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The extent and height of mangroves in Kakadu National Park

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The extent and height of mangroves in Kakadu National Park – an assessment based on orthorectified stereo colour aerial photography and derived digital elevation models

Executive Summary by K Pfitzner

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Executive summary

This report describes the processing of colour aerial photography for mapping mangroves in KNP. The project is a collaborative project between the Univerity of New South Wales (UNSW), University of Wales and the Supervising Scientist Division (SSD).

The project was aimed at obtaining baseline data on the extent and height for the majority of mangroves in KNP. Mangroves on the Wildman, West, South and East Alligator Rivers, as well as Field and Barron Islands were mapped.

eriss funded the creation of orthomosaics and digital elevation models (DEM) from aerial photography captured in 1991. One hundred and thrity-two aerial photographs (66 stereo pairs) were used to create a fine resolution “orthomosaic”. An orthomosaic is a seamless merge of imagery that is corrected to a map projection. This allows points on the imagery to be associated accurately with the ground. Orthomosaic creation is also required for change detection and GIS integration. The orthomosaics were generated at 1 m spatial resolution with an assumed positional accuracy of ± 50 m. The internal accuracy was based on the manual identification of ground control points using digitial map sheets.

From the orthomosaics, digital elevation models (DEM) were generated. A DEM displays the height of tree canopies (or land surface in bare areas). This allows the height of the mangrove canopies to be mapped which aids in magrove species delineation. The DEMs had a height resolution of 0.5 m (± 1 m). DEMs with horizontal and vertical accuracies exceeding 0.37 m and 0.5 m (respectively) were produced where there were closed mangrove canopies or patches of denser trees. In areas where the canopy is more open or bare ground existed, there were inconsistencies in the DEM height estimation.

The attached report details the processing of the aerial photographs. Section 4 of the report decsribes the results. These key findings (by Mitchell et al) are summarised:

West Alligator River

- Extensive mangroves occur on the West Alligator River.
- Communities are zoned parallel to the coastline from the landward to seaward edge.
- Typical zonation from the inland margin to the sea includes: dense *Avicennia marina* (up to 8 m high), *Rhizophera stylosa* (between 16 – 22 m in height), a transitional zone dominated by *R. stylosa*, and a seaward edge of *Sonneratia alba* (up to 16 m high).

South Alligator River

- Mangrove forest does not extend continuously along the banks.
- Tree height and species differ from that of the West Alligator communities.
- Along the tidal creeks *R.stylosa* and scattered *A.marina* are present (with tree heights up to 10 m and 16 m respectively).
- The *Avicennia* edge that has developed along the West Alligator River is either absent or only occurs as a narrow fringe on the South Alligator River.
- Mangroves follow the meanderings of the numerous tidal creeks that dominate the South Alligator coastline (evident on both the west and east banks of the main river channel).
- Along the seaward edge, mixed species are present with tree heights approaching 8 m.

- On the eastern bank of the South Alligator River, away from the mouth, more extensive communities have developed. The zonation is more structured, with a central “ridge” of *R.stylosa* between 10 – 16 m in height, away from which height decreases toward the landward and seaward edge.

- *S.alba* forms the coastal edge community, while *A.marina* occurs as a narrow strip along the inland margin.

Barron Island

- Fringing mangroves up to 10 m in height have developed along the Island’s coastal perimeter, composed largely of *S.alba* and scattered *A.marina*.

- Toward the inland edge, *R.stylosa* forms dense communities (less than 10 m in height) with a few isolated patches of *A.marina*.

- Among the coastal fringing communities there are patches of quite large trees with no younger margin, indicative of a receding coastline, while in other presumably more sheltered areas this fringe is absent.

Wildman River

- A narrow strip of mangroves has established along the coastline, extending at least 13 km from the mouth of the Wildman River to West Alligator head.

- Patches of mangroves ranging 50 – 100 m in width occur almost continuously along this strip.

- Towards the mouth of the Wildman river, communities are zoned parallel to the shoreline. These are dominated by *A.marina* on the landward edge (up to 8 m in height), a central “ridge” of *R.stylosa* (up to 18 m in height) and a mixed zone on the seawarde edge composed of *S.alba* and scattered *A.marina.*

- Further upstream, and following the tidal creek lines, the zonation is not as strict and pockets of *A.marina* are interspersed with *R.stylosa* (between 10 and 16 m in height respectively).

- Towards the river mouth on both banks of the river, there is also evidence of active erosion, where changing patterns of erosion and accretion have scoured away the shoreline mangroves, leaving large gaps in the communities.

Field Island

- A large proportion of mangroves are present.

- These communities are most extensive along the numerous tidal creeks that dissect the island.

- *R.stylosa* (between 8 – 14 m in height) and *A.marina* (up to 10 – 16 m in height) form mixed communities along the creeks.

- Towards their landward edges, dense *Rhizophera* up to 6 m in height has established, with an occasional fringe of *A.marina* up to 4 m in height.

- On the coastal margin, quite extensive stands of *Rhizophera* have developed.

- Landward of this central zone, height generally decreases from around 14 m to 6 m, but is still largely dominated by *R.stylosa.*

- The coastal community contains a transitional zone of mixed species *(R.stylosa, S.alba and A.marina*) around 12 m in height, and a seaward edge of mainly *S.alba* and scattered *A.marina*.

- As with the South Alligator River communities, there are patches of isolated mangroves on the seaward fringes indicative of changing patterns of aggradation and recession of the shoreline zone.

East Alligator River

- Mangroves occur almost continuously along the East Alligator River.
- The most extensive communities are observed at Point Farewell (northern tip of west bank) and along tidal creek meanders.
- Tidal creek communities consist mainly of *A.marina* and *R.stylosa* around 8 – 16 m in height.
- The sheltered conditions produced by the numerous creek bends has favoured the establishment of mangroves in some areas.
- Channel cutting is evident in the upstream reaches of the main channel, with pockets of ribbon-like mangroves inhabiting the scoured channels.

The results showed that the extent, height and species zonation differs in the River systems. The mosaic represents a key historical baseline dataset of the extent and height of mangroves within KNP. With photography of a similar scale at a different date, it would be possible to repeat the above process in order to observe and quantify changes of the mangrove forests in Kakadu.

The extent and height of mangroves in Kakadu National Park – an assessment based on orthorectified stereo colour aerial photography and derived digital elevation models

Report to the Environmental Research Institute of the Supervising Scientist

Anthea Mitchell[1], Brian Donnelly[1] & Richard Lucas[2]

Abstract

Focusing on mangroves of the West Alligator River (Kakadu National Park) in northern Australia, Lucas et al. (2002) outlined an approach for generating baseline datasets of the extent and height of mangroves using stereo colour aerial photography. Using this same approach, a fine (1 m) spatial resolution orthomosaic and accompanying digital elevation model (DEM) for the majority of mangroves in Kakadu National Park has been generated. The orthomosaic, which is based on 66 stereo pairs of colour photographs acquired in 1991, covers an area of approximately 742 km² and a coastal distance of 86 km. The DEM has a height resolution of 0.5 m (± 1 m). The mosaic represents a key historical baseline dataset of the extent and height of mangroves within Kakadu National Park against which to observe and quantify changes in response to, for example, sea level rise. The data sets will be available to assist management of the coastal environment, and also provide a unique insight into the distribution, dynamics and condition of mangroves within the Park.

1 Introduction

Within Kakadu National Park (NP) in Australia's Northern Territory, the mangrove communities have been largely immune to human disturbance. However, in recent years, changes in their extent have become particularly noticeable and are believed to result from a changing coastal environment. In particular, many are colonizing the tidal creeks that are gradually extending inland whilst expansion and retraction of mangroves is occurring along the coastal margin. The inland extension of creeks is of particular concern as the associated intrusion of saltwater is leading to deterioration of the proximal freshwater environments. Although the movement of the mangroves themselves is not the cause of this deterioration, this sensitive ecosystem is an indicator of a more general problem of adverse coastal environmental change.

To establish rates of change and where change has occurred, baseline datasets providing spatial information on the distribution (extent) of mangroves in a reference year are required. However, the extent of mangroves in some areas may not alter significantly but instead, their response to coastal environmental change (e.g., tidal inundation, salinity) may be manifested in a change in their structure, productivity or zonation. For these reasons, baseline datasets relating to the height, density, biomass and species/community composition are also required.

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For mapping the extent of mangroves, Lucas et al. (2002) demonstrated the use of stereo aerial photographs. Based on maps derived for the West Alligator River in Kakadu NP, changes in the extent of mangroves between 1950 and 1991 were also able to be generated. This study confirmed that mangroves were extending inland along the creeks and also revealed expansion and erosion of mangroves on the west and east banks of the river respectively. The study also demonstrated the use of these photographs for deriving digital elevation models (DEMs) of mangrove canopy height with vertical and horizontal resolutions exceeding 0.5 and 0.8 m respectively. In subsequent research (Mitchell et al., 2003; Lucas et al., 2003; Proisy et al., 2003), the use of these photographs and also fine (< 1 m) spatial resolution hyperspectral Compact Airborne Spectrographic Imager (CASI) and polarimetric airborne Synthetic Aperture Radar (AIRSAR) data for estimating tree density, discriminating species and communities and quantifying biomass and structure has been indicated.

Based on the research undertaken by Lucas et al. (2002) for the West Alligator River, and using the same techniques, this project (funded by the Environmental Research Institute of the Supervising Scientist; ERISS) has generated baseline datasets of the extent and canopy top height of most mangrove communities within Kakadu NP using available stereo colour aerial photography acquired in 1991. In undertaking this task, a unique resource for managing, monitoring and protecting the fragile ecosystems of Kakadu NP has been provided.

2 Study Area

The project focused on the mangroves of the Alligator Rivers Region (ARR) of Australia’s Northern Territory (Figure 1). The eastern and southern sections of the ARR comprise the Arnhem Plateau, which is highly dissected in nature and provides the source for these river systems. The western section of the ARR occupies the lowland region where coastal and estuarine environments exist (Brennan, 1996). Within this latter region, mangroves are extensive along the banks of the Wildman, West, South and East Alligator Rivers as well as on Field and Barron Islands (Figure 2).

The ARR has a monsoonal tropical climate, with an average annual precipitation (at Jabiru) of 1483 mm (Bureau of Meteorology 1999), mostly falling in the wet season between November and March. All of these rivers are subject to annual flooding during the wet season and, for this reason, both freshwater and estuarine sediments have accumulated to form extensive floodplains in the lower reaches. At the terminal parts of these systems, tidal inundation has occurred which has favoured the establishment of mangroves.

The mangroves of the West Alligator River, as with many in northern Australia (Woodroffe et al., 1985; Davie, 1985), occur as narrow fringes that are generally confined to the channel banks and edges of tidal creeks. Species diversity is relatively low, compared to mangroves occupying similar latitudes (e.g., in Queensland), which is attributable partly to the extremes of the wet and dry season and the associated variability in rainfall and evapotranspiration (Woodroffe, 1995). Distinct zonation patterns are typical, due largely to the differential ecological performance of species across environmental gradients (Saintilan, 1998), and differential response of species to tidal inundation (frequency and quantity), freshwater flow, soil type, salinity, and wave action (Semeniuk, 1985; Blasco et al., 1996; Storrs and Finlayson, 1997). A typical zonation of coastal fringing mangroves in the region would be *Sonneratia alba* and *Camptostemon schultzii* on the seaward margin, *Rhizophora stylosa* further inland, and *Avicennia marina* on the landward margins. In the intermediate zones of mangroves facing estuarine shores, *Bruguiera* species are frequently found, whilst *Ceriops tagal* and *Lumnitzera racemosa* favour areas further inland (Lear and Turner, 1994).

