Evaluating the feasibility of remote sensing for monitoring State of the Wet Tropics Environmental Indicators

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WET TROPICS
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The authors acknowledge the financial contribution and assistance from the Wet Tropics Management Authority in this project.

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EXECUTIVE SUMMARY

PROJECT OBJECTIVES

- To review and evaluate the capability and potential of commercially available remotely sensed data types for application in State of Wet Tropics reporting processes.
- To evaluate the feasibility of satellite and airborne imaging (remote sensing) techniques for monitoring State of the Wet Tropics (SoWT) indicators.
- To recommend an optimal choice of remotely sensed data and processing methodology for monitoring such indicators.
- To suggest preliminary steps towards a framework for fully integrating remote sensing into monitoring programs in the Wet Tropics.

KEY FINDINGS

- Remote sensing technology and data is currently suitable (and for certain indicators the only cost-effective solution) for monitoring some State of Wet Tropics indicators (as shown below).
- Remote sensing technology use is feasible for other indicators but would require further development.
- WTMA currently has the necessary technology, but not the staff expertise to implement Remote Sensing based SoWT monitoring.
- Use of Remote Sensing is restricted by a lack of understanding of its full potential.
- A lack of integration and coordination between research institutions and land management agencies is resulting in inefficiencies and reduced cost-effectiveness in application of remote sensing technologies for the Wet Tropics.

RECOMMENDATIONS - SHORT TERM

- Remotely sensed data are ‘operational’ for several State of the Wet Tropics Environmental Indicators and should be incorporated into the WTMA State of Wet Tropics reporting processes.
- A workshop should be conducted to train and provide guidance for WTMA GIS and research staff to use WTMAs remotely sensed data to monitor ‘operational’ indicators.

RECOMMENDATIONS - LONG TERM

- Establish a regional ‘remote sensing’ coordination group to integrate remote sensing activities associated with land management and research in the Wet Tropics. The group should include representatives from the Rainforest CRC, WTMA, DPI, DNRM, QPWS and EPA. The group should be set up as soon as possible to further develop potential remote sensing solutions for regional land use planning and monitoring needs.
- Develop remote sensing technology further to assist in monitoring forest edge effects and structural health in the Wet Tropics including: -
    - further research, and
    - further technology transfer

MANAGEMENT IMPLICATIONS

- WTMA have the remote sensing data and facilities (hardware/software) for processing and application to SoWT indicator monitoring, but staff require training to be able to apply these processing operations.
- Satellite remotely sensed data sets offer the only source of information for cost-effective monitoring of the biophysical condition of the Wet Tropics World Heritage Area at a bioregion scale on a regular basis.

- ⇑ Airborne datasets offer solutions as pilot studies (small scale) to extend to a bioregional scale for some SoWT indicators (e.g. infrastructure corridors)

FURTHER RESEARCH

- ⇑ There is ongoing work through the remote sensing group of the Rainforest CRC to provide training to WTMA to implement the **operational** approaches, improve communication between the two groups and develop the technologies identified as **feasible** to operational status.
- ⇑ A collaborative pilot study (or series) to establish a monitoring program for key areas, significant environmental problems (weeds of national significance) and/or SoWT indicators of concern for WTMA needs to be set up as soon as possible.

Assessment of operational status of remote sensing for monitoring selected State of the Wet Tropics Indicators

Indicator (Surrogate)	**Status**
Land cover classes	Operational
Extent of clearing by stratification (within land cover types: linear service corridors, inundation, spot clearings, boundary anomolies)	Operational
Extent of vegetation fragmentation (area of power lines, roads)	Operational
Extent of burnt area by spatial unit and assemblag (within Webb-Tracey Communities)	Operational
Extent and severity of edge effects Structural modifications of forest health	Feasible Feasible
Extent of introduced environmental weed species by spatial unit and native plant assemblage	Likely/Possible (dependent on scale of feature)
Erosion features (exposed soil)	Likely/Possible
Changes to drainage pattern (dams, stream geometry)	Feasible (dependent on scale of feature)

Operational: Able to be completed in the Wet Tropics using currently available data and software.

Feasible: Data are available for the Wet Tropics, but a suitable processing technique hasn't been established to deliver the required information. Or, the process may be so highly technical such that the technique needs refining before being suitable without an unrealistic level of training and experience.

Likely/possible: Published research indicates remotely sensed data can be used to address this problem, however, no data or processing techniques have been tested in the Wet Tropics.

INTRODUCTION

The objective of this report is to deliver an evaluation of the feasibility of the use of remote sensing techniques to monitor regional scale State of the Wet Tropics (SoWT) indicators as defined by the Wet Tropics Management Authority (Scientific Advisory Committee and Board). This will be achieved by adding to the results from the authors' first project completed for the Rainforest Cooperative Research Centre (Phinn, S., Stanford, M. and Held, A. (2000) *Remote Sensing Requirements for Management Agencies Responsible for Forest and Water Quality Monitoring in the Wet-Tropics*, Rainforest CRC, Cairns, 46p.). The previous report consisted of an extensive literature review and survey to identify the remote sensing requirements and capabilities of management agencies responsible for forest and water quality monitoring in the Wet Tropics; further research was completed to extend our results to achieve the following objectives:

- To **assess** and **evaluate** the capability of commercially available remotely sensed data types for the purpose of **monitoring defined SoWT indicators**.
- To recommend an **optimal choice of remotely sensed data and processing methodology** for monitoring each of the following SoWT indicators (provided by WTMA).

The collection of remotely sensed data to produce information for assessing SOWT indicators has to proceed at specified spatial and temporal scales. For this reason we have identified three spatial scales from our previous study at which information is required: (i) regional scale, i.e., the entire Wet Tropics World Heritage Area (> 10000km^2); (ii) provincial scale, i.e., (100-1000km^2); and (iii) local scale, i.e., within Local Government Areas (< 100km^2). The temporal scale for collection of information on indicators was set a yearly repeat cycle to meet WTMA Annual reporting requirements. In some cases (e.g., fire and cyclone disturbance) event driven monitoring has been recommended.

INDICATORS

The indicators to be evaluated for SoWT reporting and their potential links to remotely sensed data are listed below:

Land cover classes

These baseline data are derived directly from remotely sensed data. It may be possible to further discern classes from the broadly defined WTMA habitat type categories listed here.

Extent of clearing by stratification (after WTMA, 1999)

It is a requirement of Queensland legislation for WTMA to be informed of infrastructure developments within the WHA. The location of these types of clearing will be known at the outset. The clearings are mainly of a linear nature subdividing natural habitat areas (Table 1).

Extent of vegetation fragmentation

External fragmentation or vegetation patches within the landscape matrix. The nature and location of these areas would largely be known by WTMA. Spot clearings would need to be located at a regional scale then monitored at a local scale once accurately located and identified.

Extent and severity of edge effects

An edge may be viewed as a marginal zone of altered microclimate and ecological conditions that contrasts with the integrity of the forest interior. For the purposes of this report, edge effects refer to all measurable changes (including anomalies) at an ecosystem boundary and within adjacent ecosystems. Changes in the ecosystem usually are beyond the visual edge caused by the impact. The ecotone that results from a disturbance is the result of interactions between the type and intensity of the disturbance event and the ecological dynamics within the adjacent, undisturbed environment.

Table 1: Clearing types and area from the WTMA Annual Report 1998-1999

Clearing Type	Area (ha)
Linear service corridor clearings	
Powerlines	1461
Roads	631
Railways	172
Cableways	6
Inundation	
water impoundments	1986
Spot clearings	
clearings unclassified	191
gravel quarries, scrapes & mines	44
army camps	59
recreation areas	41
Airstrips	34
sawmill sites	9
forestry camps	8
rifle ranges	4
Radio tower/met. Station	3
Boundary anomalies	
Paddocks	205
Sugarcane	66
pine plantations	39
Orchards & plantations	35
Other clearings	
fire degraded hillsides	493
Buildings & settlements	115

Structural modifications/forest health

Outbreaks of disease such as patch death from the root rotting fungus *Phytophthora cinnamomi* may be measured directly or inferred from stressed or dead patches of vegetation appearing in remotely sensed imagery.

Extent of burnt area by spatial unit and assemblage

The extent of burnt area may be measured directly using remote sensing

It is suggested that monitoring using remote sensing would be integrated strongly with geographic information system (GIS) operations as often as possible. The operations may be based on the native plant assemblage information available in Webb and Tracey (1976).

Extent of introduced environmental weed species by spatial unit and native plant assemblage

Plant species not native to the area. The ability to discern environmental weeds using remote sensing depends largely on the growth form and the mode of behaviour of the weeds. For example, species such as camphor laurel (*Cinnamomum camphora*) with a tree growth form is more easily distinguishable than coffee (*Coffea arabica*) with a shrub growth form beneath the canopy.

Similarly, hydrophytes such as water fern (*Salvinia molesta*) is easily discernable as it begins to form thickets or monocultures of the order of metres across. Remote sensing lends itself to this type of monitoring by spatial unit.

Erosion features (exposed soil)

Exposed soil is used as a surrogate for erosion features to infer the erodability of an area of interest.

Changes to drainage pattern

This indicator is a modification of the landscape due to hydrology including artificial water impoundments. This means an alteration in the number of channels and/or their characteristic geometry.

The status of current remote sensing technologies (data and processing techniques) to address each indicator will be identified as:

Operational

For indicators of this category, results have been or are being produced over broad areas relevant to the scales of the State of the Wet Tropics reporting process. The relevant data expertise and infrastructure are in place to continue of extend these operations.

Feasible

Present knowledge and case studies suggest that relevant information can be derived from available data, but large scale operational demonstrations have not been performed.

Likely/possible

This group includes indicators where present data are inadequate, but future studies are anticipated. It includes indicators where there is knowledge of relationships between the indicator and remotely sensed data, but further research is required to identify suitable processing for State of the Wet Tropics reporting.

Unlikely/ impossible

For these indicators, the assessment is that remote sensing is unlikely to deliver operational results, either because of lack of ability to measure the indicator of interest, or because the scale and logistics suggest that monitoring for State of the Environment reporting purposes would be impracticable.

STATE OF THE ENVIRONMENT REPORTING AND REMOTE SENSING APPLICATIONS

Wallace and Campbell (1998) conducted a survey of remote sensing practitioners and experts in Australia to evaluate the feasibility of remote sensing for monitoring National State of the Environment. The focus of the survey was on identifying the operational status (operational, feasible, possible or impossible) of remote sensing to deliver information on specific indicators. In total, 37 indicators were reviewed relating to vegetation and ground cover, chlorophyll detection, soil erosion, salinity and additional indicators. None of the indicators or example applications dealt specifically with remote sensing applications in tropical rainforest environments. Each indicator was reviewed in detail in terms of surrogate remotely sensed measures, suitable platforms, repeat monitoring capability and costs. The limited coverage of tropical forest applications is symptomatic of the general absence of published work in scientific or grey literature on remote sensing of tropical rainforests in Australia, with the exception of select works by Mckenzie et al. (1991) and Vanclay and Preston (1990). The majority of the cited articles dealt with applications developed for AVHRR and Landsat sensors (MSS and TM), with select examples of airborne multispectral and hyperspectral image data.

