, could also be incorporated. The inclusion of additional parameters would most certainly have improved the accuracy of the habitat-suitability maps produced; however, these data are not readily available in a spatial format suitable for use in a GIS. Transformation of available environmental data that may enhance the habitat model is a priority for further research. This research establishes the basis for such further investigations, aimed at

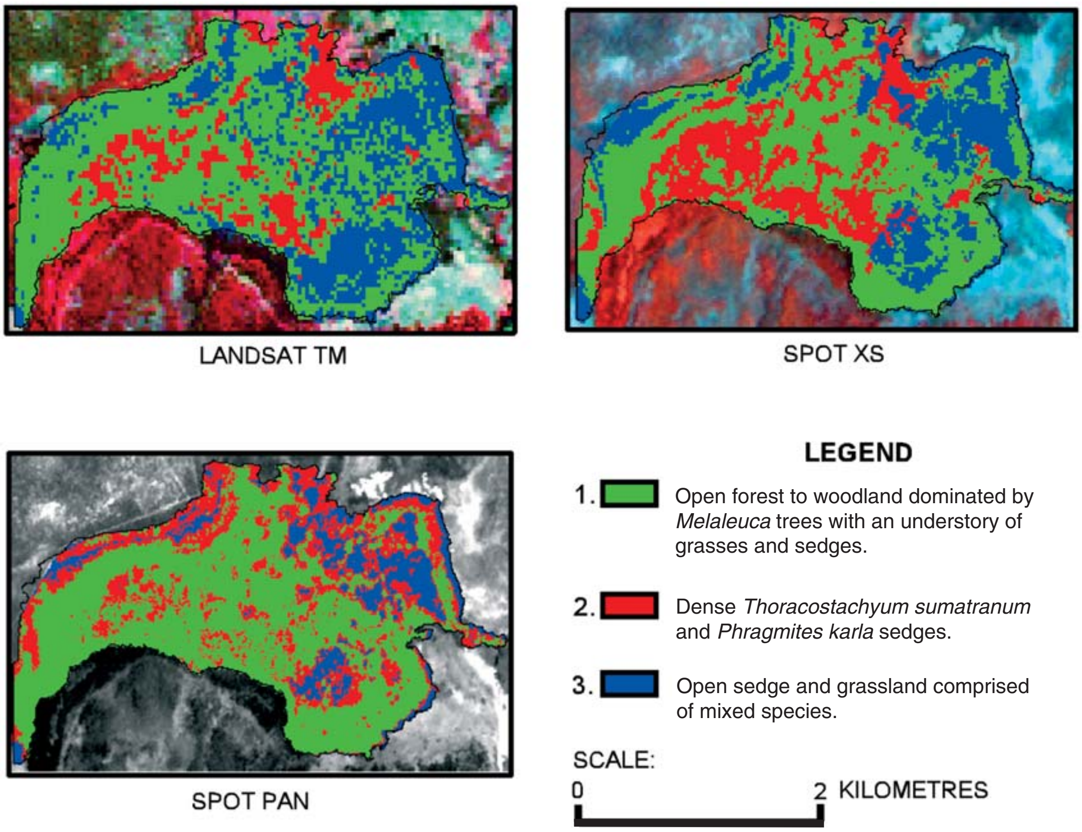

Fig. 7. Cover-type maps of Melacca Swamp derived from Landsat TM and SPOT satellite imagery.

developing a set of criteria that can be used to identify suitable nesting habitats for *C. porosus* across the Northern Territory.

Spectral similarity of the cover types of mangrove forest and woodland (especially *Melaleuca* spp. in a swamp environment) prevented their distinction from each other. Spectral similarity between these cover types was also noted by Crerar (1997) and Capehart *et al.* (1977). A method to successfully delineate these cover types is yet to be established. This is a problem as confusion of these cover types, with contrasting suitability for *C. porosus* nesting, restricts the capabilities of remote sensing to distinguish between suitable and unsuitable nesting habitats in general. Future research will need to investigate methods suitable for this purpose, which will proabably involve the incorporation of environmental parameters such as elevation and salinity. The development of such a method will be useful for all tropical wetland mapping applications.

Mapping freshwater swamp nesting habitats – Melacca Swamp

At Melacca Swamp, which is recognised as a premium nesting area in the Northern Territory (e.g. see Whitehead and Chatto 1995; Anon. 1996; Jaensch 1996), the most highly favoured nest sites are characterised by clumps of *Melaleuca* trees with a sedge (*Thoracostachyum sumatranum*) understorey (Fig. 2*b*). According to standard land-cover definitions (e.g. Specht 1970), these habitats are classified as woodland or open woodland. Nests are found in other swamp habitats featuring dense tree cover (open forest and forest) and completely open areas (sedges), but nest density in these habitats is lower than in the prime habitats described.