Figure 1. The location of the Alligator Rivers Region (ARR)
in Kakadu NP, Australia's Northern Territory.

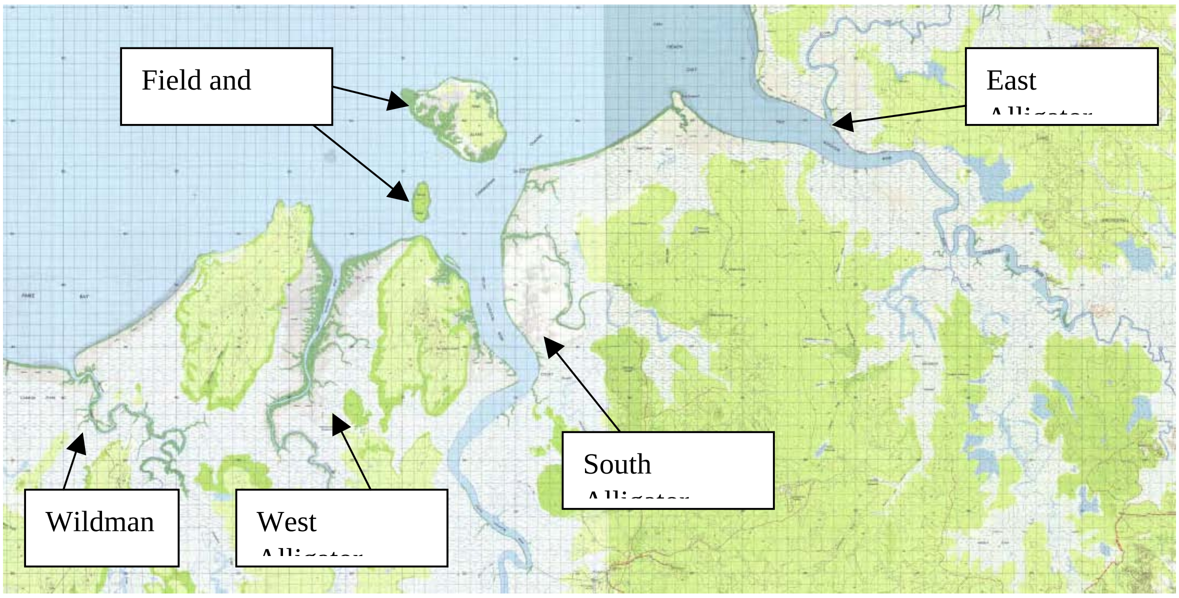

Figure 2. Main areas of mangroves within Kakadu National Park

The mangrove communities within the ARR have remained relatively undisturbed and any changes in their extent and height can be attributed largely to changes in the coastal environment and hydrological regimes. The reasons for the observed inland intrusion of creeks has not been agreed on, although it is acknowledged that headward movement of tidal creeks has allowed salt water to enter areas that were previously associated with fresh water. Mangrove extension has occurred along these creeks and it is anticipated that future global climate change and sea level rise could exacerbate this situation and result in even further extension of mangroves and other saline wetland communities (Baylis et al., 1997; Eliot et al., 1999).

3 Methods

The following sections provide an overview of the available aerial photographs and the methods used to generate the orthomosaics and associated DEMS.

3.1 Acquisition and pre-processing of aerial photographs

Aerial photographs from 1991 were available for all mangroves in the ARR (Table 1). In total, 132 photographs (66 stereo pairs) provided near complete coverage for the West, South and East Alligator Rivers as well as the Wildman River and both Field and Barron Islands. Photographs were also available for selected parts of the coastline. The photographs were taken at a flying height of 13,000 ft (3960 m) and with a camera with a focal length of 152 mm.

Table 1. Stereo colour aerial photography available for the Kakadu region.

Photo date	Film Number	Region	No. of photographs
May, 1991	KNP800	Wildman River	16
		West Alligator R.	20
		South Alligator R.	29
		East Alligator R.	50
		Field Island	13
		Barron Island	4

All photographs were obtained and scanned by Airesearch (Darwin) such that digital images with a pixel resolution of between 12-15 µm were generated. At this resolution, the uncompressed image files are of the order of 800 Mb in size. Images were provided in jpeg compressed tiff format on cd-rom to the University of New South Wales (UNSW). The compression factor was of the order of 4 so that little or no detail was lost in the decompression of the image. The unnatural colour of some images was attributed to the lack of (or inadequate) colour balancing applied to the raw scanned images. Corrections have been applied although further adjustment may be needed.

Following scanning, the images were imported into a digital photogrammetric workstation (DPW) running the LH Systems Socet software. Each image was imported into Vitec format (default format for Socet) and an image pyramid was generated commencing with the smallest scale (1:1024 minification; a term used to describe the generation of image pyramids) and finishing with the largest scale (1:1 minification). The approximate position of the camera during acquisition was scaled from the topographic maps and defined in the import properties dialog, as this was a requirement for the successful computation of the bundle adjustment (described below).

3.2 Aerial Triangulation

Aerial photography for mapping purposes is acquired in strips with 60 % overlap between successive photographs in the strip and 20 % overlap between adjoining strips. The term “exterior orientation of a camera” is used to describe the position (in three dimensions) and the direction of pointing when a photograph is exposed. The term “interior orientation of a camera” refers to the internal optical parameters of a camera. As aerial survey cameras are calibrated at regular intervals, parameters such as focal length and lens distortion are available for determination of exterior and interior orientation. Furthermore, calibrated marks (i.e., fiducial marks) on each photograph are available for measurement thereby allowing the calibration parameters of the camera for each photograph to be extracted.

Following determination of the interior and exterior orientation of the overlapping photographs, stereo images can be viewed in a stereo plotter such that three-dimensional measurement of objects in the stereo overlap area can be undertaken. Within a DPW, the measurement process automatically generates digital elevation models (DEM) of the ground surface in the overlap area.

To determine the exterior orientation of a strip or block of aerial photographs, a small number of ground control points (GCPs) were used in a process known as aerial triangulation. This process consisted of two phases. In the point measurement phase, the image coordinates of common points in the overlap area and GCPs were measured. Using the DPW, this was accomplished semi-automatically using image-matching techniques. The ground coordinates of the GCPs together with their accuracy (in metres) were also recorded. Once the measurement phase was complete, all exterior orientation parameters were computed simultaneously in a least squares solution using a rigorous mathematical model, referred to as a bundle adjustment. The term bundle refers to each photograph being modelled as a bundle of rays joining the object points, the perspective centre of the camera and the corresponding image points.

To assist in this process, the study area was broken down into more manageable blocks, with each block containing a set of photographs for a particular river system (Figure 3). This was undertaken to first minimise the disc space requirements for each job (as each image and corresponding image minifications required approximately 1.2 Gb of disc space, and second, as difficulties arose when joining all the blocks together in a single block due to insufficient overlapping photographs.

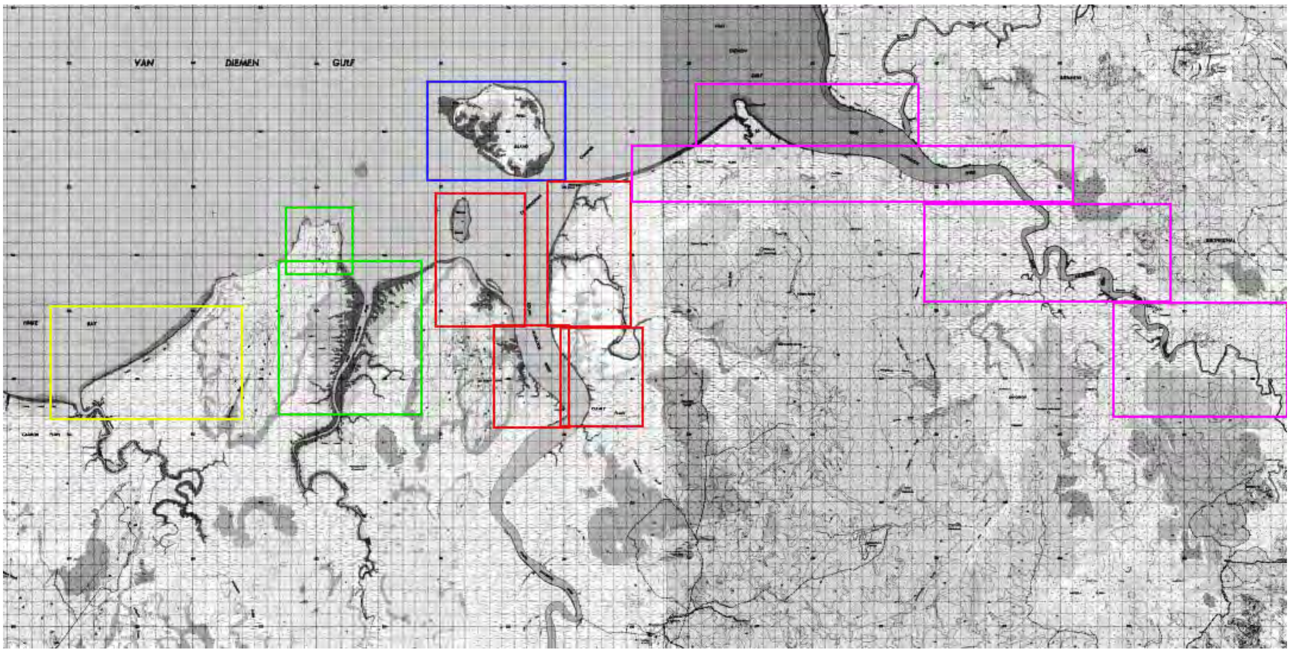

Figure 3. Topographic mosaic with individual blocks highlighted

For the exterior orientation, GCPs were digitised from two 1:100 000 topographic maps of the area produced in 1971. Scanned images of the maps were supplied by ERISS for this purpose. In conventional mapping projects, GCPs are measured to an accuracy of better than the resolution of the photography which would imply accuracy in this study of the order of 0.3 m. Also, the GCPs should be identifiable on the photographs to this accuracy. Neither of these criteria were achievable in this study due to the coarseness of the basemap. GCP digitised from a 1:100 000 scale map implies an accuracy of 0.5 mm on the map and 50 m on the ground. The resolution of detail on the maps was far lower than that of the photographs so that it was difficult to identify common points.

GCPs were distributed broadly across the images, and assigned a horizontal accuracy of 50 m and a vertical accuracy of 2 m. Positional accuracy was also determined through identification of height points, which were accurate to within 1-2 m on the topographic map and could subsequently be used as control on the images. Numerous tie points were located in the overlapping areas of images to help stabilise adjoining images. The vertical datum of the coordinate system was established by identifying areas along the coastline, and assigning an arbitrary height value of 1 m above mean sea level. The accuracy of this measurement was set as 2 m so as to establish a base level datum. Spot heights within tidal flat and upland forest areas were also retrieved from the topographic maps and assigned an accuracy of 1 m.

GCPs were then edited, where necessary, to reduce the root mean square (r.m.s.) errors to less than one pixel. Horizontal accuracies of less than 50 m were considered acceptable. Following the successful triangulation of a block of photographs, adjoining strips were added using the same GCP file. GCPs that occurred in the overlapping region between strips were assigned the coordinates from the triangulated images, so as to maintain the stability between strips.