Another key consideration raised in this review was the issue of costs, specifically the underestimation of project costs for using remotely sensed data due to the data acquisition costs only being a minor cost component of the budget. Examples were provided for a number of monitoring projects and example costs associated with: project planning, image rectification and normalisation, integration of ancillary data, mapping /change-detection, interpretation of mapping and change results, validation, refinement and correction, and production of reports and summary products.

Other important factors requiring consideration in designing a monitoring project included measurement and minimisation of errors in geometric rectification, atmospheric calibration and on-ground accuracy assessment.

"Operational remote sensing applications" for mapping indicators that could apply to tropical rainforest environments include:

- Vegetation (remnant or woody vegetation)
- Burnt area by spatial unit and assemblage
- Mangroves
- Land use categories

"Feasible [not yet subject to large scale operational demonstrations] remote sensing applications" for mapping indicators that could apply to tropical rainforest environments include:

- Extent of vegetation fragmentation
- Structural classes of vegetation (from stereophotos)
- Sediment plumes in estuaries
- Algal blooms
- Trends in vegetation cover
- Urban Land use
- Land surface temperature

"Likely/possible (in context of SoE reporting) remote sensing applications" for mapping indicators that could apply to tropical rainforest environments include:

- Introduced floral species (Except in specific circumstances)

REMOTE SENSING APPLICATIONS IN TROPICAL FOREST ENVIRONMENTS

One of the most striking and effective applications of remote sensing to natural resource mapping to date, have been the visualizations of forest clearing produced by the Landsat satellite series over areas of the Amazon rainforest (e.g. Rondonia). Recent reviews of this technology for traditional and new remote sensing applications to rainforest monitoring and management throughout the world, and the tropics in particular have indicated a vast array of studies aimed at mapping tropical rainforest (Lucas et al., 2001; Phinn *et al.* , 2000). Over 280 additional papers on this subject were reviewed for this project.

Several recurrent themes were evident from these, in terms of the types and scales of monitoring applications for which remotely sensed data had been used and the types of variables measured. The two most common applications were regional scale mapping programs (areas > 1000km^2) to identify forest types and land-use, deforestation, or to map vegetation cover in South America, South-East Asia and central African countries using predominantly the Landsat Thematic Mapper and NOAA-AVHRR data sets. The majority of these studies were concerned with baseline mapping the extent of forest and non-tropical forest areas and the changes to these types of land-cover over time. Biophysical or quantitative measures of vegetation cover, in terms of tree density, structural parameters and canopy parameters such as LAI were only estimated in a small number of projects. GLOBAL Accuracy assessment of these projects was also very limited, both in terms of field validation and in terms of use of aerial photographs to verify mapped changes in cover or composition. In decreasing frequency of occurrence, the main tropical forest remote sensing applications identified were:

- Mapping forest extent and change in extent (i.e. cover and deforestation);
- Deforestation studies;
- Mapping internal composition of forest;
- Mapping structural and biomass component of the forest;
- Mapping the health and condition of the forest; and
- Evaluation of sensor capabilities (SAR, TM, AVHRR, hyperspectral) for forest monitoring

As a consequence of the focus on deforestation and land-cover change mapping, the most common biophysical variable extracted from remotely sensed data of tropical forests was surface composition at a very general level, i.e., forest cover as opposed to cleared and grassland. Relatively few studies examined community and species composition due to the high degree floristic diversity and spatial heterogeneity within rainforest environments at local to regional scales. A number of aerial photograph based projects did map community level composition, however, this had not been extended to regional scale from satellite image data sets. Optical image data sets and derived indices of vegetation cover have been used extensively for mapping forest canopy attributes from regional to global scales. In some cases these applications have also been to estimate local-regional scale quantities of photosynthetically active radiation to parameterise global and regional climate models.

Sub-canopy attributes and vegetation structural properties have also been examined extensively from satellite based synthetic aperture radar systems. These systems provide a less weather dependent and more reliable data capture and constitute the basis of a number of large area monitoring projects, such as Tropical Resources Environment monitoring by Satellite (TREES) project by European Space Agency and the Commission of European Communities Joint Research Centre (Malingreau et al. 1995) (http://esapub.esrin.esa.it/eoq/eoq48/ mali48.htm), the Japanese Space Agency's global rainforest mapping program (http://southport.jpl.nasa.gov/GRFM/) , NASA's Pathfinder Humid Tropical Forest Inventory Project/ Tropical Rainforest Information Centre at Michigan State University (http://www.bsrsi.msu.edu/overview/pathfinder1.html).

The sensitivity of active system to forest canopy structure and volume also makes them inherently suitable for estimation of biomass, due to the limited success of optical indices in relation to forest biomass. As with the actual monitoring applications, the majority of biophysical parameters estimated have mainly been at regional to global scales. In decreasing order of occurrence, the following biophysical parameters had beenextracted from remotely sensed data of tropical forests as reported in the articles:

- Composition (land-cover, community, species);
- Structure (vertical);
- Structure(horizontal);
- Biomass;
- Leaf area;
- Foliar chemical;
- Photosynthetically Active Radiation;
- Carbon flux; and Temperature

REPORT FORMAT

Indicators for the State of the Wet Tropics

This section explains the concepts of ecological/environmental indicators, defines the WTMA indicators to be assessed, and identifies parameters for each indicator enabling it to be linked to suitable forms of remotely sensed data (spatial scale, temporal scale and surrogate variables).

Remotely Sensed Data Sources and Their Processing Requirements

In the first of two sections, a comprehensive summary is provided of currently available remotely sensed data sets (optical, radar/laser, airborne and satellite) in terms of their spatial resolution (ground resolution size, extent), spectral resolution, radiometric resolution and temporal resolution, source, costs and archive. Information/variables on tropical forests able to be derived from each data type will also be defined. In the second section, processing techniques used to convert image data sets to relevant biophysical variables or surrogates will be listed, along with their input data requirements and output information. Both sections were taken directly from a previous report by Phinn et al. (1999) that required and identical evaluation of the capabilities of remote sensing, bit focussed on wetland environments.

Evaluation of Remotely Sensed Data and Processing Approaches for SoWT Indicator Monitoring

Each indicator and its surrogate(s) will be directly compared to relevant remotely sensed data sets and processing approaches to determine the suitability of remotely sensed solutions for monitoring an indicator, and the level of suitability (i.e., Operational, Feasible, Likely/possible or Unlikely/ impossible).

Optimal Remotely Sensed Data and Processing Approach(es) for SoWT Indicator Monitoring

A summary matrix will be derived for each indicator indicating the most suitable remotely sensed data set and processing technique(s) and an assessment of data and processing requirements for monitoring the indicator in the wet tropics (actual costs and time).

Specific output from the project include:

- ⇑ Listing of SoWT indicators, suitable surrogates, and an evaluation of the operational status of remotely sensed data and processing techniques to provide this information.
- ⇑ Extensive literature review and survey on current remote sensing applications in wet tropical forests.
- ⇑ Optimal choice of remotely sensed data set and processing technique(s) capable of providing SoWT indicator information.
- ⇑ Estimate of time and cost required to acquire, process and verify optimal remotely sensed data sets for monitoring a set region within the Wet Tropics.
- ⇑ Outline of the approach to be taken for using optimal remotely sensed data and processing techniques for monitoring change in select SoWT indicators.
- ⇑ Assessment of the key operational issues (.e.g. field checking, data ownership, data sharing, intellectual property, emerging technologies and future research issues).

INDICATORS FOR THE STATE OF THE WET TROPICS

Environmental or ecological indicators are singular or integrative variables or indices (physical, chemical or biological) acknowledged to be strongly related to the structure, condition or functioning of specific environments. The concept of ecological and environmental indicators was drawn from water quality testing approaches developed in the 1980s and has since been adopted in both national and statewide “State-of the Environment” reporting in Australia (McKenzie *et al.* 1992, Wallace and Campbell 1998). Wallace and Campbell(1998) provided a preliminary evaluation of the feasibility of remote sensing for monitoring an extensive set of national scale state of the environment indicators. As noted in the previous section there was very limited attention paid to specific environments in the report, with minimal coverage of rainforest ecosystems, due to the national scope of the report. This report has been written with the intent of building on the results of Wallace and Campbell (1998) and represents a model for further assessment of remote sensing to monitor regional ecosystems or bioregions.

This section defines the WTMA indicators to be assessed, and identifies parameters for each indicator enabling it to be linked to suitable forms of remotely sensed data (spatial scale, temporal scale and surrogate variables). The approach taken was to define the characteristics or attributes of the SoWT indicators that could be used to select remotely sensed data and processing techniques capable of providing the required information at appropriate spatial, temporal, accuracy and cost levels. This approach build on an internationally reviewed and recognised technique developed by Phinn (1998) that has been applied in a number of different environments to determine the feasibility of remote sensing for specific environmental monitoring and management problems (Phinn et al. 1998, Phinn et al. 2000b RSE). The key to this approach is defining the spatial and temporal scale(s) of data and information required to address each indicator or it’s surrogate. These parameters are summarised for each indicator in Table 1, along with known outputs from remote sensing products that match the indicators and references to example projects. The spatial and temporal scales of required indicator/surrogate information (and type of information) provide a direct link to remotely sensed data, i.e. , remotely sensed data sets are differentiated primarily on their spatial and temporal dimensions, while their spectral resolution determines the type of information able to be extracted.

- Land cover classes
- Extent of clearing by stratification
- Extent of vegetation fragmentation (from infrastructure corridors)
- Extent and severity of edge effects
- Structural modifications/forest health
- Extent of burnt area by spatial unit and assemblage
- Extent of introduced environmental weed species by spatial unit and native plant assemblage
- Erosion features (exposed soil)
- Changes to drainage pattern

Table 2: Evaluation matrix for State of the Wet Tropics Indicators and links to environmental variables that can be measured using remote sensing data and spatial-image analysis techniques. Remote sensing at different scales as it relates to the State of the Wet Tropics reporting is largely based on geographic areas and their location not the authors interpretation of the Wet Tropics Plan. A baseline data collection would be used along with Tracey and Webb (*Vegetation of the Humid Tropics of North Queensland, 1975)* to detect changes. The spatial scale section of Table 1 (below) has defined three scales, 1) regional – the extents of the World Heritage Area (WHA), 2) Province (100 km^2-1000km^2) - … and 3) local scale (<100 km^2). The monitoring incorporates A, B and C (see) type clearing which includes known areas of clearing that is, areas that may be cleared for new roads or powerlines that WTMA is informed about and are part of the planning process.