The spatial layout of canopy vegetation in Melacca Swamp, where scattered clumps of trees favoured by nesting *C. porosus* may be only 100 m^2 in area, poses a problem when using satellite remote-sensing methods. While such spatial patterning can be resolved from large-scale colour aerial photographs (Fig. 4), it is beyond the capabilities of current Earth-resources satellites (Fig. 5). This study confirms that high-resolution imagery, such as aerial photography, is the only remotely sensed data capable of mapping premium microhabitats within a typical freshwater swamp complex. The map of nesting habitats at Melacca Swamp derived from large-scale aerial photographs in this study appears to be the most accurate and detailed available. The use of this habitat map as a base for recording information at nest sites may help to standardise data collection. It may also provide a basis for comparisons of habitat availability over time.

This study indicates that the spatial resolution of current satellite sensors is sub-optimal for detailed mapping of highly heterogeneous freshwater swamp environments. However, Landsat TM and SPOT XS imagery were found to be quite adequate for mapping general land-cover classes within Melacca Swamp. It should be noted that SPOT PAN imagery, with more advanced spatial resolution (10 m), was not suitable for mapping nesting habitats of *C. porosus*; this was probably a function of the decreased spectral information provided. The prime nesting areas in Melacca Swamp occur within the open forest or woodland cover type classified from the satellite imagery. Other areas used for nesting were classified in the open sedge class. In terms of survey efficiency, and especially where extrapolation to extended regions is concerned, a logical mapping procedure would be to use satellite data as an initial sieve to identify potential nesting sites in freshwater swamps. Such reconnaissance mapping could then be followed by more detailed assessment (using interpretation of aerial photos or helicopter surveys) of key habitat areas.

Nesting habitats in Melacca Swamp are geographically related to a spring-fed creek. This creek could be delineated on aerial photography but was not evident on the satellite imagery, as the dense vegetation associations prevented its detection. In the absence of this contextual information there is a heavier reliance on the cover types exhibiting distinct spectral signatures, a factor likely to lead to misclassifications in wetland environments. Johnston and Barson (1993) suggest that the difficulty distinguishing between vegetation types in wetland environments may be because the spectral response is dominated by the presence or absence of water. Furthermore, Cowardin and Myers (1974) found it difficult to distinguish between cover types in areas that are flooded year-round, and Ringrose *et al.* (1988) and Catt and Thirarongnarong (1992) also encountered problems with class separation of cover types in wetland environments. These findings have obvious implications for the delineation of nesting habitats of *C. porosus* in permanently inundated freshwater swamp environments.

On the basis of the findings of Johnston and Barson (1993), as discussed above, we could suggest that the spectral response of cover types within Melacca Swamp is not a function of the vegetation type present but is determined by hydrological relationships. Melacca Swamp maintains a level of inundation throughout the year; therefore, if water dominates spectral response of cover types used for nesting, all nesting habitats in this area could be expected to exhibit similar spectral responses. In this study, the negative effects of water on class separation were minimised by optimising image acquisition to capture data when water levels were at the lowest for the year. Several authors consider optimisation of image acquisition to be an integral part of using remotely sensed data to investigate wetland environments (e.g. Jensen *et al.* 1984; Catt and Thirarongnarong 1992; Phinn and Stow 1996). Imagery acquired in the dry season (May–October) was considered most suitable for mapping the nesting habitats of *C. porosus* as conditions in the late dry season are thought to have a great influence on where female crocodiles will choose to construct nests during the following wet season (Magnusson *et al.* 1978; Graham 1981). Acquiring imagery at this time of year was therefore a logical way to capture these conditions.

Confusion between grassland and woodland classes within Melacca Swamp and similar cover types in areas surrounding the swamp were also observed in this study. Distinction between *Melaleuca* forest, associated with *C. porosus* nesting, and surrounding woodland areas, was not facilitated by the satellite imagery classifications. Sader *et al.* (1995) suggest that overlap between forested wetland areas and upland areas is due to canopy reflectance dominating spectral response with no indication of the hydrological system below. This would indeed explain the overlap exhibited between the woodland cover types in this study, but its acceptance somewhat contradicts the suggestion that spectral response is dominated by water. The reasons for the spectral patterns observed have not yet been thoroughly investigated. Future research will be directed to answer these questions.

The methods adopted in this study, through identifying areas that might contain nesting habitats of *C. porosus*, may provide for the economic expansion of the ranching industry and facilitate the identification of areas of conservation significance. This research successfully used Landsat TM satellite imagery and additional spatial information to model the distribution of potentially suitable nesting habitats for *C. porosus* in the Adelaide River and Melacca Swamp wetlands. Restrictions on the utility of the model, as it is, were identified and will be the subject of further research. Even with the inclusion of some areas that are not suitable for nesting, the areas to be searched for nests using more labour- and cost-intensive methods are still greatly reduced.

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