Output from the bundle adjustment gives residuals to all measurements for each point in image coordinates. These residuals were checked and if necessary points re-observed until the residuals were less than 1 pixel, thus ensuring that the relative positioning within the block is of the order of 1 pixel or 0.37 m on the ground. The residuals on the GCPs were checked to ensure that they were within the predicted horizontal accuracy, ie. 50 m standard deviation and vertical accuracy of 2 m standard deviation.

Due to the low horizontal accuracy of the GCPs, the absolute accuracy of the position of any object point on the orthophoto-image is of the order of 50 m. The accuracy of the scale of the orthophoto-image is higher as it depends on how far apart the GCPs are; the further apart, the more accurate the scale. Hence, relative measurements between points on the orthophoto-image are more accurate than the absolute accuracy of their positions.

3.3 Image resampling

Following triangulation, stereo model images were generated through the pairwise rectification process (Figure 4). Stereo pairs were rotated such that the epipolar direction was horizontal, and resampled to the same ground sample distance (0.37 m). The basic outcome of the process is that it enables stereo visualisation of image pairs, and automatic extraction of surface heights, thus generating digital elevation models (DEMs) of greater accuracy.

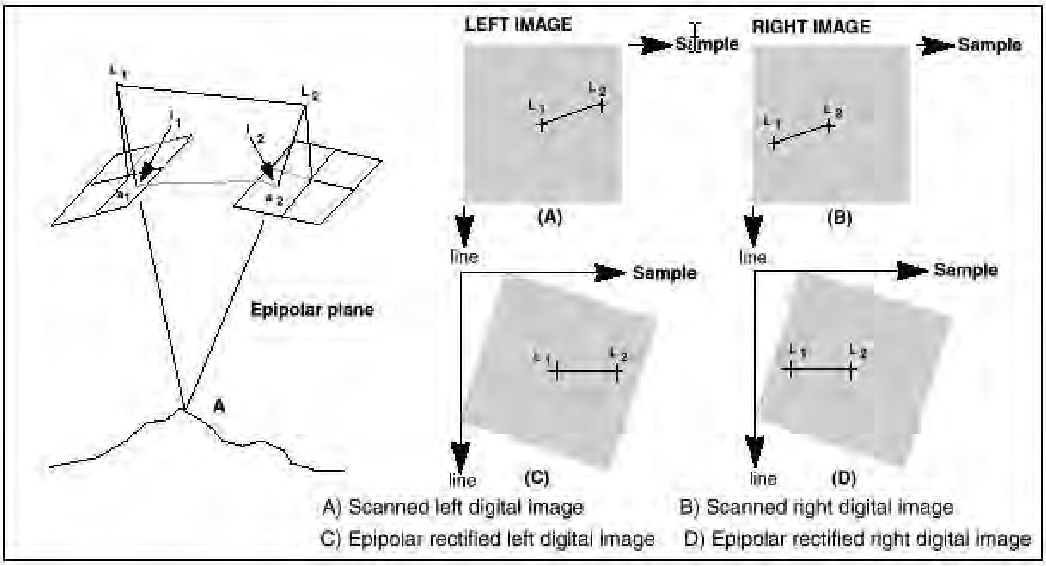

Figure 4. The image rectification process involving rotation along the epipolar plane and resampling of stereo pairs.

3.4 Generation of DEMs

DEMs were generated using the Automatic Terrain Extraction (ATE) module available within the SOCET software. The Socet ATE module provides an automated routine (Figure 5) that identifies conjugate points in the stereo pairs using image-matching techniques. Similarly textured features are located in sequential images, and then the height of each feature is derived from the image orientation data. Elevation is determined by measuring shifts in the x-direction (x parallax) of the rectified images. An iterative algorithm is used which begins with the smallest scale minification image and a sparse post spacing, and then increases the post density for each minification level until the 1:1 level is reached. This process conserves the amount of storage space required, while maintaining a high level of post coverage for the determination of feature heights.

From the orientated colour images, DEMs were derived using Socet software. For each resampled pair, regular grid DEMs were generated initially using the entire image space (at a spatial resolution of 20 m) for use in orthophoto production. The post spacing was selected due to the relatively even terrain across the entire image, with elevations not exceeding 3-4 m above height datum (AHD). A coarser post spacing would have created an enormous file of largely redundant data. Water bodies were extracted, as no elevation data could be retrieved over these areas, and assigned a constant value of 0 m. All of the 20 m DEMs for a particular block were then merged to create one DEM file.

The process was then repeated for only those areas supporting mangroves and at 5 m spatial resolution. In this case, our aim was to preserve the information relevant to the vegetation so that mangrove canopy height could be determined. The post spacing was selected as a trade-off between DEM quality and file size. Extraction of a height point every 5 m across the mangrove zone was considered sufficient, as fairly even aged stands of trees (with homogenous canopies) were commonplace. Areas of low texture, including mudflats and water were extracted from the DEM file and assigned a constant value of 0 m and 1 m respectively. All of the 5 m DEMs were then also merged to create one DEM file.

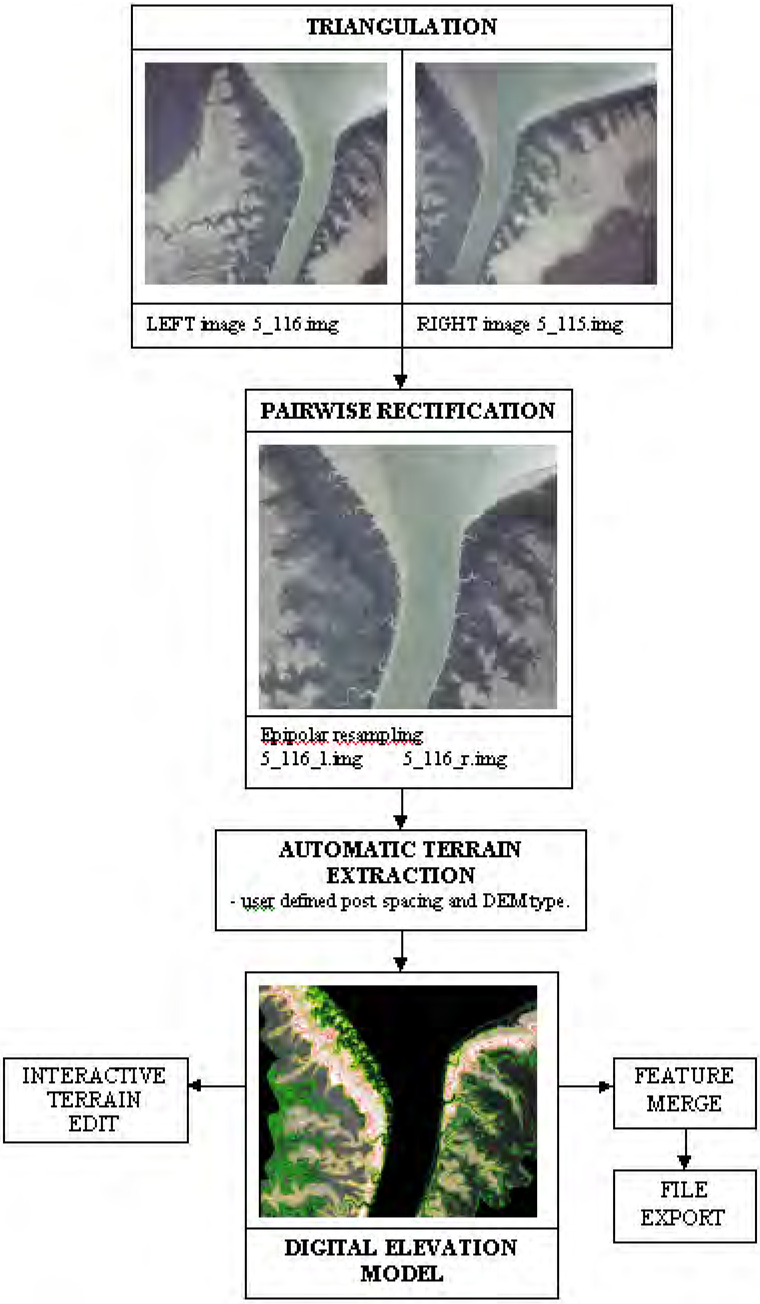

Figure 5. Flow chart outlining the DEM generation process whereby ATE is performed in the area of overlap of a stereo pair. User-defined options include the density of elevation points to be collected and the format of the data (grid, TIN triangles). The resulting DEM can be overlain on the stereo pair as continuous contours for editing as required.

Following merging, an interpolation program was applied to the 5 m DEMs to generate elevation data at 1 m spacing. The final products contained those points at a spatial resolution of 1 m. Interpolation of the points from 5 m to 1 m resolution was considered optimal as processing constraints limited the initial generation of a 1 m DEM. In particular, the generation of a 1 m DEM in Socet results in the storage of millions of posts and the creation of an excessively large file that cannot be readily displayed. No appreciable loss in the quality of elevation data was evident as a result of the interpolation.

3.5 Generation of orthomosaics

Orthomosaics were generated using all of the available photographs for 1991. This process is illustrated in Figure 6. Essentially, each mosaic is an orthogonally corrected image produced from a set of input images, and represents what would be seen if observing straight down at the ground from an infinite distance above. An orthographic projection (parallel to the z or 'depth' axis) was used to project the object space (ground space) to the output mosaic space.