Indicator *Surrogate*	**Spatial Scale**		**Temporal Scale**		**Remotely Sensed Variable**	**Remote Sensing Information Source**	**Example applications**
	Extent	**Min.Map Unit**	**Frequency**	**Time of Year**			
Land cover classes	Region (Requested) (10,000km^2)	1ha	Annual eg by June for December delivery or event driven (WTMA Baseline data collection for land coverNot specified		Land-cover	Satellite multispectral Satellite radar	Achard, 1995; Adams, 1995; Alves, 1996; Amaral, 1992; Antikidis, 1999; Apan, 1997; Archard, 1990; Batista, 1997; Belward, 1994; Boyd, 1995; Brondizio, 1996; Bruenig, 1985; Chatelain, 1996; Conway, 1997; Cross, 1991; Cross, 1991; Dirzo, 1992; Eggen, 1994; Estreguil, 1996; Foody, 1994; Foody, 1994; Foody, 1996; Foody, 1996; Foody, 1997; Freeman, 1995; Gastellu-Etchegorry, 1993; Gilruth, 1990; Gilruth Peter, 1995; Grover, 1999; Hill, 1999; Hoekman, 1999; Hoekman, 2000; Jeanjean, 1997; Kimes, 1999; Kramer, 1997; Kuntz, 1999; Lambin, 1995; Lambin, 1997; Lambin, 1999; Lannom, 1995; Laporte, 1995; Laporte, 1998; Lucas, 1996; Lucas, 1993; Luckman, 1997; Mayaux, 1995; Mayaux, 1997; Mayaux, 1999; Moran, 1994; Murdiyarso, 1995; Nelson, 1993; Nelson, 1993; Paradella, 1997; Raucoules, 1999; Rey Benayas Jose, 1995; Rignot, 1997; Roy, 1991; Saatchi, 2000; Saatchi Sasan, 1997; Salami, 1999; Sanchez Azofeifa, 1999; Sader, 1994;
	Province (1000km^2)	< 1ha			Land-cover	Satellite multispectral Satellite radar	
	Local (100km^2)	100 m^2	Not specified		Land-cover	Aerial Photography Satellite multispectral Airborne multi and hyperspectral	

Indicator	**Spatial Scale**		**Temporal Scale**		**Remotely Sensed Variable**	**Remote Sensing Information Source**	**Example applications**
Surrogate	**Extent**	**Min.Map Unit**	**Frequency**	**Time of Year**			
							Singh, 1987; Skole, 1993; Stone, 1994; Townshend, 1987; Townshend, 1991; Tucker, 1985; Tucker, 2000; Tuomisto, 1994; Van, 1997; van der Sanden Joost, 1999; Woodwell, 1987; Yanasse Corinda Da, 1997.
Extent of clearing by stratification (within land cover types: linear service corridors, inundation, spot clearings, boundary anomalies)	Region (Requested) ($10,000km^2$) note: this is for areas associated with linear features ie generally in the order of 100's of ha but may be located anywhere in the geographic extents of the WHA Province ($1000km^2$) Local ($100km^2$)	1ha < 1ha $100\ m^2$	Annual eg by June for December delivery or event driven (WTMA to comment) Not specified Not specified		Land cover change Land cover change Land cover change	Satellite multispectral Satellite radar Satellite multispectral Satellite radar Aerial Photography Satellite multispectral Airborne multi and hyperspectral	Begue, 1997; Berta, 1990; Blair, 1999; Brown, 1997; Chomentowski, 1994; D'Souza, 1994; Di-Maio-Mantovani, 1997; Drake,; Eva, 1995; Fearnside, 1990; Foody, 1994; Foody, 1996; Foody, 1997; Green, 1990; Herwitz, 1998; Imhoff, 1995; Instituto Nacional De Pesquisas, 1998; Jeanjean, 1997; Jha, 1994; Joyce, 1994; Kasischke Eric, 1997; Kiel, 1995; Kuntz, 1999; Lambin, 1996; Lambin, 1997; Lambin, 2000; Lawrence, 1994; Lawrence, 1995; Le Toan, 1995; Li, 1994; Luckman, 1997; Luckman, 1997; Malingreau, 1989; Malingreau, 1991; Malingreau, 1992; Mausel, 1993; Murdiyarso, 1995; Paudyal, 1997; Saatchi, 1997; Sader, 1989; Salami, 1999; Shimabukuro, 1998; Skole, 1993; Souza Jr, 2000; Steininger, 1996; Steininger, 2000; Stone, 1991; Stone, 1998; Tuomisto, 1994; Westman, 1989; Yanasse Corinda Da, 1997.

Indicator *Surrogate*	Spatial Scale Extent	Min.Map Unit	Temporal Scale Frequency	Time of Year	Remotely Sensed Variable	Remote Sensing Information Source	Example applications
Extent of vegetation fragmentation (area of powerlines, roads)	Region (Requested) ($10,000km^2$)	1ha	Annual eg by June for December delivery or event driven (WTMA to comment)		Land cover (power-line and roads)	Satellite multispectral Satellite radar	As above
	Province ($1000km^2$)	< 1ha	Not specified		Land cover change (power-line and roads)	Satellite multispectral Satellite radar	
	Local ($100km^2$)	100 m^2	Not specified		Land-cover change (power-line and roads)	Aerial Photography Satellite multispectral Airborne multi and hyperspectral	
Extent and severity of edge effects Structural modifications forest health	Region (Requested) ($10,000km^2$)	1ha	Annual eg by June for December delivery or event driven (WTMA)		Land-cover (clearing, linear infrastructure) Vegetation Index Structure/biomass estimation	Satellite multispectral Satellite radar Satellite multispectral Satellite multispectral Satellite radar	Chapman, 1994; Drake,; Gastellu-Etchegorry, 1998; Gerard, 1997; Huete, 1997; Imhoff, 1995; Mougin, 1999; Nichol, 1995; Proisy, 1996; Ravan Shirish, 1995; Riou, 1997.
	Province ($1000km^2$)	< 1ha	Not specified		Land-cover (clearing, linear infrastructure) Vegetation Index Structure/biomass estimation	Satellite multispectral Satellite radar Satellite multispectral Satellite multispectral Satellite radar	
	Local ($100km^2$)	100 m^2	Not specified		Land-cover (clearing, linear	Aerial Photography Satellite multispectral Airborne multi and	

Indicator ***Surrogate***	**Spatial Scale** **Extent**	 **Min.Map Unit**	**Temporal Scale** **Frequency**	 **Time of Year**	**Remotely Sensed Variable**	**Remote Sensing Information Source**	**Example applications**
					infrastructure) Vegetation Index	hyperspectral Airborne multi and hyperspectral	
					Structure/biomass estimation	Airborne multi and hyperspectral	
Extent of burnt area by spatial unit and assemblage (within Webb-Tracy Communities and landcover types)	Region (Requested) (10,000km^2)	1ha	Annual eg by June for December delivery or event driven (WTMA)		Landcover Vegetation indices	Satellite multispectral Satellite radar	Belward, 1994; Christopher, 1998; Cochrane, 1999;; Fang, 1998; Frederiksen, 1990; Holdsworth, 1997; Kasischke, 1994; Kaufman, 1998; Konig, 1996; Lambin, 1997; Leong, 1998; Leue, 1998; Malingreau, 1990; Malingreau, 1994; Pereira, 1993; Rauste, 1997; Riggan, 1993; Setzer, 1994; Siegert, 2000; Thompson, 1993; Tiwari, 1996; Tseng, 1999.
	Province (1000km^2)	< 1ha	Not specified		Landcover Vegetation indices	Satellite multispectral Satellite radar	
	Local (100km^2)	100 m^2	Not specified		Landcover Vegetation indices	Aerial Photography Satellite multispectral Airborne multi and hyperspectral	
Extent of introduced environmental weed species by spatial unit and native plant assemblage	Region (Requested) (10,000km^2)	<1ha	Annual eg by June for December delivery or event driven (WTMA)		Vegetation type (land cover)	Satellite multispectral Satellite radar	Foody, 1996; Foody, 1997; Li, 1997; Lucas, 1998; Luckman, 1997; Misra, 1998; Rignot, 1994; Ruimy, 1994; Simard, 1998.
	Province (1000km^2)	< 1ha	Not specified		Vegetation type - (land cover)	Satellite multispectral Satellite radar	
	Local (100km^2)	< 100 m^2	Not specified		Vegetation type (land cover)	Aerial Photography Satellite multispectral Airborne multi and hyperspectral	
Erosion features (exposed soil)	Region (Requested) (10,000km^2)	1ha	Annual eg by June for December delivery or event driven (WTMA)		Land-cover – exposed soil Soil indices Vegetation Indices	Satellite multispectral Satellite radar	Bannari,; Foody, 1996; Fuller, 1998; Henebry, 1996; Huete, 1997; Iverson Louis, 1993; Kasischke Eric, 1997; Kramer, 1997; Krug, 1995; Gregoire, 1990; Lal, 1993; Lambin, 1995; Milne, 1997; Oza, 1996; Pope, 1994;
	Province		Not specified		Land-cover –	Satellite multispectral	

Indicator ***Surrogate***	**Spatial Scale** **Extent**	 **Min.Map Unit**	**Temporal Scale** **Frequency**	 **Time of Year**	**Remotely Sensed Variable**	**Remote Sensing Information Source**	**Example applications**
	($1000km^2$)	< 1ha	Not specified		exposed soil Soil indices Vegetation Indices	Satellite radar	Raich, 1991; Rey Benayas Jose, 1995; Shimabukuro, 1998; Singhroy, 1998; Tiwari, 1996.
	Local ($100km^2$)	100 m^2			Land-cover – exposed soil Soil indices Vegetation Indices	Aerial Photography Satellite multispectral Airborne multi and hyperspectral	
Changes to drainage pattern (dams, stream geometry)	Region (Requested) ($10,000km^2$)	1ha	Annual eg by June for December delivery or event driven (WTMA)		Land cover – water bodies	Satellite multispectral Satellite radar	As above
	Province ($1000km^2$)	< 1ha	Not specified		Land cover – water bodies	Satellite multispectral Satellite radar	
	Local ($100km^2$)	100 m^2	Not specified		Land cover – water bodies	Aerial Photography Satellite multispectral Airborne multi and hyperspectral	

REMOTELY SENSED DATA SOURCES AND PROCESSING APPROACHES

To provide a basis for evaluating the suitability of various forms of remotely sensed data and their associated processing techniques to environmental monitoring in the Wet Tropics, the following section defines:

- the type of remotely sensed data sets available, and
- the information able to be extracted from a range of common processing techniques.

In 1999 as part of the National Wetland Inventory for Australia a project was completed to review the types of remotely sensed data and processing techniques applicable to remote wetlands monitoring in Australia. The brief for that project is almost identical to the WTMA project brief, the only exception being the different applications environments.

The following section of text has been taken directly from the wetlands report (Phinn, S.R. , Hess, L. and Finlayson, C.M. (1999) "An assessment of the usefulness of remote sensing for wetland inventory and monitoring in Australia." In: Finlayson, C.M and Speirs, A.G. (eds.) Techniques for enhanced wetland inventory and modelling, Supervising Scientist Report 147, Supervising Scientist, Canberra, 44-83.) and has been updated and modified to match the needs of assessing remote sensing requirements in tropical forest environments.

A comprehensive listing of past and current remote sensing data types is included in the assessment, from field based radiometers and laser ranging systems, to aerial photographs, airborne multi/hyperspectral sensors, satellite multispectral and satellite synthetic aperture radar (SAR). The most significant change is the addition of Table 4 which provides a detailed review of the currently available sources of remotely sensed data. A key element of Table 4 is the specification for each image data type of information that enabled us to determine its suitability for addressing the SoWT Environmental indicators. This included the area covered by each image, the smallest feature detectable, the number of spectral bands, the repeat frequency of image acquisition and restrictions on data acquisition (e.g. cloud). Most importantly, the costs of these data sets and supplier information are also supplied. The processing methods discussed have also been revised from Phinn et al. (1999) to focus on tropical forest applications. Organisation of the review of the techniques was based on the type of output information they produced, starting with manual interpretation approaches, field based radiometry, spectral-mixture analysis, image classification, landscape pattern analysis and development of models (to estimate biophysical properties).

DATA SETS

Aerial Photography

Camera systems used for acquiring photographs of tropical forest and wetland environments range from standard 35 mm and metric cameras to large format and panoramic cameras. Differences between these systems affect the field of view and geometric integrity of photos. Further variations in photographic data depends on the altitude at which photos are acquired and the type of film and filters. Lower altitude photographs provide greater spatial resolution, down to scales of 1: 1000 (eg 0.235 km and 0.05 km^2) for examining individual stands or trees, and can extend to 1:50 000 high altitude photographs, that provide regional coverage (eg 11.75 km by 11.75 km, 138 km^2). Different film types add a spectral dimension, enabling panchromatic (black and white) or colour photos of visible wavelengths, and black and white near-infrared and colour infrared (green, red and NIR). Photographic prints or transparencies may be scanned (at a suitable resolution, eg 200 microns) to produce digital format images, able to be geometrically corrected and subjected to image processing operations.

Digital multi-spectral cameras are now commercially available and being used extensively for airborne imaging operations in the Australia, United States and Europe (Stow *et al.* 1996). If processed appropriately these systems have the geometric integrity of aerial photographs and the spectral and radiometric capabilities of multi-spectral image data. Their main advantage in the context of tropical forest and wetlands applications is that they have all the characteristics of analogue aerial photographs, but are already in digital format. In addition, digital camera images may be subject to radiometric processing operations commonly limited to digital satellite data. Image data can be acquired by these systems for GRE dimensions down to 0.5 m up to 5.0 m. Individual frames can be processed to provide a seamless mosaic for an area.

The main purpose of camera systems has been to collect analogue data for use in manual interpretation work that may later be digitised as a vector coverage or scanned in as raster. Such operations provide a basis for discriminating different surface cover types, vegetation communities or landforms, mapping structural classes and disturbance features, based on established interpretation cues at specific scales.

There has been limited systematic consideration of the potential role(s) that the next generation of high spatial resolution satellites and digital camera systems would perform in a monitoring tropical environments. Aerial photography is: time consuming to process; insensitive to structural and sub-canopy properties; has limited application for quantitative estimates of biophysical properties or their change over time; and is not considered cost effective for a regional scale inventory and monitoring (Dobson *et al.* 1995, Wilen & Bates 1995, Taylor *et al.* 1995, Stow *et al.* 1996). Tropical forests and wetlands and their internal composition are best detected through reflectance features in the infra-red portion of the spectrum according to the Federal Geographic Data Committee (1992) and Gross *et al.* (1990) and in combination with microwave images to provide data on structural and sub-canopy elements (Hess & Melack 1994, 1995). With the spatial resolution of new satellite sensors approaching resolution used in aerial photography, consideration could be given to a hierarchical approach, in inventory and classification, utilising coarse scale data at the broadest level and moving down to finer scale digital data, and analog if required (Blackman *et al.* 1995, Dobson *et al.* 1995, Taylor *et al.* 1995).

Hand-Held Instruments (radiometers and spectrometers)

A radiometer is any instrument recording the strength of electromagnetic radiation incident upon its collection optics. “Radiometer” normally refers to broad-band radiometer, which can be fitted with various interference or absorption filters to determine the wavelengths of light incident on the sensor. “Spectral radiometers” or “spectrometers” are narrow band radiometers, recording the strength of reflected EMR from 10 to 256 narrow bandwidths. If the response of a sensor can be calibrated to a known source of EMR at different levels, output can be produced in spectral radiance and reflectance for targets.

Radiometers are used to acquire information on the spectral reflectance characteristics (radiance or reflectance) of surface cover types in the field or in the laboratory (Curtiss & Goetz 1994). This enables acquisition of spectral reflectance information under controlled atmospheric and surface conditions. By controlling acquisition parameters, several important advantages are gained:

⥣ atmospheric interference effects are minimised and/or can be measured
⥣ data can be from different view angles
⥣ the structural, condition and biophysical characteristics of surface cover type can be collected at same time as spectral information
⥣ data can be acquired from pure or mixed cover types
⥣ repeated visits to same site in the field over time
⥣ laboratory measurements can be used with precise control on illumination and other factors
⥣ use to acquire data coincident with airborne or spaceborne imaging of a site.

For the purposes of monitoring tropical environments these data provide a basis for determining spectral reflectance characteristics of different surface cover types and factors that control variation in these characteristics (Gross *et al.* 1989, Phinn & Stow 1996b). Specifically, collecting ground radiometric data enables control of the surface cover structural, condition and biophysical characteristics and its spectral reflectance characteristics can be established. This provides an initial assessment of the utility of remotely sensed data to discriminate between vegetation cover types and to estimate biophysical properties of these environments (Ustin *et al.* 1993).

Hand-held radiometer and spectrometer data also provide information necessary to fine- tune remotely sensed investigations of tropical environments. By measuring atmospheric conditions at the time of data acquisition the effect of varying amounts of cloud cover, water vapour and illumination geometry on the spectral reflectance characteristics of different surface cover types can be established. Acquiring spectra at different viewing angles enables the effect of off-NADIR views and interaction with illumination geometry and surface cover type to be established. Acquiring reflectance spectra from pure and mixed cover types provides a basis to test the spectral band(s) in which they exhibit significant differences. Repeated visits to the same site in the field over a day or growing season may help to determine the time to best acquire image data to maximise the potential for discriminating different cover types or estimating a biophysical property. Finally, by acquiring radiometer or spectrometer data coincident with airborne or spaceborne imaging of a site, ground data provide a basis for atmospheric correction and calibration of image data.

Hand-held radiometry and spectrometry is a fully operational activity, with several different types of radiometers and spectrometers being made commercially (eg Curtiss & Goetz 1994). Specific applications have focussed on the applications outlined above, mainly for individual plant to patch scales, 1m^2-100's m^2. Disadvantages associated with this approach pertain to the small area covered on the ground and the ability to scale measurements made at this scale to minimum sample units in satellite imaging systems.

Airborne Imaging Sensors – Optical/Passive (relying on reflected sunlight)

Airborne platforms including piloted aircraft, remotely piloted vehicles, helicopters and balloons contain a scanning or framing sensor, capable of acquiring images with GRE between 0.5 m and 30 m, over areas 1 km^2-100's km^2, in a limited number of spectral bands. A scanning sensor utilises a laterally oscillating field of view (FOV) to provide across flight line coverage and platform movement provides along flight path movement. Multi-spectral capability is provided by different sensor elements for each pixel. In framing sensors an array of CCD's instantaneously acquires an image line and is displaced to the next line by movement along a flight path.

Multi-spectral scanners provide high to medium spatial resolution multi-spectral image data in visible, short wavelength IR and TIR bands. Image data are processed using ground information and laboratory tests to produce radiance and reflectance images. With geometric and radiometric processing these data may be joined together to produce image mosaics for larger areas then subject to image processing algorithms to delineate cover types or examined in other ways to estimate biophysical and biogeochemical properties (eg macrophyte production in Jensen *et al.* 1986 and projective foliage cover in Phinn *et al.* 1997).

A similar set of criticisms may be established for airborne scanner systems, as were identified for aerial photography. Specifically, the spatial resolution and multi-spectral data able to be achieved by these sensors will soon be available from the next generation of commercial small satellites. In addition, the new satellites will provide much larger area coverage, and permit construction of regional to national scale mosaics. Advantages of airborne scanner data for tropical forest environment applications include: scale specificity for smaller area applications; an ability to obtain data when requested and when suitable atmospheric (cloud or smoke) conditions become available; minimal atmospheric interference; data acquisition under cloud, and a capability for calibration to ground data reference data as a basis for scaling between plant/patch/ community/regional scales and multi-temporal analyses.

Due to the reliance of these sensors on reflected sunlight limitations to their applications are caused by cloud cover, atmospheric moisture and haze. Data acquisition may be restricted for forests in areas subjected to continual cloud cover or fog during specific times of the year. This may be offset by their ability to be mobilised for image acquisition at short notice. Inherent problems with the scanning geometry and "hotspot" effects limits the geometric and radiometric utility of these sensors for producing mosaics of larger sites. Due to the nature of reflectance from wetland vegetation types, these sensors portray canopy structure, chemical and moisture content and provide limited ability to penetrate the canopy to establish volumetric information or sub-canopy information.

Satellite Imaging Sensors - Optical /Passive (relying on reflected sunlight)

Digital multi-spectral imaging systems on polar orbiting satellite platforms provide regional to global scale coverage at repeat cycles from twice daily to approximately once monthly. These sensors (eg Landsat multispectral scanner [MSS] and Thematic Mapper [TM], SPOT-MSS and Indian Resource Satellite [IRS]-1C) deliver medium (10-30 m) to coarse (30-80 m) spatial resolution multi-spectral image data in visible, short wavelength IR and thermal IR bands. Image data are processed using ground information, satellite ephemeral data and atmospheric conditions to correct for geometric and atmospheric distortions to the spatial and radiometric integrity of the data. As with airborne multi-spectral sensors these data are then subject to image processing algorithms to delineate cover types or examined in other ways to estimate biophysical and biogeochemical properties.