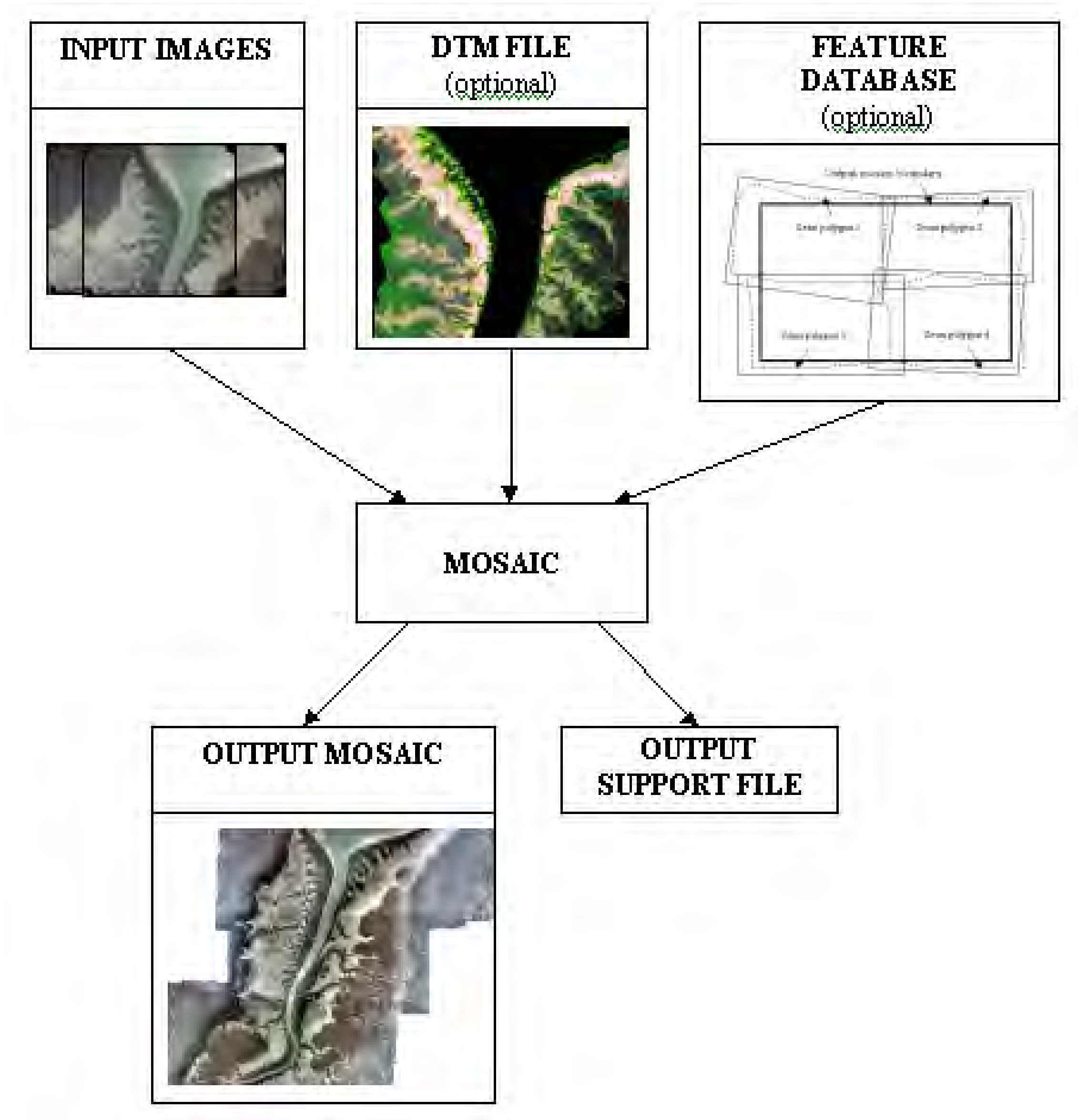

Figure 6. Flow chart outlining the generation of an orthomosaic. Typical inputs include one or more triangulated images, a DEM, a feature database of seam polygons (that define each image space), and an output boundary.

Each mosaic consisted of the orientated photographs for a particular river system or coastal section, the extent of which was defined by the boundary of the 20 m DEM generated over the area. All mosaics were resampled with a ground sample distance (GSD) of 1 m. Default image balancing was applied to reduce the appearance of seam lines for adjoining photographs.

The images were mosaicked using the most nadir method, which minimises the errors due to topographic features as the most orthogonal regions of each input image are used. Nearest neighbour resampling was used to create the output mosaic space. This algorithm uses the nearest pixel without any interpolation to create the output image.

There was insufficient photographic coverage to generate an entire mosaic for the ARR mangroves, hence the need to generate independent mosaics for each river system or coastal section. A mosaic was generated for each orientated block of photographs and then mosaicked in ENVI. Block shifts were applied to maintain the geographic integrity of the images. In the case of the South Alligator River, separate mosaics were necessarily produced for both the east and west banks. It was not possible to generate one entire mosaic as several photographs contained only water bodies and could not be included in the block adjustment.

4. Results

The following sections present the mosaics and associated DEMs and provide a brief summary and interpretation of each. Please refer to the attached file (knp_results.doc) for all illustrations.

4.1 Wildman River

Figures 7a and b illustrate the orthomosaic and DEM generated for the Wildman River. A narrow strip of mangroves has established along the coastline, extending at least 13 km from the mouth of the Wildman River to West Alligator head. Patches of mangroves ranging 50 – 100 m in width occur almost continuously along this strip. Towards the mouth of the Wildman River, communities are zoned parallel to the shoreline, and dominated by *A.marina* on the landward edge (up to 8 m in height), a central “ridge” of R.stylosa (up to 18 m in height) and a mixed zone on the seaward edge composed of *S.alba* and scattered *A.marina.* Further upstream, and following the tidal creek lines, the zonation is not as strict and pockets of A.marina are interspersed with R.stylosa (between 10 and 16 m in height respectively). Towards the river mouth on both banks of the river, there is also evidence of active erosion, where changing patterns of erosion and accretion have scoured away the shoreline mangroves, leaving large gaps in the communities.

4.2 West Alligator River

Figures 8a and b illustrate the orthomosaic and DEM for the West Alligator River. Extensive mangrove forest has developed along the West Alligator River, with dense communities at and away from the river mouth as well as further upstream. From the landward to seaward edge, communities are zoned parallel to the shoreline and adjacent tidal creeks. A typical species distribution includes dense *Avicennia marina* on the inland margin (up to 8 m in height), an intermediate belt of *Rhizophera stylosa* (between 16 - 22 m in height, a transitional zone of mixed species dominated by R.stylosa, and a seaward edge of *Sonneratia alba* (up to 16 m in height). *R.stylosa* and scattered *A.marina* are also observed extending along the tidal creeks, with largely *A.marina* at their furthest reaches.

4.3 South Alligator River

Figures 9a and b illustrate the orthomosaics and DEMs for the South Alligator River, and also include Barron Island to the north. Mangrove forest does not extend continuously along both banks as evident in the communities of the West Alligator River. Tree height and species distributions are markedly different as well. Along the tidal creeks *R.stylosa* and scattered *A.marina* are present (with tree heights up to 10 m and 16 m respectively), however the *Avicennia* edge that has developed for these same communities along the West Alligator River is either absent or only occurs as a narrow fringe. Mangroves have developed in a finger-like distribution that closely follows the meanderings of the numerous tidal creeks that dominate the South Alligator coastline. This pattern is evident on both the west and east banks of the main river channel. Along the seaward edge, mixed species are present with tree heights approaching 8 m.

On the eastern bank of the South Alligator River, away from the mouth, more extensive communities have developed. The zonation is more structured, with a central “ridge” of *R.stylosa* between 10 – 16 m in height, away from which height decreases toward the landward and seaward edge. *S.alba* forms the coastal edge community, while *A.marina* occurs as a narrow strip along the inland margin.

Barron Island is situated directly north of the headland that separates the West and South Alligator Rivers. Fringing mangroves up to 10 m in height have developed along the Island’s coastal perimeter, composed largely of *S.alba* and scattered *A.marina*. Toward the inland edge, *R.stylosa* forms dense communities (less than 10 m in height) with a few isolated patches of *A.marina*. The extent of mangroves around the island is a direct response to the changing accretion and erosion patterns as a result of tidal variations within Van Dieman Gulf. Among the coastal fringing communities there are patches of quite large trees with no younger margin, indicative of a receding coastline, while in other presumably more sheltered areas this fringe is absent.

4.4 Field Island

Figures 10a and b illustrate the orthomosaic and DEM generated for Field Island. Field Island, situated to the north of the South Alligator River, contains a large proportion of mangroves relative to its size. These communities are most extensive along the numerous tidal creeks that dissect the island. *R.stylosa* (between 8 – 14 m in height) and *A.marina* (up to 10 – 16 m in height) form mixed communities along the creeks. Towards their landward edges, dense *Rhizophera* up to 6 m in height has established, with an occasional fringe of *A.marina* up to 4 m in height. On the coastal margin, quite extensive stands of *Rhizophera* have developed. Landward of this central zone, height generally decreases from around 14 m to 6 m, but is still largely dominated by *R.stylosa.* The coastal community contains a transitional zone of mixed species *(R.stylosa, S.alba and A.marina*) around 12 m in height, and a seaward edge of mainly *S.alba* and scattered *A.marina*. As with the South Alligator River communities, there are patches of isolated mangroves on the seaward fringes indicative of changing patterns of aggradation and recession of the shoreline zone.

4.5 East Alligator

Figures 11a and b illustrate the orthomosaic and DEM generated for the East Alligator River. Mangroves occur almost continuously along the banks of the East Alligator River, and are most prolific at Point Farewell (northern tip of west bank) and selected areas upstream. Numerous tidal creeks extend inland from the main river channel and are aligned with abundant mangroves. The most common species inhabiting the tidal creeks include *Aivcennia* and *Rhizophera*, up to 16 m in height. The mangroves have taken advantage of the sheltered conditions afforded by the numerous meanderings of the main channel. Despite the steep rise of the East Alligator banks on both sides of the channel, scattered mangroves can be found inhabiting the mudbanks adjacent to these areas. There is much evidence for channel cutting along the course of the East Alligator, with scoured channel mouths and pockets of ribbon-like mangroves even in the upstream reaches.

5. Technical assessment

5.1 Height extraction for vegetated and non-vegetated areas

From the DEMs, height profiles were extracted to evaluate the integrity of the data. In all cases, these were relatively smooth, indicating the successful retrieval of canopy height data with minimal noise using the technique (Figure 12). The variation in tree height across the zones was evident in the observed undulations within the profile. The only limitations of the DEM were that the height of the understorey canopy could not be accounted for, and no information on the underlying terrain could be retrieved. However, this is perhaps a unique feature of the DEMs for mangrove forest, as the dense canopies are perhaps an optimal medium from which to extract height.

Manual editing of the DEMs was necessary to alleviate the potential generation of erroneous elevation data or noise in areas of low texture, including bare or sparsely vegetated ground and mudflats. These areas were delineated with polygons in the Socet Interactive Terrain Editor (ITE module) and assigned a constant elevation, which resulted in relatively smooth DEM profiles. The difficulty in retrieving height estimates for these areas is related directly to the difficulty of feature-based matching in isolated areas with flat or smooth surrounding texture.

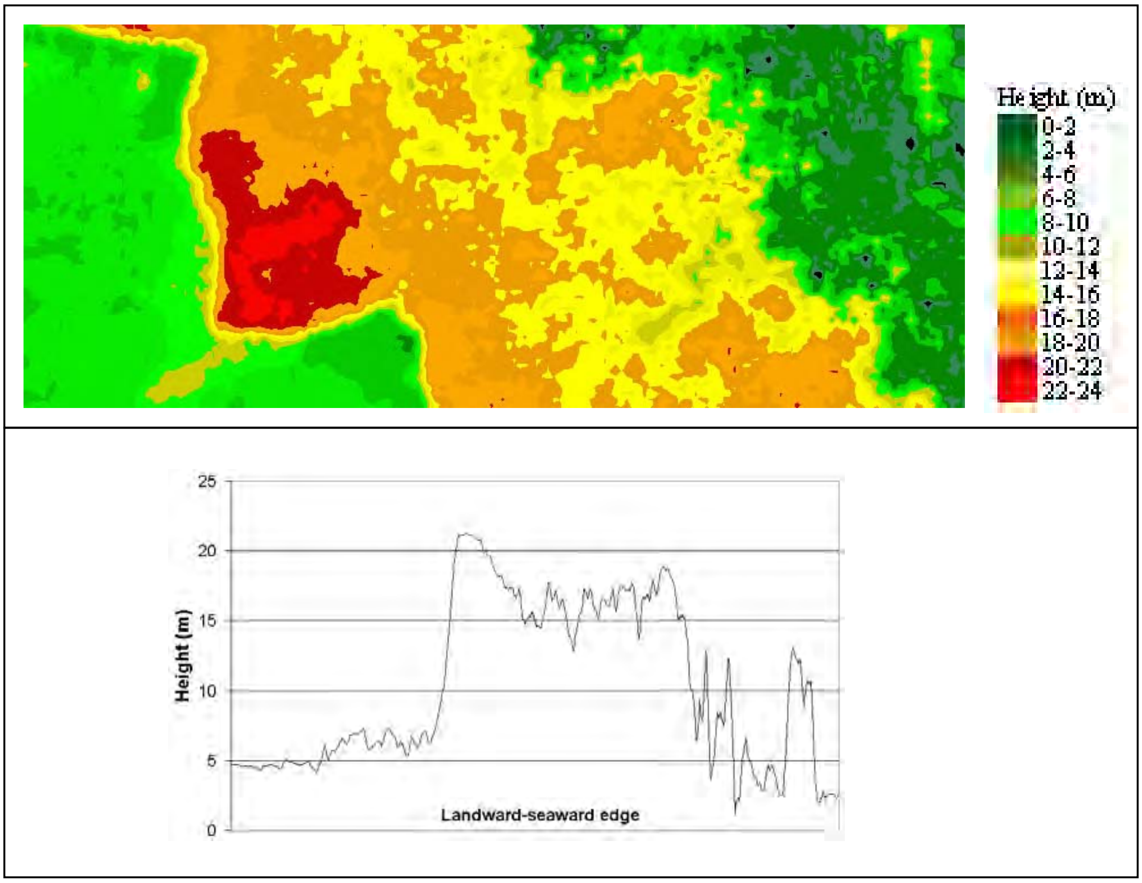

Figure12a) DEM generated over an area of mangrove forest; and b) Height profile extracted from the landward to seaward edge.