Dominant controls on the type of information able to be extracted from satellite images is dependent on their GRE and the type of classification selected. Spatial resolution refers to minimum dimensions of the sensor's sampling element on the ground, ie the area from which reflected or emitted EMR is measured, referred to as GRE or pixel dimensions. Interaction with landscape features determines smallest feature visible on an image. Trial applications of these sensors for mapping internal composition and biophysical properties of tropical environments (eg Johnston & Barson 1993, Blackman *et al.* 1995, Dobson *et al.* 1995, Mertes *et al.* 1995) indicates that they may only be useful for regional overview and delineation, but not for mapping species composition unless used in association with aerial photography or ground calibration (Federal Geographic Data Committee 1992, Taylor *et al.* 1995). Refer to Appendix ?? for details on applications of satellite multi-spectral data to tropical forest monitoring.

The "next generation" of commercial resource monitoring satellites should be given serious consideration as potential sets for monitoring tropical environments because of their high spatial resolution (GRE <= 15m), large area coverage, multi- to hyper-spectral configuration, radiometric precision, availability and cost. Sensors to be launched from August 1997 and into 1998 include the Lewis hyperspectral instrument, Earthwatch Earlybird, Space Imaging Systems and Orbview. With the exception of Lewis these sensors are part of commercial groups designed to provide high quality image data for environmental monitoring applications on a global scale. Of particular concern is that these sensors will provide image data down to the scales able to be obtained from aerial photography. The high spatial resolution satellite data may still not be able to separate vegetation communities with similar spectral responses, but delimiting smaller patches and structures will be possible. These sensors may provide aerial photographic scales and temporal resolution with satellite multi-spectral and large area coverage, enabling smaller features to be detected (< 1 ha) and their internal composition to be estimated. Test data sets for these sensors have been generated from multispectral digital camera systems and applied in several wetland environments (over much smaller areas than a typical satellite scene). Successful geometric and radiometric calibration of these data sets demonstrated their utility for mapping cover types within them and estimating their biophysical properties (Phinn and Stow 1996a, 1996b, Jupp *et al.* 1986).

Hyperspectral Imaging Sensors - Optical /Passive (relying on reflected sunlight)

Imaging spectrometer systems are currently carried on aircraft and will soon (as of late 2000) be carried on satellites. These systems operate in the same mode as optical sensors discussed in the previous sections, but collect reflected and emitted EMR in at least 20 narrow spectral bandwidths.

The large number of spectral bandwidths enables a complete spectral signature to be established for each pixel element within an image. Hence, detailed analyses can be conducted on the atmospheric column constituents of each pixel, surface composition and surface biogeochemical elements (Goetz 1992, Vane 1993, Curtiss & Goetz 1994). Data sets from imaging spectrometers occupy much larger volumes, as image cubes, ie instead of having 4-8 spectral bands per pixel there may be up to 240 spectral bands. Geometric distortions are similar to other scanning and solid state sensor systems, and may be corrected from aircraft/satellite ephemeral data and GCPs. Radiometrically, image values may be converted to sensor and to surface radiance and reflectance using modelled atmospheric parameters (to extract interference absorption/scattering, eg MODTRAN) (Vane 1993). Due to the increased data dimensionality, different image processing and analysis procedures have been applied to hyper-spectral data sets (c/f. multi-spectral). The most commonly applied algorithms are for spectral-unmixing, to provide information on the type(s) of feature present at surface and its fractional cover of each element within each pixel (Roberts *et al.* 1993, Adams *et al.* 1995).

Operational monitoring applications in tropical environments are not common for hyperspectral imaging sensors due to their limited availability and coverage of existing data sets. The majority of hyperspectral data Australia have been collected from the NASA-AVIRIS (airborne visible and infra-red imaging spectrometer) sensor, Hyvista Corporation 'HYMAP' and the Itres Inc. *casi* (compact airborne spectrographic imager). The AVIRIS sensor is limited to pre-scheduled flights, mainly in the continental USA, and typically acquires images with 20 m GRE. The *casi* sensor provides images with pixels 0.5 m and up to 10 m, but only for narrow width images, but has been used in a variety of environments (MacCleod *et al.* 1995, Held *et al.* 1998, Green *et al.* 1997, Zhang *et al.* 1997). The Hymap sensor collects hyperspectral image data also in the short-wave infra-red (1000 – 2500 nm) spectral range. With the anticipated launch of the Hyperion, Obview-4, MERIS and ARIES satellites and their high spectral resolution imaging sensors projected for 2000-2001, multi-temporal hyperspectral data will be available over more geographic areas and more readily. Due to the anticipated increase in data volumes and processing requirements of hyperspectral data, further assessment is required to determine their suitability to operational monitoring in tropical environments (a current focus of Project 1.2 in the Rainforest CRC).

Airborne and Satellite Radar – Active (does not require sunlight)

Synthetic aperture radars (SARs) are active sensors operating in the microwave region (roughly 1 mm to 1 m in wavelength). Unlike passive sensors which measure radiation from natural sources such as reflected sunlight, SARs both transmit and receive pulses of specific wavelength and polarization; they thus operate independently of solar illumination. Operating at much longer wavelengths than optical sensors, imaging radars can penetrate clouds and smoke and are sensitive to structural elements of vegetation canopies such as leaves, branches, and boles. They are particularly well suited to monitoring tropical environments because of their ability to operate in cloudy or smokey environments . The following sections will briefly review SAR data sources, microwave scattering mechanisms, and results of SAR studies in Australia and elsewhere.

SAR system characteristics

SAR instruments operate from both airborne and spaceborne platforms and are characterized by their band and polarization (Table 4). Satellite SAR sensors are currently limited to single-frequency, single-polarization systems, either C-band (5.6 cm) or L-band (23.5 cm); airborne systems also operate at X-band (3 cm) and P-band (65 cm). Radars transmit plane-polarized waveforms, oriented either horizontally (H) or vertically (V), and then receive one or both polarizations. The satellites listed in Table 4 all record a single polarization, either HH (horizontal send, horizontal receive) or VV. Horizontal send, vertical receive (HV) is currently available only from airborne SARs. Incidence angle refers to the imaging geometry of the radar. It is equal to the angle between the radar beam and a line perpendicular to the ground surface, and may be fixed or variable.

Table 3 Synthetic aperture radar (SAR) systems and their characteristics.
[Bands refer to wavelength: X (3 cm), C (5.6 cm), L (23.5 cm), and P (65 cm).H and V are horizontal and vertical polarizations. Nominal resolution is generally 1.5 to 2.5 times larger than pixel spacing. Asterisks denote 11-day SIR-C missions flown in April and October 1994.A planned third SIR-C mission will generate digital elevation models for most of the earth's land surfaces using interferometry. Airborne SAR systems are too numerous to list; the Jet Propulsion Lab AIRSAR is given as an example.]

Platform	**Satellite**			**Space Shuttle**		**Aircraft**
Sensor	ERS-1/2	Radarsat	JERS-1	SIR-C/X-SAR		JPL AIRSAR
Operator	Europse	Canada	Japan	USA/Germany/Italy		USA
Radar band	C	C	L	C L	X	C L P
Polarization	VV	HH	HH	HH VV HV	VV	HH VV HV
Pixel Spacing (m)	12.5	6.25-50	12.5	12.5	12.5	3-12
Swath width (km)	100	50-500	75	15-40	15-40	6-12
Repeat cycle (d)	35	1-24	44	_	_	< 1
Incidence angle	23	20-50	35	20-50	20-50	15-60
Launched	1991	1995	1992	1994		1988

After pulses transmitted by a SAR sensor are reflected, scattered, and/or absorbed at the earth's surface, the intensity and timing of the energy scattered back toward the sensor (backscattering) are received and recorded. The brightness of an object in a SAR image corresponds to its radar backscattering coefficient s×. Because of the large dynamic range of SAR systems, the unitless s× is normally expressed in decibels (s×$_{\mathrm{dB}}$ = 10 log s×$_{\mathrm{linear}}$). The signal detected by SAR is the coherent sum of signals from randomly distributed scatterers within an image pixel. Random constructive and destructive interference in the addition of these signals causes variability in s× among pixels, even for homogeneous targets. The resulting salt-and-pepper appearance, called speckle, poses problems in digital classification due to the high within-class variance of targets. Speckle is reduced during signal processing by multiple-look summing and can be further reduced during image processing by median or other filters.

Microwave interaction with water, soil, and vegetation

SAR wavelengths are very long compared to atmospheric constituents, so they are not significantly scattered or absorbed by the atmosphere as are visible and infrared wavelengths. The longer SAR wavelengths (L- and P-bands) are virtually unaffected by clouds or rain, while the shorter wavelengths can penetrate all but the densest cloud (C- and X-bands) and rain (C-band). Scattering from most earth surfaces usually involves a combination of surface scattering, where the medium encountered by the radar wave is homogeneous or nearly so (eg a water surface, and to a first approximation, a soil surface), and volume scattering, where the medium is inhomogeneous (eg a vegetation canopy). For surface scattering, the roughness of the surface determines the angular radiation pattern of the scattered wave, while the relative complex dielectric constant of the surface determines the strength of the scattered wave (Ulaby *et al.* 1981). The smoother the surface relative to the radar wavelength, the greater the coherent specular component reflected away from the radar. The rougher the surface relative to the wavelength, the greater the diffuse component backscattered to the radar.

The dielectric constant of a material is a measure of how absorptive or reflective it will be of an incident wave; for most natural surfaces, dielectric constant is a function of water content. Because of the high dielectric constant of liquid water, moist soils, for example, are more reflective than dry soils.

In volume scattering, the density and dielectric constant of scatterers within the volume, such as leaves and branches within a forest canopy, determine the scattering strength, and the angular scattering pattern is a function of the boundary surface roughness, the average dielectric constant of the medium, and the sizes of the scattering objects in the volume (Ulaby *et al.* 1981). The contrast between herbaceous and woody vegetation is greater at longer wavelengths.

Two smooth surfaces oriented perpendicular to one another, such as a paved surface and a building, constitute a corner reflector: the specular reflection from the first surface is directed back toward the radar by the second surface, causing a strong return. These double-bounce returns are the mechanism for enhanced backscattering from flooded trees or macrophytes (Richards *et al.* 1987). Specular reflections from the smooth, highly reflective water surface are bounced back toward the radar by vertically oriented trunks, branches, or stalks. Double-bounce reflections also occur in unflooded situations, but returns are much weaker because scattering off an unflooded soil surface has a much greater diffuse than specular component, and is less reflective because of its lower dielectric constant.

Trunk-ground or canopy-ground double-bounce returns can occur only when the radar penetrates the canopy to reach the ground; extinction of the radar signal by absorption and scattering within the canopy volume can prevent this if the canopy layer is sufficiently dense or deep. Longer wavelengths penetrate further into canopies than shorter ones, so L-band is more likely than C-band to penetrate a forest canopy.