In vegetated areas, the lack of noise in the DEM was attributed to the closed mangrove canopy, which obscured the underlying ground surface from the view of the camera. As a result, ATE was performed over the canopy itself, and the height of trees was determined from the base level established during triangulation. In areas where the canopy is more open however, there were inconsistencies in height estimation. Along the coast, the mangrove zone was composed of large trees (typically *Sonneratia alba)* with sparser canopies than those found inland, and patches of bare ground were common. The DEM generation process generally failed to consistently determine heights in these low textured areas, as illustrated in figure 13. Abrupt changes in height were observed within the zone, where an attempt to measure the height of the terrain was made. Where there are patches of denser trees, the height estimates generated from the photography reflected the actual tree height.

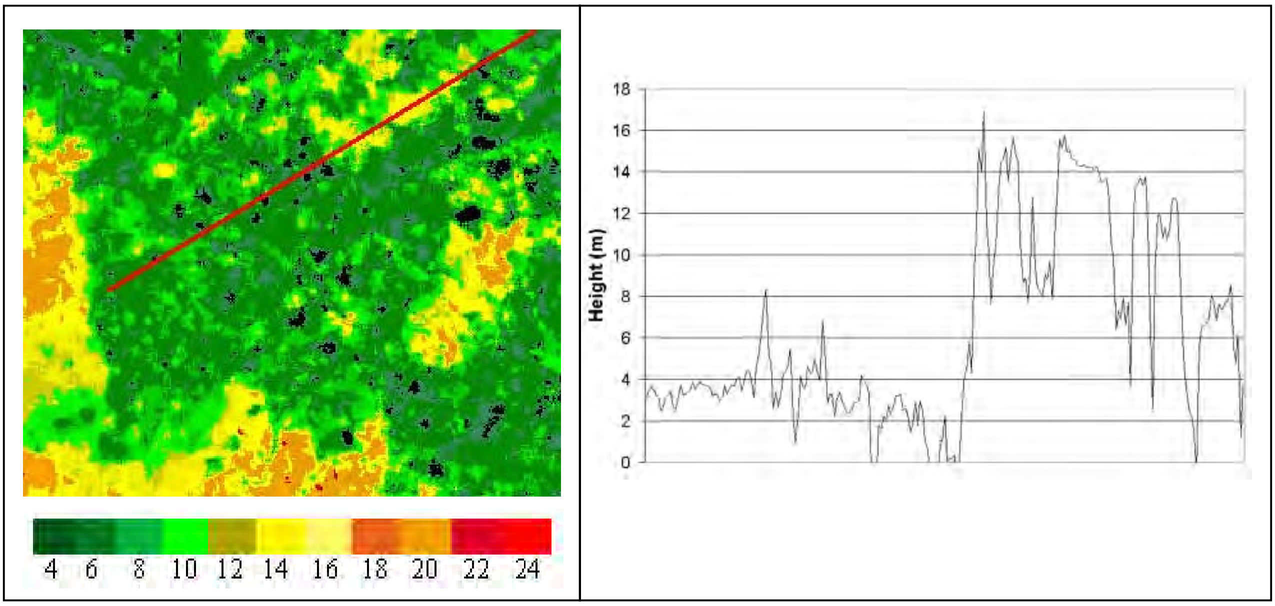

Figure 13. Inconsistencies in height estimation associated with DEM generation for open forest: a) 5 m DEM; and b) Profile extracted through mangroves.

5.2 Establishing scale and position in orthomosaics

The orthomosaics were generated at 1 m spatial resolution with an assumed positional accuracy of ± 50 m. The internal accuracy was based on the manual identification of GCPs using digital map sheets and subsequent height control. As there was some discrepancy between the dates of photo acquisition and the map sheets, a slight shift in the internal orientation was to be expected, but this was considered to fall within reasonable limits.

Within each block of photographs, errors were associated with scale and geographic position. As the orientation of images was undertaken on individual blocks, which were then subsequently mosaicked, there were positional differences (shifts) between the adjoining blocks. To correct for these differences, image mosaics were output for each block and then imported into ENVI for adjustment. Block shifts were applied in ENVI so that the image space of one block matched that of the other, geographically. ENVI's mosaic module was then used to generate georeferenced mosaics with the updated imagery.

6. Summary and conclusions

- For the majority of mangroves in Kakadu NP, 1 m spatial resolution orthomosaics and DEMS of canopy height are being produced. These data sets include the coastal sections of the Wildman River, the West, South and East Alligator Rivers, and Field and Barron Islands.
- DEMs are being produced with horizontal and vertical resolutions exceeding 0.37 m and 0.5 m respectively, representing perhaps the most comprehensive data set of its kind worldwide.
- The only difficulties that arise in the DEM generation process are associated with open canopy forest and bare ground. Consistent elevation data cannot be extracted for areas with smooth surrounding texture. The DEMs represent canopy top heights with no information on the underlying terrain being retrieved.
- A particular advantage of the approach is that historical data can be used. However, it is recommended that the use of lidar or even SAR interferometry be considered when updating the height maps.
- An interpretation of the DEMs and how they reflect coastal change is currently being undertaken and will be the focus of future publications.
- Important to recognize that although the datasets represent a baseline against which to assess change, the DEMs and orthomosaics can be used to indicate where change has occurred. For example, at the mouth of the Wildman River, there is clear erosion of the tallest mangroves. Also, there is the abrupt drop off in the height of *Rhizophera* on the West Alligator River, which might indicate cyclone damage.

7. Recommendations

- That these data be fully interpreted to assess their usefulness for scientific research (e.g., long term response of mangroves to coastal environmental change such as sea level rise) before further mapping is done elsewhere.
- To identify key areas of the coastline where change has occurred in the past and which may be vulnerable and to undertake mapping for these sites.
- To repeat the survey (for key sites) on a 10 year basis using either photography or laser/interferometry although the utility of these needs to be fully evaluated.

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Figures

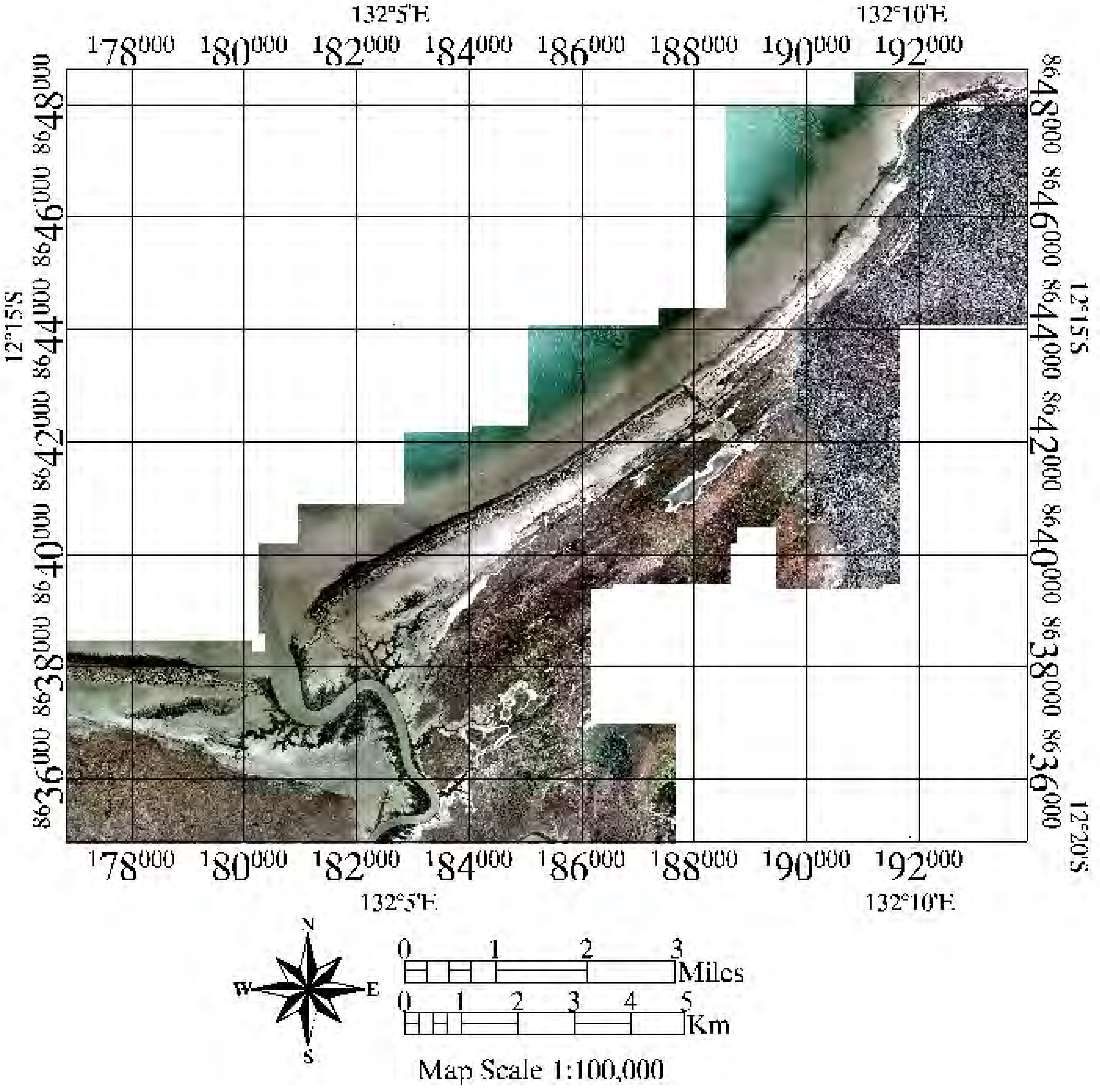

Figure 7a. Orthomosaic for the Wildman River.

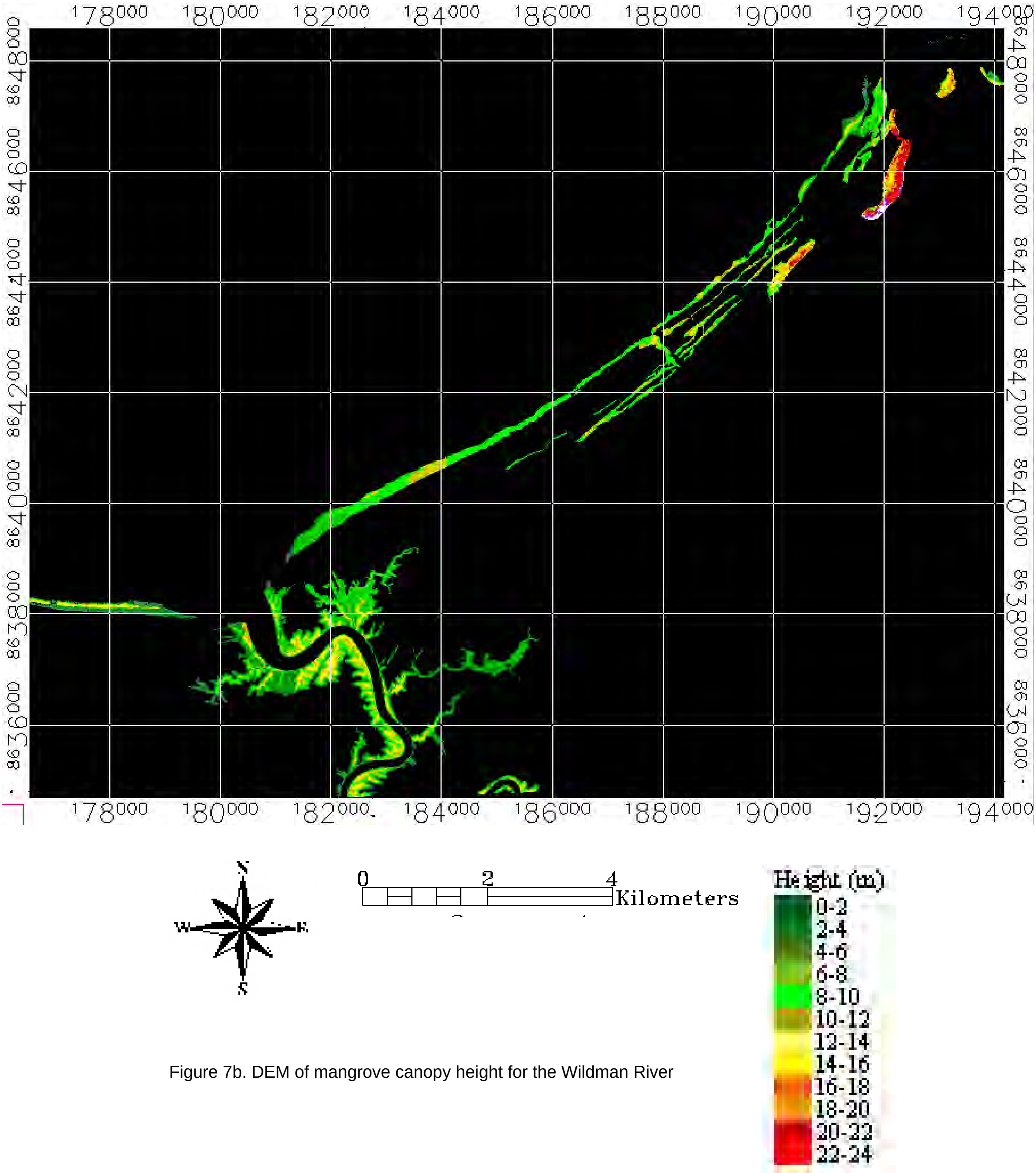

Figure 7b. DEM of mangrove canopy height for the Wildman River

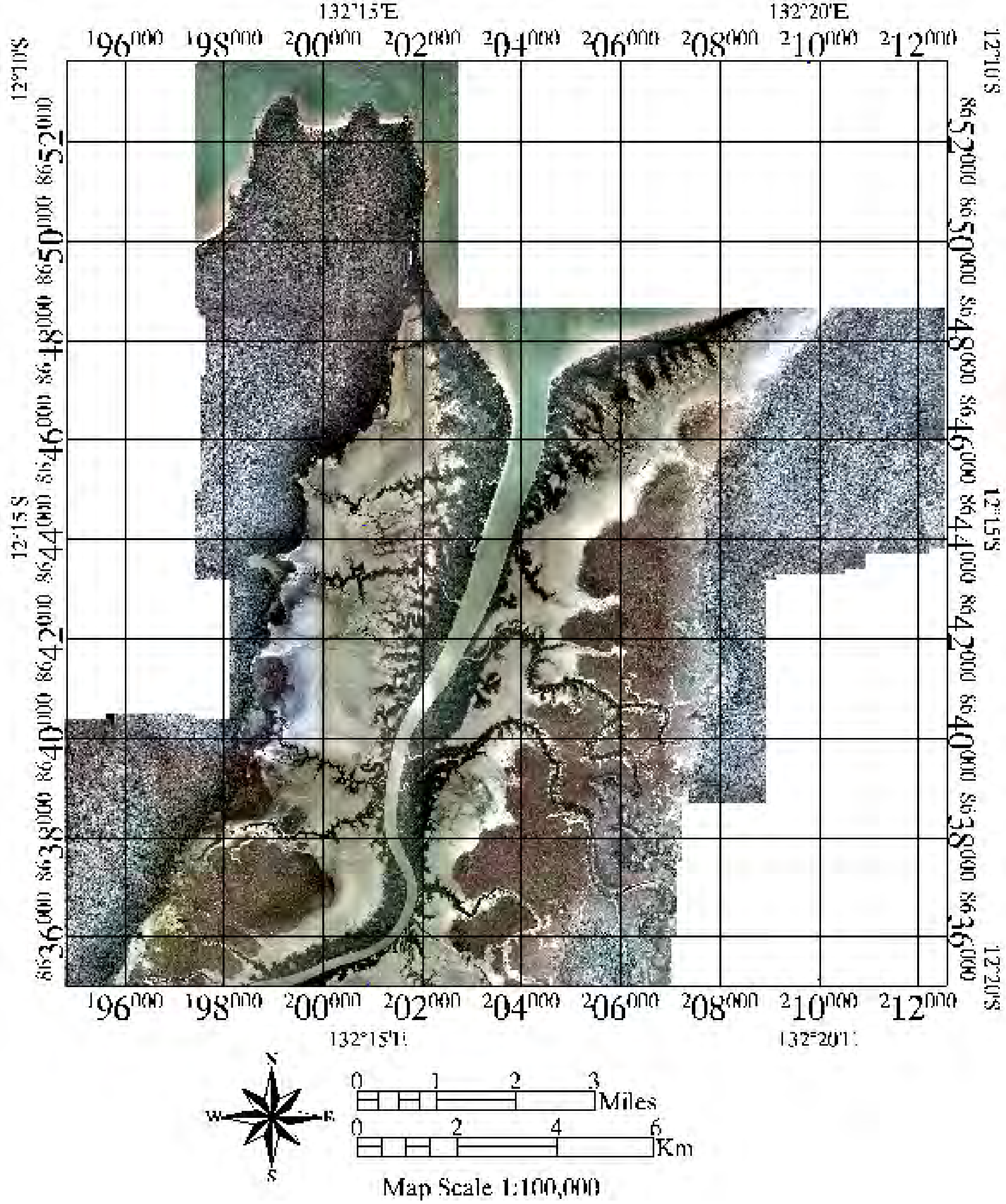

Figure 8a. Orthomosaic for the West Alligator River.

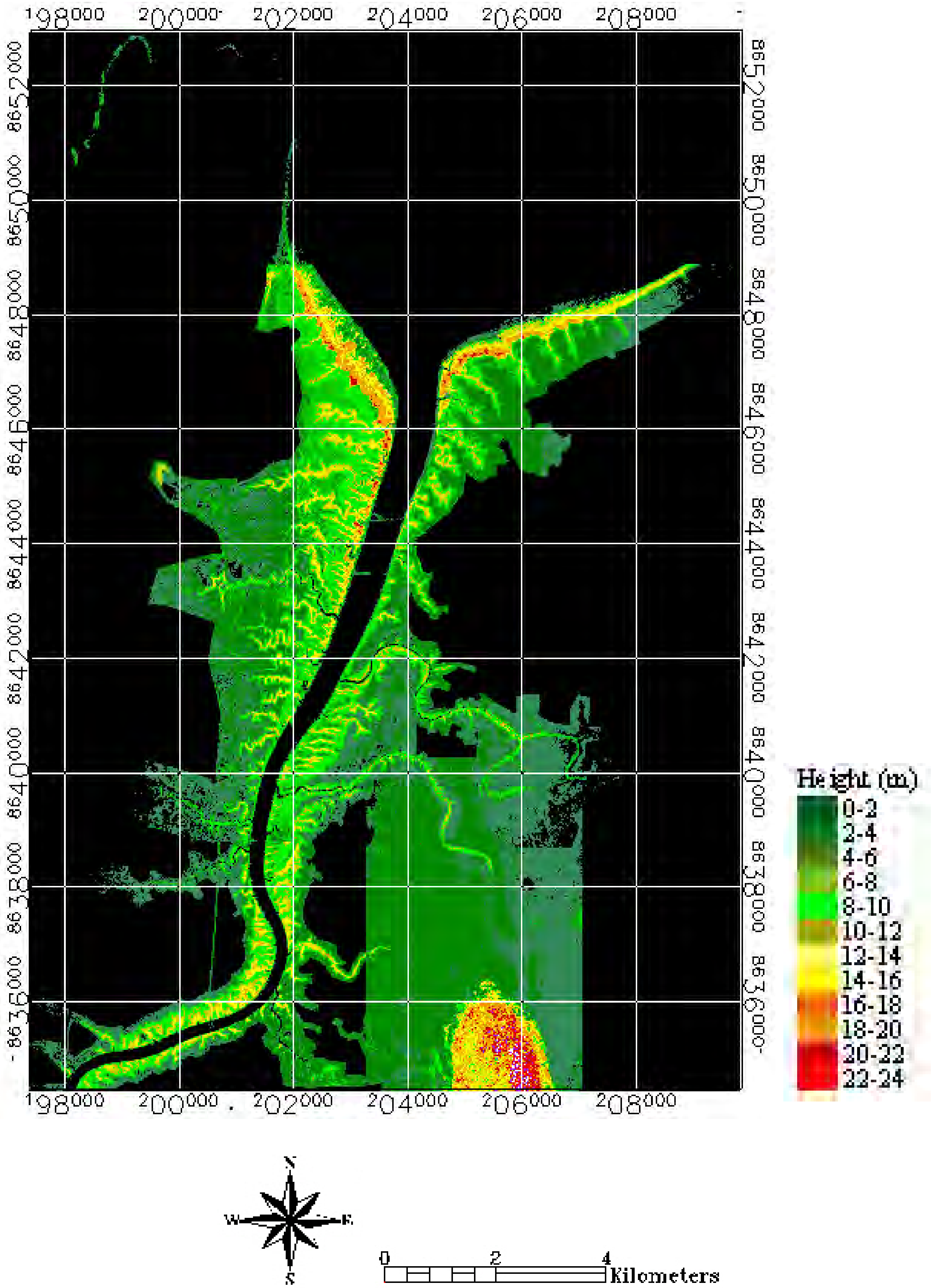

Figure 8b. DEM of mangrove canopy height for the West Alligator River.