NOTES FOR INTERPRETATION OF TABLE 4

Spatial resolution

The spatial scale of remotely sensed data have been categorised into:

1.	extremely fine	<5m
2.	fine	5-20m
3.	medium	20-250m
4.	coarse	250-1000m
5.	extremely coarse	>1000m

Spectral resolution

This refers to the wavelength intervals (types of light) in which data are collected. Spectral resolution controls the information which can be derived from image data.

1. high (hyperpsectral, Greater than 20 spectral bandwidths)
2. medium (multispectral, 3-20 spectral bandwidths)
3. low (panchromatic or analog images)

Radiometric resolution

Radiometric resolution defines the sensitivity or precision of the imaging sensor and is a quantitative measure of the level of variation in reflected light able to be detected by the sensor. The higher the radiometric resolution, the more detailed changes in reflected light able to be measured, i.e. smaller changes in biophysical properties (e.g. canopy cover) are able to be detected.

Temporal resolution

Pertains to the time of day image data are collected (AM or PM) and the frequency at which images are collected over a site.

1.	Extremely high -	multiple daily
2.	High -	daily
3.	Medium -	weekly
4.	Low -	< monthly, seasonally or yearly

Table 4: Listing of commercially available remotely sensed data dimensions and sources (October 2000)

OPTICAL PASSIVE						
Data Type Sensor (platform)	**Spatial Scale** **Extent (GRE)**	**Spectral Resolution**	**Radiometric Resolution**	**Temporal Resolution Frequency (Time of Day)**	**Source/Cost**	**Archive**
Field spectrometers	Field sample plots < 1m^2	High Range:350 – 2500nm #bands: > 1000	High > 10 bit (>1024 levels)	User controlled	Hire From: S.Phinn (Univ.of Qld) A.Held (CSIRO Land & Water) Purchase for AU$10k	Site specific for Rainforest CRC project from 9/1999 onwards.Contact S.Phinn (U.Q.) or A.Held (CSIRO)
Aerial photographs PAN stereo Colour stereo CIR stereo	Extremely fine to fine (local) 1:5000 – 1:25000 Extent: 1.3 – 33km^2 Per photo GRE: 5m – 250m	Low - Broad band - Visible - Colour - Green, Red, NIR	Medium Not applicable (depends on scanning device)	User controlled (subject to weather and aircraft availability)	$90 frame to fly and buy hardcopy Scanning and georeferencing are project dependent Qld Department of Natural Resources Airesearch Mapping Aerometrics Wet Tropics Management Authority Environmental Protection Agency - Coastal Management	Contact companies or agencies to determine (at least annual from 1970)

Data Type Sensor (platform)	Spatial Scale Extent (GRE)	Spectral Resolution	Radiometric Resolution	Temporal Resolution Frequency (Time of Day)	Source/Cost	Archive
Airborne multi-spectral Specterra DMSV Daedalus-1268 ADAR	Extremely fine to fine (local) Extent: 100km^2 GRE: 0.5 – 3.0m	Medium Range:350 – 2500nm #bands: 3 - 20	Medium 8 bit (256 levels)	User controlled (subject to weather and aircraft availability)	Contact companies for quotes (approx $2- $6/km^2 for georeferenced image): Specterra Systems AirTarget Services	Contact companies for details. ADAR data held by Univ.of Qld for 7/2000 for Cairns, Skyraiul and Daintree-Cape Tribulation area.
Airborne Hyperspectral CASI Hymap	Extremely fine to fine (local) Extent: 100km^2 GRE: 0.5 – 10m	High Range:400 – 2500nm #bands: > 20	High > 12 bit (4096 levels)	User controlled (subject to weather and aircraft availability)	Contact companies for quotes (approx > $20/km^2 for georeferenced image): Ball AIMS (CASI) Hyvista Corporation	Contact companies for details. CASI and HYMAP data held by A.Held CSIRO for 9/1999 and 7/2000 for Cairns, Skyrail and Daintree-Cape Tribulation area.
Satellite multispectral						
Ikonos Quickbird	Extremely fine (local) Extent: 10 - 20km GRE: 1m (pan)or 4m(multi)	Medium Range:400 – 1000nm #bands: 3	Medium 8 bit (256 levels)	AM 3 days - pointable	Geoimage US$29/km^2 for georeferenced image	Collected since, no archive for CRC
Landsat ETM Landsat TM	Medium (Province – Region)	Medium Range:400 – 2500nm	Medium 8 bit (256 levels)	AM 16 days	Geoimage or ACRES $1950 for geocoded	CRC Rainforest has an archive of

Data Type Sensor (platform)	Spatial Scale Extent (GRE)	Spectral Resolution	Radiometric Resolution	Temporal Resolution Frequency (Time of Day)	Source/Cost	Archive
SPOT XS IRS	Extent: 34225 km^2 Or 185 x 185km GRE: 15-30m	10μm – 12.5μm #bands: 4 - 7		AM 16 days AM 26 days - pointable AM 24 days	full scene (200km)	MSS 1972, TM 1988, 1994, 1999 and 2000. Contact S.Phinn, A.Held or D.Hilbert.
SPOT VMI NOAA AVHRR	Coarse (Region) Extent: 2500km wide GRE: 1km	Medium Range: 400 – 2500nm 10μm – 12.5μm #bands: 4	High 10 bit (1024 levels)	AM 2 days AM + PM twice daily	Department of Natural Resources JCU (W.Skirving) CSIRO Marine – Hobart Environ. Australia (AVHRR cost ?)	Collected since 1969, no archive for CRC.
SeaWifs (Orbview2 Or SEASTAR)	Coarse (Region) Extent: 2200km wide GRE: 1km	Medium Range: 400 – 885nm #bands: 8	High 10 bit (1024 levels)	AM 1 day	Same sources as AVHRR	Collected since 8/1997, no archive for CRC..
Satellite hyperspectral						
MODIS (EOS-AM)	Coarse (Region) Extent: 2048km wide GRE: 250, 500, 1000m	High Range: 400 – 2500nm 10μm – 12.5μm #bands: 36	High 10 bit (1024 levels)	AM - 2 days	EOS Data Information System eos.nasa.gov/eosdis	Collected since 1/2000, no archive for CRC.
Hyperion	Medium (Province) Extent: 7.5 x 100km GRE: 30m	High Range: 400 – 2500nm #bands: 220	High 10 bit (1024 levels)	AM – 16 days (follows ETM)	EOS Data Information System eos.nasa.gov/eosdis	No archive

ACTIVE LASER						
Data Type **Sensor (platform)**	**Spatial Scale** **Extent (GRE)**	**Spectral Resolution**	**Radiometric Resolution**	**Temporal Resolution Frequency (Time of Day)**	**Source/Cost**	**Archive**
Field laser ranging	Field sample plots $< 1m^2$, individual trees.	Not applicable	Not applicable	Not Applicable	Hire from Univ. of Queenland, Queensland Dept.of Natural Resources ABC Lasers - Brisbane $5500 per laser	Archive from 9/2000 field trip for Cape Tribulation, Skyrail and Curtain Fig sites.
Airborne laser altimeters AAM surveys Optech ALTM 1210 - Profiling laser Enerquest Systems - Scannning laser	Extremely fine to fine (local) Extent: $100km^2$ Sampling intensity: 5000 – 10000 pulses per second. 2- 10 samples per $1m^2$	Not applicable	Not applicable	User controlled (subject to weather and aircraft availability)	Rotor Resources $12.50ha for georefernced DEM + aircraft mobilization ex-Brisbane South-West Pacific Helicopters	No archive.

ACTIVE SAR						
Data Type Sensor (platform)	**Spatial Scale** **Extent (GRE)**	**Spectral Resolution**	**Radiometric Resolution**	**Temporal Resolution Frequency (Time of Day)**	**Source/Cost**	**Archive**
Airborne SAR						
NASA - AirSAR	Medium (Province) Extent: 12 x 120km GRE: 10m	Medium C band (5cm) L band (24cm) P band (60cm)	Not applicable	Restricted to research missions November 1996 September 2000 To be announced 2002	NASA JPL http://airsar.jpl.nasa.gov/ No costs Or S.Phinn (UnivQld) and A.Held (CSIRO Land & Water)	Archive from 11/1996 of Daintree Estuary and 9/2000 Daintree – Cooktown at CSIRO land & Water
Satellite SAR						
Radarsat	Medium (Province Region) Extent: 100x100km GRE: 30m	Low C band (5cm)	Not applicable	AM 3~5 days	Geoimage or ACRES US$3500 for georeferenced 100k x 100km scene	Collected since 1995, no CRC archive.
ERS-1/2	Medium (Province Region) Extent: 100x100km GRE: 10 - 30m	Low C band (5cm)		AM - 35 days	$2200 for georeferenced single scene	Collected since 1995, no CRC archive.
JERS 1	Medium (Province Region) Extent: 75x100km GRE: 18m	Low L band (24cm)		AM – 44 days Ceased operation in 2000	$1500 for georeferenced single scene	Collected 1992 – 1998, no CRC archive.
ASAR (ENVISAT)	Medium (Province) Extent: 100x100km GRE: 150m	Low L band (24cm)		AM - 3 ~5 days	Not available	

PROCESSING TECHNIQUES

Processing remotely sensed data to extract data or information relevant to defining the extent of tropical forests and wetlands, mapping their internal composition or estimating biophysical properties requires application of the appropriate technique and considerations of their input requirements and limitations. The following sections provide an overview of the range of techniques that have been successfully applied to remotely sensed data to produce information for micro to global scales for environmental monitoring. These techniques may also be applied in a multi-temporal context to detect change or map dynamic properties, and requirements are discussed for implementing them as such.

Manual Interpretation and Digitising

Visual interpretation of aerial photographs has been the most frequently applied methodology for delimiting tropical forests and wetlands and mapping their internal composition over a wide range of spatial scales and types of environments (Gross *et al.* 1989, Green *et al.* 1996, Lucas et al. 2000, Phinn et al. 2000). Pre-defined vegetation classification schemes are used to provide a basis for a series of interpretation keys, usually only applicable to a set range of wetland types, and specific scales and types (eg colour or infra-red) photographs (Cowardin & Golet 1995, Blackman *et al.* 1992). At large scales, ie, areas of limited spatial extent, aerial photographs still provide optimal data sets for establishing topographic and vegetative boundaries, as well as their internal composition, often down to a species level (Federal Geographic Data Committee 1992). Specific scales of photographs may be selected from existing coverages generated by Federal, State and Local agencies, corresponding to appropriate levels within a hierarchically structured classification system (eg Blackman *et al.* 1992, Scott & Jones 1995, Paijmans *et al.* 1985).