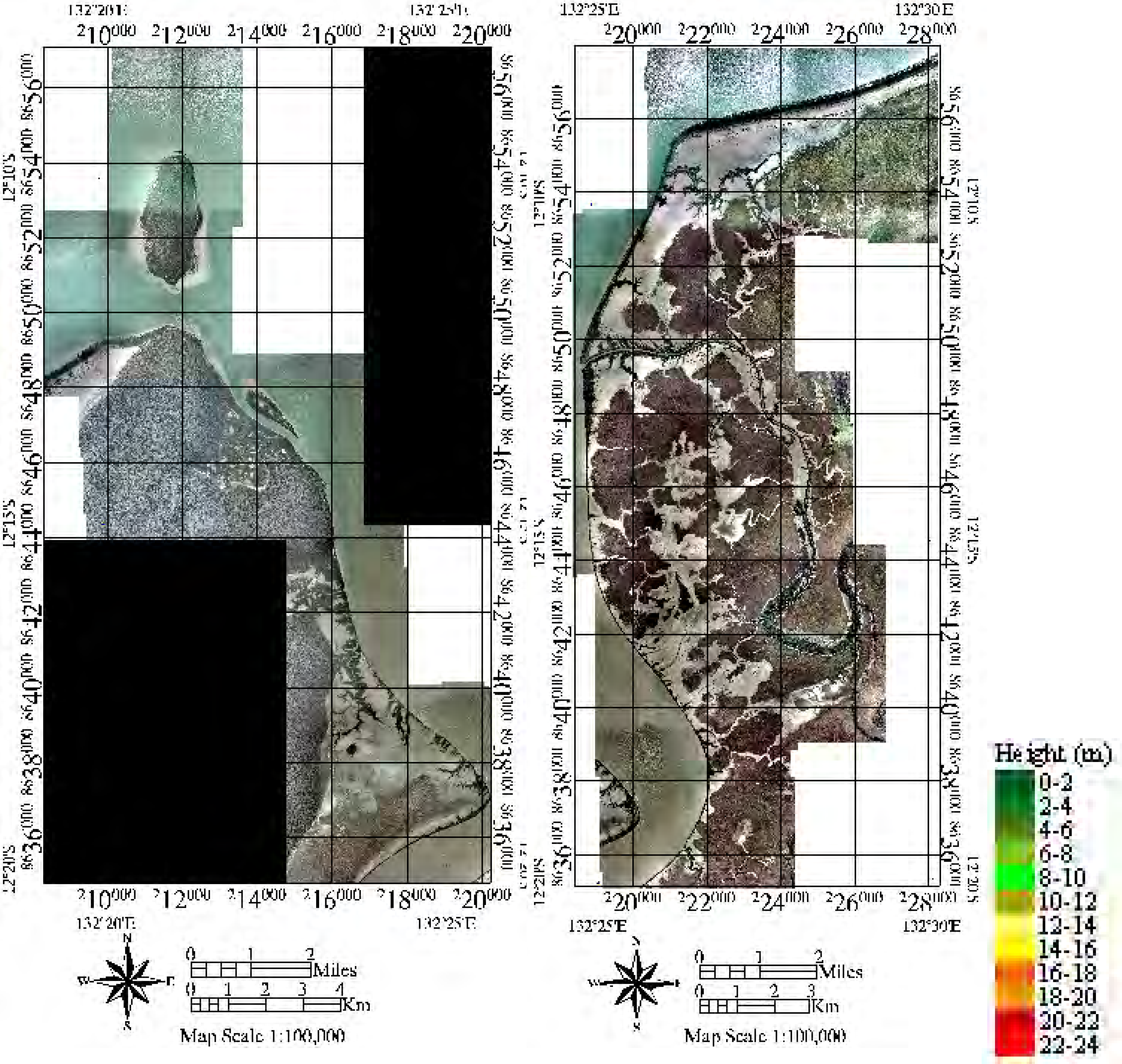

Figure 9a. Orthomosaics for the west and east banks of the South Alligator River.

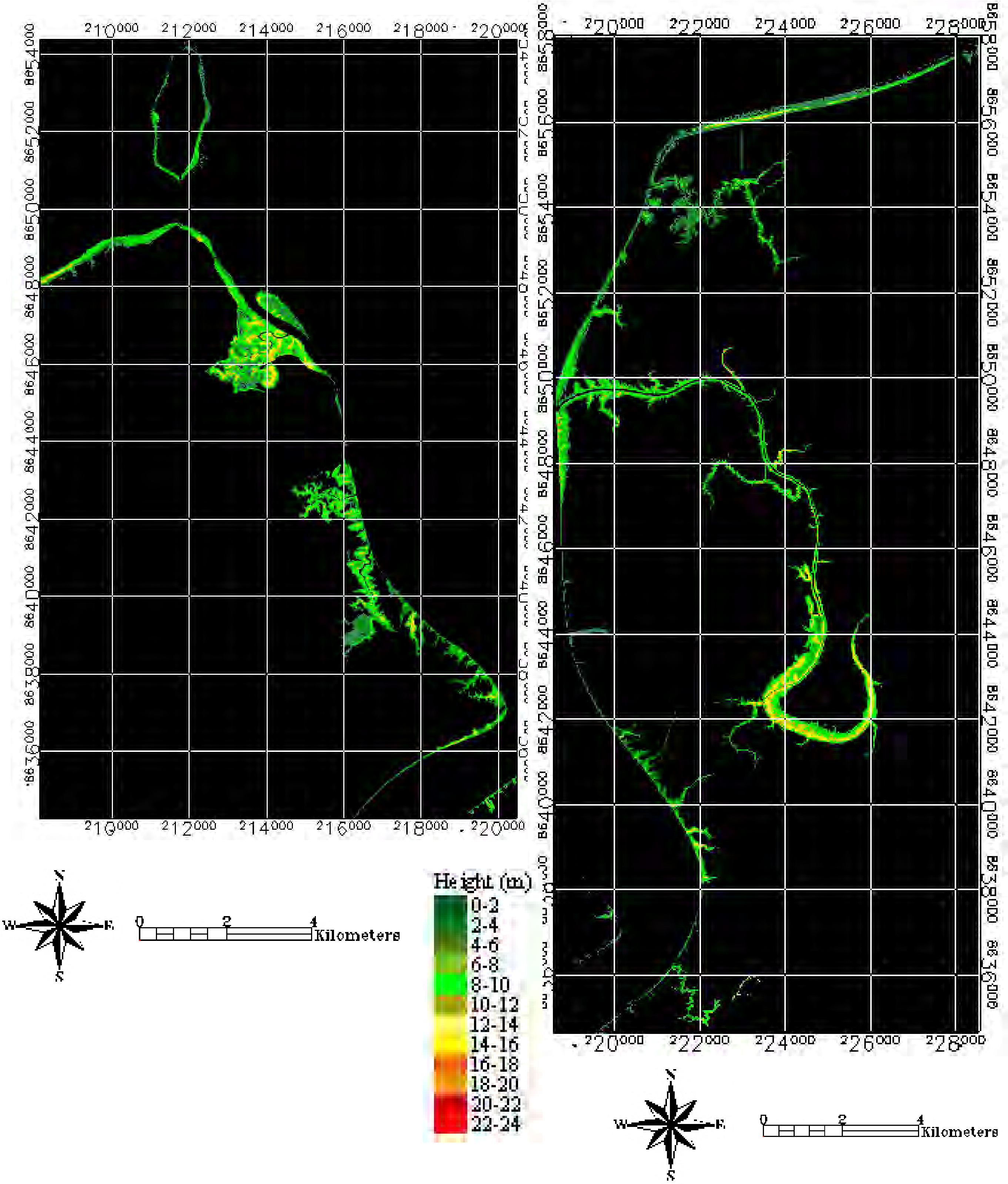

Figure 9b. DEMs of mangrove canopy height for the South Alligator River.

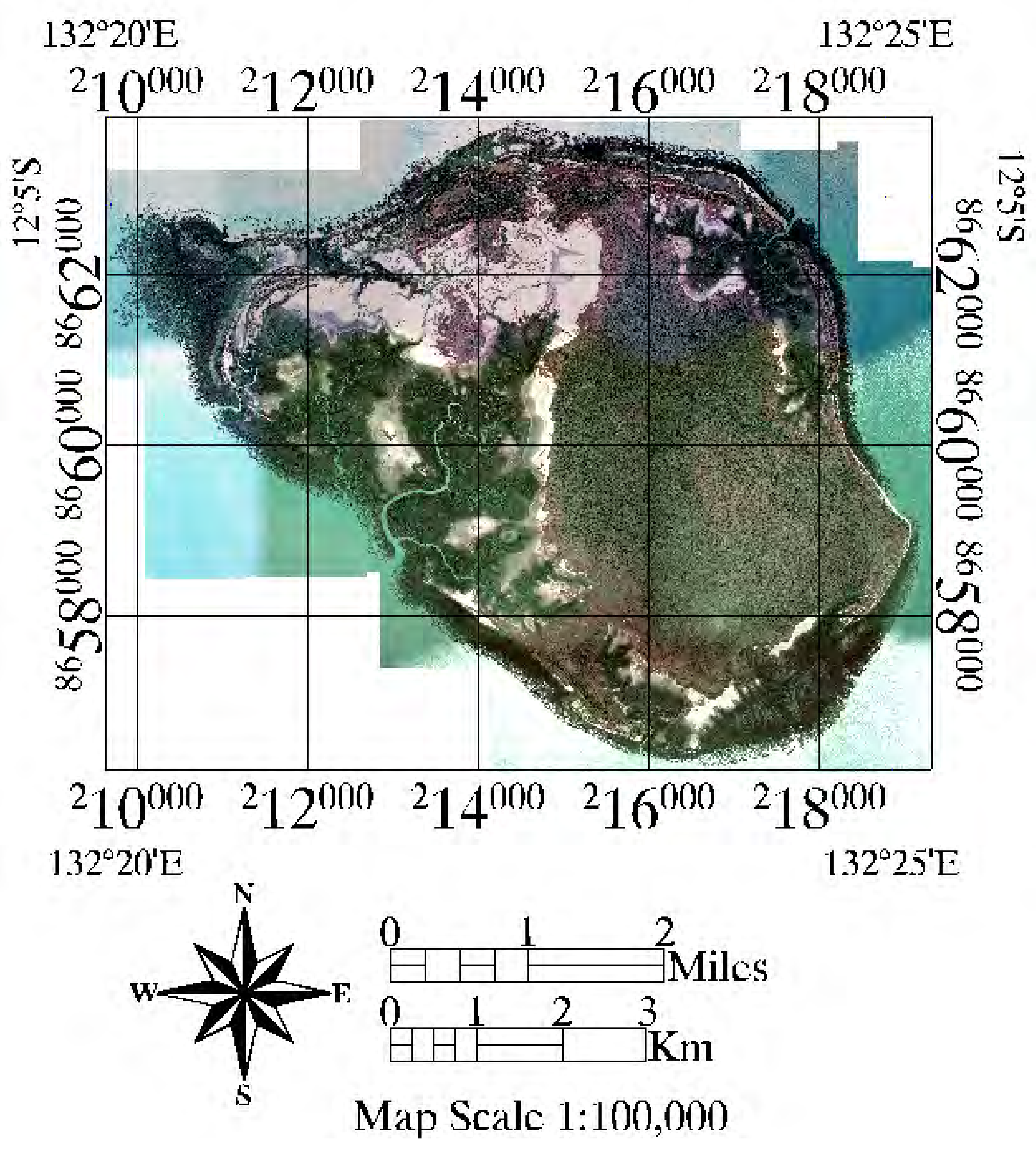

Figure 10a. Orthomosaic for Field Island.