Interpretation practices vary depending on the type of film used for interpretation, with infrared, colour and colour-infrared being the most successfully applied from 1:100 to 1:50,000 scales. Two types of interpretation procedures are commonly followed. In the first, standard photographs (23.5 cm x 23.5 cm) or enlargements are analysed by trained interpreters using a pre-defined classification scheme (and field notes), polygons delimiting relevant classes of cover are traced onto mylar film, prior to digitising into a GIS for final map composition. The second approach, utilises aerial photographs that have been scanned into digital format (at high spatial resolution, eg, 300 um). By displaying the scanned photographs using image processing or GIS software, polygon boundaries can be digitised directly from the photograph (heads up digitising). This approach still uses an interpretation key, but also enables the scanned photographs to be subject to correction processes to remove geometric distortions inherent in aerial photographs and to construct mosaics for the area of interest (Jensen 1996).

Limitations of aerial photography for mapping and monitoring in tropical environments concern the cost of extensive photo-acquisition runs, the time required and errors introduced in manual delimitation, and problems of normalising photos from different dates (removing variations in solar geometry and intensity) to quantify changes in forest or wetland extent, composition or biophysical properties (Johnston & Barson 1993, Jensen 1996, Stow *et al.* 1996, Green *et al.* 1996). Manual delineation and interpretation of high spatial resolution digital camera data and next generation satellite data, may provide information equivalent to that for 1:5000 photographs for digital cameras (0.5 m pixels) and 1:125 000 photographs for high spatial resolution satellites. These data sets can also be obtained for extensive areas in georeferenced mosaics, may be resampled to larger pixel sizes, and are capable of radiometric calibration for estimating biophysical properties and their changes over time (Haines-Young *et al.* 1993, Kramer 1994).

Hand Held Spectrometry & Radiometry

Processing techniques applied to radiometer and spectrometer data sets provide information on the spectral reflectance characteristics (radiance or reflectance) of surface cover types in the field or in the laboratory (Asrar 1989). Most successful applications to tropical forest and wetland environments have been based on hand-held measurements made in on the ground (or canopy) and observations from light planes. In both cases plot level results provided relationships capable of “”scaling-up” to larger pixels of satellite sensors, hence testing the types of vegetation and cover types able to be spectrally discriminated or estimate biophysical properties for (Gross *et al.* 1989, Jensen 1996, Phinn *et al.* 1996b, Zhang *et al.*. 1997). In relation to monitoring forest environments several specific questions can be addressed:

⥣ The control of the surface cover type’s structural, condition and biophysical characteristics on its spectral reflectance characteristics can be established (determine spectral bands for discrimination or estimation of a biophysical parameter).

⥣ Repeated visits to same site in the field over a day or growing season may help to determine the time to best acquire image data to maximise the potential for discriminating different cover types or estimating a biophysical property.

⥣ By acquiring radiometer or spectrometer data coincident with airborne or spaceborne imaging of a site, these ground data provide a basis for atmospheric correction and calibration of image data.

Output from radiometers and spectrometers is processed with sensor gain/offset and calibration coefficients to produce spectral radiance and spectral reflectance from calibration panels. Useful information may then be extracted for radiometer data from graphical plots of signatures for cover type, accumulated statistics for multiple measurements to define cover type variance and statistical analysis in association with solar geometry or biophysical data. For spectrometers, extraction of information is facilitated by graphical plots of voltage, radiance or reflectance for each spectral band produces a spectral signature curve; visual comparison of spectral curves; automated curve matching routines for use with spectral libraries for discrimination of surface cover type; spectral unmixing of component signals to provide fraction of sample area occupied by each cover type, mineral or chemical composition; statistical measures of curve separability in different spectral bandwidths using analysis of variance, variance measures and derivative analysis; and statistical analysis in association with solar geometry or biophysical data

Spectral Mixture Analysis

Spectral mixture analysis (SMA) or spectral unmixing was developed to address the “mixed pixel” problem. Because the size of the ground sampling element on imaging systems is often large in relation to surface cover patches and these patches are not internally homogenous, a mixture of surface cover types produces pixel response (digital number). The goal of SMA is to apply reflectance or radiance spectra obtained from homogeneous areas of each cover type (endmember) to determine the fraction of each pixel occupied by a cover type. SMA was developed from factor analytic inversion techniques in chemistry and optics to identify independent sources of variability (Adams *et al.* 1995). Initial remote sensing applications were in semi-arid environments by Pech *et al.* (1986), Huete (1986) and in forested to wetland environments by Ustin *et al.* (1993), Adams *et al.* (1995), Mertes *et al.* (1995) and Sippel *et al.* (1992).

The principle of the SMA approach (for linear mixing) is presented on the next page.

1. Define endmembers (scene structure and number of bands)

2. Aim is to solve for the fraction of each endmember in a pixel

Fraction images provide more intuitive assessment of scene structure and applicability for mapping.

$DN_c = \Sigma^N_{i=1} F_i DN_{i,c} + E_c$

where,

$\Sigma^N_{i=1} F_i = 1$

DN_c = uncalibrated radiance in channel c of image pixel
N_i = Number of endmembers
F_i = Fraction of endmember i (parameter to solve for)
$DN_{i,c}$ = radiance/ reflectance of endmember i in band c
E_c = Residual or error for channel based on the fit of N spectral endmembers

SMA techniques have only recently been applied to tropical forest and wetland environments in a number of published research projects. Forest composition, wetlands, inundation and turbidity levels have been examined using this technique and Landsat TM data (Mertes *et al.* 1995) and microwave data (Sippel *et al.* 1992). Results from these studies demonstrate the utility of SMA for single and multi-date mapping of the fractional cover of end-members (eg vegetation species, communities, live/dead biomass, surface moisture, inundation, and turbidity levels), as well as biophysical and biogeochemical information.

Image Classification Approaches

The common goal of the following algorithms, loosely grouped as classification approaches, is to identify groups of pixels with similar spectral reflectance values and assign a label to each group as a type of landcover. That is, their end goal is to produce a thematic map of surface cover types. By compiling image maps of the same areas based on a common classification scheme, but using images collected on successive dates in time (days, weeks, months, stages in tidal/flooding or phenological cycles), maps of change and dynamics may also be produced (Graetz 1990).

Per-pixel classification routines use both parametric and non-parametric classification algorithms to evaluate whether each pixel is assigned to an image class (eg parallelipiped, minimum distance to means, maximum likelihood). Application of the routines is either by a supervised approach where the analyst identifies groups of pixels to be used as training sites, or an unsupervised approach where a data clustering routine is used to identify groups of similar pixels in spectral space. This approach is the most widely applied, simple, flexible, applicable to different data types, computationally non-intensive, and able to be fine tuned to an appropriate image data set and environment. However, its principal disadvantage relates to input data requirements (normal distributions), mixed pixel problems, mis-classification, minimum mapping unit size. Classification algorithms have provided the basis for delimiting forest and wetlands and mapping their internal composition from Landsat TM data (eg Klemas *et al.* 1993, Johnston & Barson 1993, Harris 1994, Blackman *et al.* 1995), airborne scanner data (Jensen *et al.* 1986) and digital camera data (Phinn and Stow 1996a, 1996b).

Image segmentation applies region growing routines that examine pixel digital numbers and texture values to grow segments up to specified dimensions (Woodcock & Harward 1992, Shandley *et al.* 1996). Segments are labelled using a per-pixel classification and dominance/plurality rules. This approach does require knowledge of the spatial structure of existing ground cover types, ie, typical patch size and/or hierarchy of sizes. No examples were found of forest applications for these approaches in the literature, although they may provide a useful approach to mapping forests with complex internal structures.

Each classification procedure requires multi-spectral digital image data or fraction images (produced from SMA) and varying degrees of information on the number of image classes required and their spectral variability and spatial extent. Non-remotely sensed data may also be used as input in the classification process, if it is in a conformal coordinate system and spatial resolution. For example, digital elevation and soils data have been used to improve the accuracy of wetland delineation and separation of low, middle and high marsh vegetation zones. Multi-sensor data sets, eg, optical and radar data sets may also be subjected to image classification approaches, as successfully demonstrated by Hess & Melack (1994, 1995). Output from these applications are thematic maps used as input into GIS database for multi-temporal analyses and also as the basis for further modelling, using the image data in each cover type or models that require information on the area of each cover type.

There are several essential considerations to be made before applying classification techniques to any environment. First, the size of the target vegetation and landscape elements (eg patches and communities) should be able to be defined by the image sampling element dimensions (pixel or GRE size). Definition of landscape features within an image requires the GRE to be a least 1/10th the linear dimensions of a feature. The number and placement of available spectral bands should be sufficient to detect differences between target land cover types. Finally, is it possible to produce a map of the required covered types within acceptable error levels, taking into account the nature of the landscape and the number of image classes required.

Multi-temporal analyses of changes in extent, composition or biophysical properties of tropical forest and wetland environments may be achieved by several modified classification approaches. Direct differencing of radiometrically normalised images acquired at two dates for the same area can be used to produce a difference image (Jensen 1996). A classification approach may then be applied to group areas with similar changes and assign them labels. The most commonly applied approach, based on images subject to the same classification systems, is post classification comparison (Jensen *et al.* 1993, Jensen 1996). Other approaches based on multi-temporal classification work that have been successful include examining trajectories to produce maps of landscape dynamics (Graetz 1990).

Landscape Pattern Analysis and Spatial Statistics

Applying landscape pattern analyses and spatial statistics can yield quantitative information on the spatial structure of the landscape (ie its configuration) from either an unprocessed multi-spectral image or from an image map of cover types (Turner & Gardner 1991, Rossi *et al.* 1992). To define the size, shape, adjacency, frequency and connectivity of different landscape elements. Algorithms in this area can be broken into two groups, those that define dimensions of landscape elements based on image data (spatial structure functions) and those that define dimensions and patterns based on raster or vector based digital maps raster (pattern metrics).

Algorithms grouped under spatial structure functions include spatial statistics such as semi-variance, scale-variance and power spectrum analyses. Scale variance analyses establish the total variance at increasing block (pixel window) sizes and presents the results on a plot of variance versus block size. This enables the effects of varying GRE size to be established in terms of the pixel size or feature size at which most variation occurs on average in the landscape (Woodcock & Strahler 1987). Semi-variance analysis is based on regionalized variable theory and examines variance levels between pixels separated at increasing distances to determine at what distances these values are similar or dis-similar. Output from semi-variance analysis at each distance interval (lag) is plotted on a semi-variogram. Like scale variance analysis, this approach facilitates an assessment of the dominant scales of spatial variation, ie feature dimensions, in a landscape (Curran 1988, Woodcock *et al.* 1988). Output from power spectrum analyses can be used to identify scale(s) of repeated patterns in the landscape. In these approaches two dimensional Fourier transforms are applied to decompose data by spatial frequency, rather than just dominant patterns or structure (Smith *et al.* 1988).