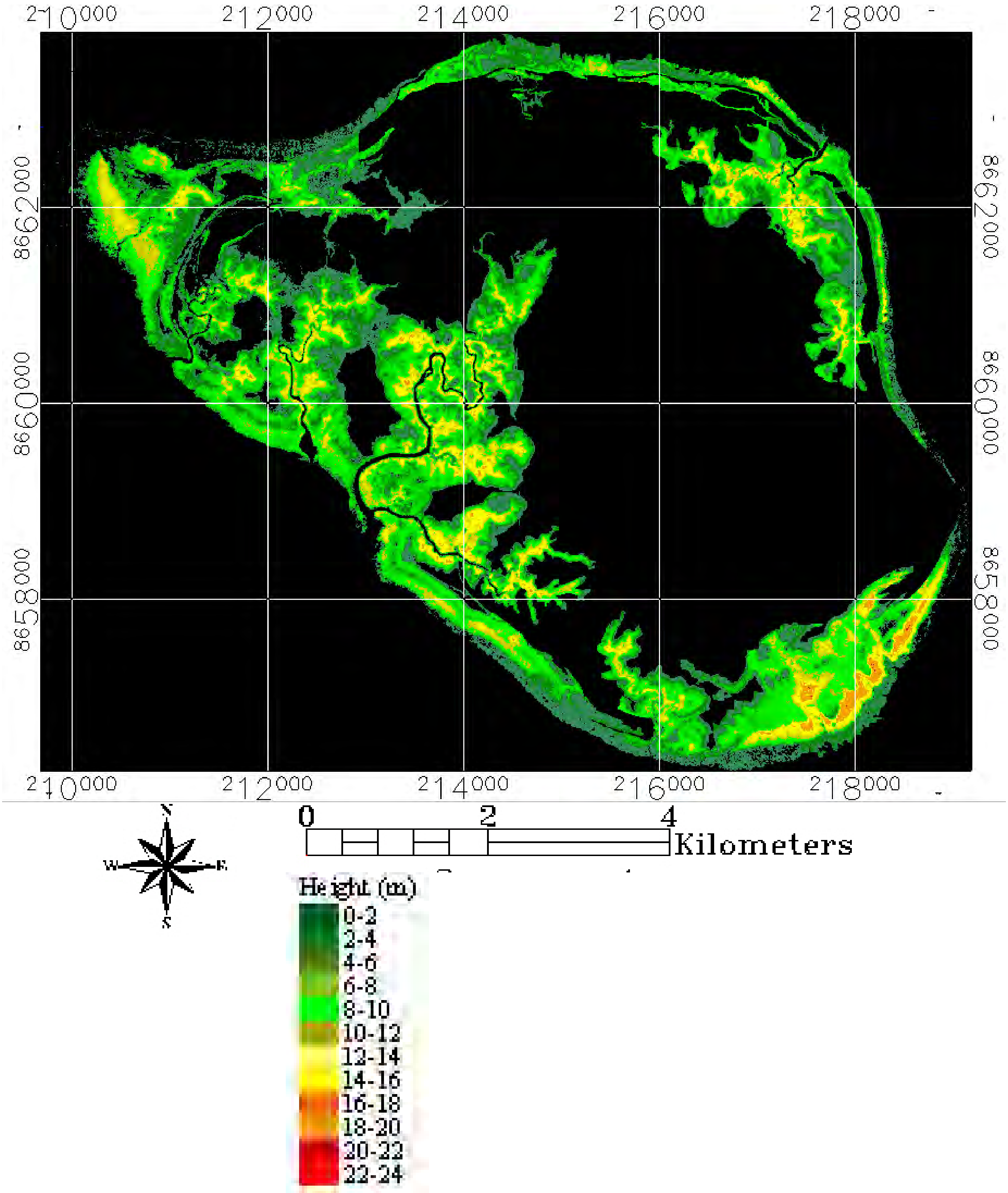

Figure 10b. DEM of mangrove canopy height for Field Island.

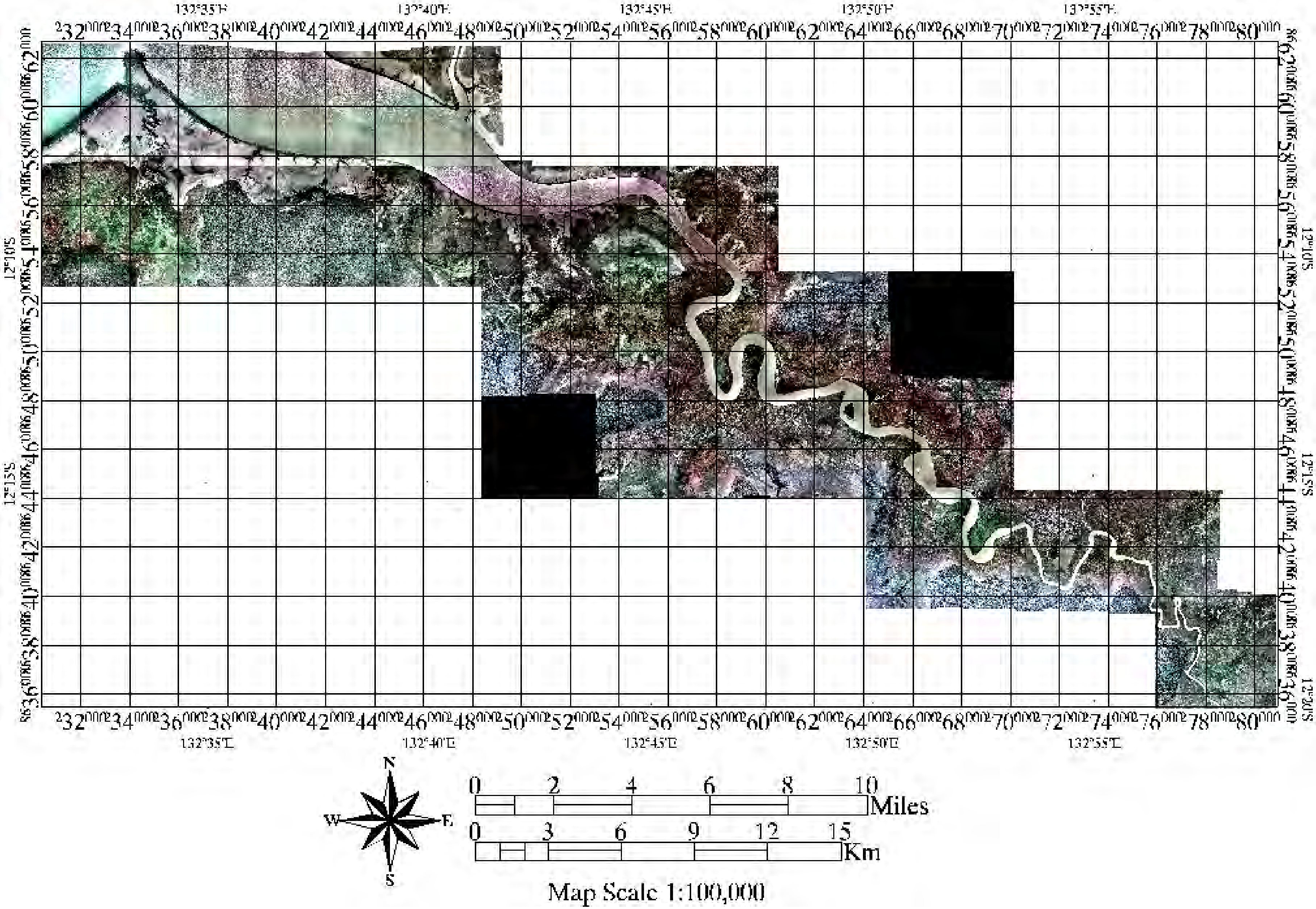

Figure 11a. Orthomosaic for the East Alligator River.

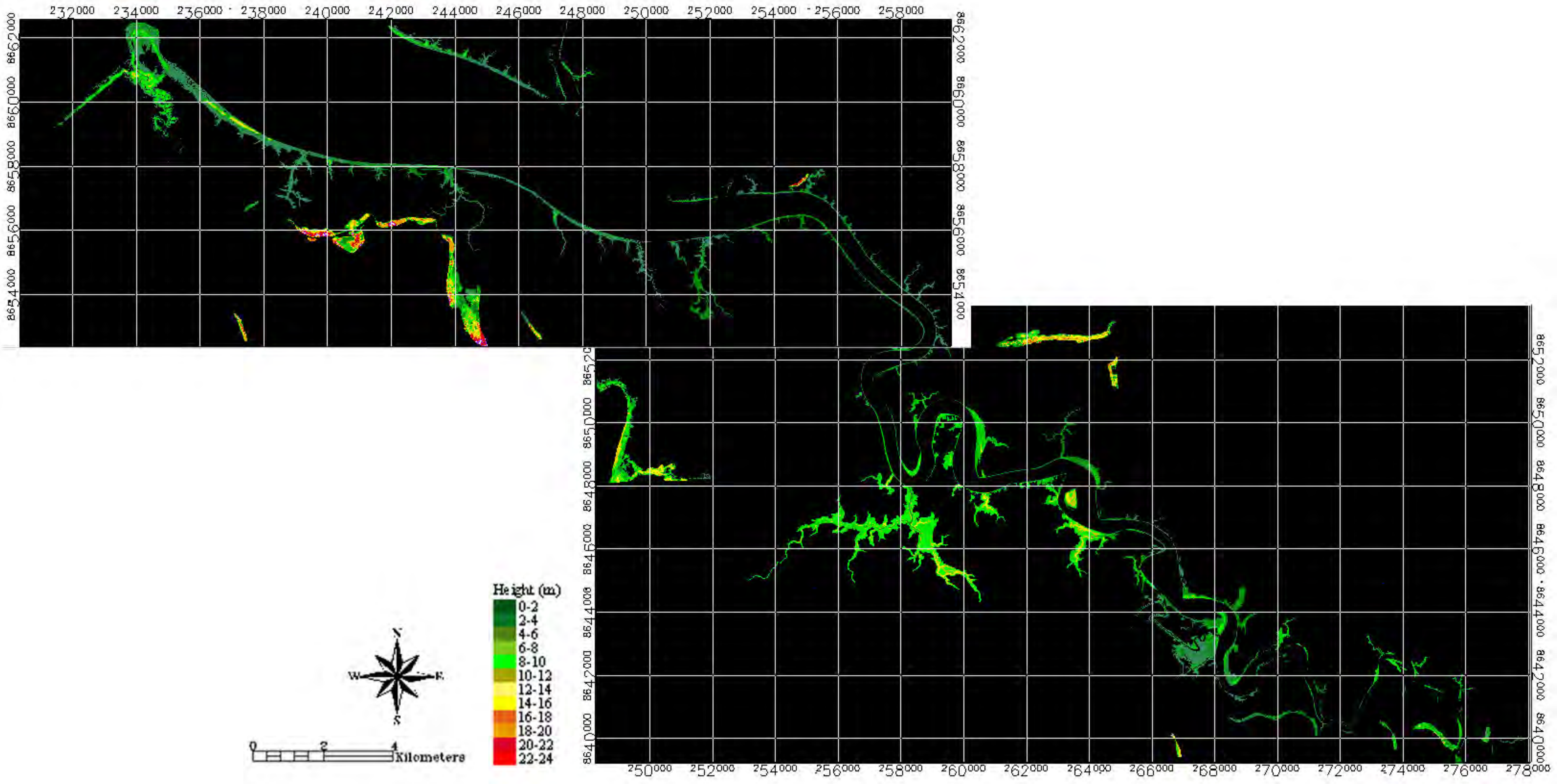

Figure 11b. DEM of mangrove canopy height for the East Alligator River.