Pattern metrics have been developed in landscape ecological applications to provide quantification of landscape structure dimensions, particularly the dimensions of patches of individual cover types and their arrangement in the landscape and in relation to each other (Turner & Gardner 1991, Turner *et al.* 1991, McGarigal & Marks 1994). Examples of patch dimensions, commonly calculated for individual patches of a specific cover type include: area (mean and variance), core area; perimeter; shape (perimeter:area, fractal dimension); density; edge; and diversity (compositional variation within patches). Spatial statical functions provide the basis for measures of pattern, including contagion, interspersion (scale of aggregation/dispersion) and clustering. A review by Riitters *et al.* (1995) of 55 different landscape metrics applied to 85 USGS air-photo interpreted land use maps established redundancy between many indices. Up to 87% of the variance in land-use pattern was able to be accounted for by the following six metrics: average perimeter-area ratio; contagion; standard patch shape; patch perimeter area scaling; number of attribute classes; and patch density area scaling.

To date there have only been several published results of landscape structure analyses in tropical forest and wetland environments based on spatial statistics and pattern metrics (Mertes *et al.* 1995, Phinn and Stow 1996b). Spatial statistics and pattern metrics have been applied extensively in non-wetland environments (Turner & Gardner 1991, Haines-Young & Chopping 1996) and warrant consideration for providing quantitative dimensions of landscape pattern in forests. However, attention should be paid to the limitations of these approaches before applying them. Specifically, statistical assumptions for their application and significance testing (stationarity, sinusoidal variation, gridded data, regular periodicities) and the fact that many of the measures of spatial association were not developed for data dense and contiguous data sets (eg remotely sensed images). Results will also be dependent on how classification units were derived and the scale at which analyses are conducted.

Implementation – Overview (brief)

Spatial statistics allow the quantification of the spatial structure from sampled data, while landscape metrics characterise the geometric and spatial properties of mapped data(e.g. mosaic of patches). They describe the degree of spatial autocorrelation of the values of a variable that has been sampled at various geographical coordinates. The quantitative knowledge about the spatial structure of the data can then be used to group samples into relatively (spatially) homogeneous clusters of patches. Field data may be classified into a mosaic of patches so quantitative-numerical data are transformed into qualitative-categorical maps. The new characteristics of these maps are then measured using landscape metrics, which quantify the properties of the patches (e.g. area, perimeter, shape etc.) and the spatial arrangement and diversity over the landscape. These qualitative data may also be analysed using spatial statistics.

Some technologies are available to define the optimal scale for the assessment of landscape patterns based on statistical methods. However, if the most appropriate methods are to be used, some preliminary information on the patterning of landscapes is needed. Remotely sensed data provide the necessary coverage to define the basic pattern within landscapes, and therefore to help with the choice of the best analytical method (Innes, 1998).

Some available packages standalone other ‘add-on’ to GIS packages such as ArcInfo/Arcview, also, there is always the option of exporting the spatial data from vector to a dedicated statistics package such as SPSS, Statistica or SAS. The more common packages are: Fragstats*ARC; Fragstats; LEAP II; Patch Analyst; Utools (watershed analysis); Apack; SPAN; PATN. These software packages generate an array of metrics (see Table 5), including a variety of area metrics, patch density, size and variability metrics, edge metrics, shape metrics, core area metrics, diversity metrics, and contagion and interspersion metrics.

Area metrics: describe the extent of patches, classes or total landscape. This can be done in absolute values, as mean values or in percentages.

Patch metrics: describe the total number of patches and their relative proportion in a given area.

Edge metrics: describe the amount of occurring edges between patches or classes. This is done by perimeter calculations of each patch. These indices can give information about the spatial variance of an area. A high number of edges can indicate variable ecological conditions, which is e.g. necessary for the occurrence of specific species. Low edge frequency indicates monotonous conditions for the investigated subject.

Shape metrics: are based on perimeter-area relationships of the patches, where for instance the perimeter of a patch is compared to the perimeter of a square with the same area (raster version, vector version compares with a circle). High values indicate the occurrence of many patches with complex and convoluted shapes, while low values represent the dominance of simple geometric shapes, like rectangular shapes.

Core area metrics: core area is defined as the area within a patch beyond certain edge distance or buffer width. Core area metrics compute statistics regarding the inner central parts of patches in relation to the total patches. This metrics can give information about habitat quality for certain species. Some species might not be able to exist within narrow forests like riparian forests, even if the total area of this forest could be theoretically large enough.

Nearest-neighbour metrics: are based on the distances from patches to the nearest neighbouring patch of the same type. These indices are calculated by using the minimum distance measured as edge to edge distance from one patch to the nearest neighbouring patch of the same class type. Nearest neighbour indices quantify landscape configuration. These measures can be used for describing migration possibilities of species or species interaction of separated populations. This type of indices clearly describes the spatial configuration of landscapes and of the different land cover classes.

Diversity metrics: measures landscape composition and are function of the richness and evenness of the patch types in the landscape. Dependent on the probability of the occurrence of all cover types this is a measure indicating whether or not all cover types are more or less evenly proportioned in terms of their spatial extent. Vice versa, this index measures the extent to which one or a few class types dominate the landscape.

Contagion metrics: are calculated using the actual rate of adjacency of each occurring class type with all other class types. The resulting values express the probability of adjacency of different class types. Herewith, contagion can give an idea about the extent of aggregation or clumping of patches. High values indicate big continuous areas, while small values represent many small dissected areas. Therefore this measure can be used for describing forest fragmentation

There are a number of caveats of a landscape metrics approach. For example:

⇑ Are patches in the categorical map ecologically meaningful?
⇑ Boundaries are not sharply defined in nature
⇑ Species vary in the scale of their response to landscape structure
⇑ Many landscape configurations may produce the same metric value (Gustafson, 1992)
⇑ Metrics may confound differences in patch size/shape with differences in spatial arrangement of patches (Hargis, 1998).

Table 6 describes how WTMA might implement the use of landscape structure indices (or types of indices/categories that might be selected) and how they relate to a *general example* for monitoring landscape change.

At the class and landscape level, some of the metrics quantify landscape composition while others quantify landscape configuration. The composition and configuration can affect ecological processes independently and interactively. Clearly, a sound understanding of each metric is important to know which aspect of the landscape is being quantified.

Table 5: Landscape Structure Indices and their descriptions

INDICES	INDEX DESCRIPTION / CALCULATION
Area metrics (patch)	
Total landscape area (ha)	total area of landscape (defined as total area minus 'background')
Largest patch index	percentage of landscape accounted for by largest patch
Number of patches	no. of disjunctive patches in the landscape
Patch density (n/100 ha)	no. of patches per 100 ha
Mean patch size (ha)	average patch size
Patch size 5D (ha)	patch size standard deviation (ha; absolute variability)
Patch size CV	patch size standard deviation in terms of average patch size;
Permeability	% variation (relative) area of unsuitable patches (for transmission) divided by total area
Dominance	extent to which one few patch types dominate a landscape (from information theory)
Edge metrics	
Total edge (m)	total length of all edges; may or may not include landscape boundary
Edge density (nvha)	length of edge per hectare
Contrast-weighted ED (m/ha)	length of edge per hectare, weighted by edge contrast weights
Total edge contrast index (%)	sum of edge lengths, multiplied by contrast weight, divided by total edge x 100 sum of patch edge segments x contrast weight/total patch perimeter/no. patches x 100
Mean edge contrast index (%)	sum of (sum of patch edge segments x contrast weight/total patch perimeter x patch area/landscape area)
Area-weighted MECI (%)	% edge adjoining similar patch types
Isolation	ratio of sum of edge lengths to total area (measured against square or circle standard)
Shape metrics	
Landscape shape index	sum of patch perimeter/square root of patch area, adjusted by constant/no. of patches
Mean shape index	sum of patch perimeter/square root of patch area, adjusted by constant x patch area/total area
Area-weighted MSI	departure of landscape mosaic from Euclidean geometry (how plane-filling shape is)
2 x log fractal dimension	mean fractal dimension for all patches
Mean patch fractal dimension	mean fractal dimension adjusted for proportion of total area
Area-weighted mean patch FD	diagonal of smallest enclosing box divided by average main skeleton width
Elongation	sum of (main skeleton length/skeleton depth)/ (area x number of skeleton pieces)
Deformity	
Core area metrics	
Total core area (ha)	area of interior habitat, defined by specified edge buffer width
No. core areas (n)	no. of core areas (may be > or < than no. of patches)
Core area density (n1100 ha)	no. of core areas per 100 ha
Mean core per patch (ha)	average amount of core area per patch (ha)
Core area SD1 (ha)	standard deviation of core area per patch (ha; absolute variability)

.......Table 5 continued

........Table 5 continued

INDICES	INDEX DESCRIPTION / CALCULATION
Mean area per disjunct core (ha) c	standard deviation of core area per patch in terms of the average; % variation (relative)
Core area CV1	average core area when no. of core areas is denominator (rather than no. of patches)
Nearest Neighbour indices	
Nearest-neighbour distance (m)	average distance to nearest patch of same patch type
Proximity index	
Mean nearest-neighbour distance (m)	
Nearest-neighbour standard deviation (m)	
Nearest-neighbour coefficient of variation	standard deviation in terms of mean nearest neighbour distance
Mean proximity index	average proximity of patches to similar patches within specified distance
Diversity indices	
Shannon diversity index	richness & evenness index based in information theory
Simpson diversity index	probability that 2 patches are similar
Modified Simpson diversity index	
Patch richness (no.)	no of patch types in a landscape
Patch richness density (no./100 ha)	patches in landscape per 100 ha
Relative patch richness (%)	patch richness as % of max potential patch richness
Shannon evenness index	
Simpson evenness index	
Modified Simpson evenness index	

Deterministic and Empirical Biophysical Models

The common goal of the following approaches is to provide estimates of biophysical or biogeochemical properties over an area for output as a thematic map or as input into a dynamic model. Biophysical properties able to be estimated from remotely sensed data include: vegetation density (Gross et al. 1989); vegetation cover (Gross et al. 1989); plant basal area and height (Phinn et al. 1997); plant biomass (live, dead, above, below ground) (Ustin et al. 1993); plant productivity (Hardisky et al. 1983 a,b, Gross et al. 1989); vascular versus non-vascular plants (Roberts et al. 1993); and soil cover versus non-photosynthetic vegetation.

Complete inversion of remotely sensed data relates the measured reflectance, absorption and transmittance characteristics of the scene element to its physical dimensions or biophysical properties. For vegetation patches this may include estimating the horizontal and vertical structure of plants along with the amount of live and dead biomass present. Two approaches are used to invert the data, the first is a statistical or empirical approach whereby spectral data and corresponding physical data are collected and a mathematical form of relationship is derived using regression analysis (eg NDVI and biomass). Applications of airborne and satellite sensor data to estimate biomass in forests was provided by Lucas et al. (2000) and Gross et al. (1989). In the physical or deterministic approach an existing understanding of the physical interaction between EMR and the property of interest is used specify a model of their relationship (eg latent heat transfer). Goel (1989) and Strahler & Jupp (1991) provide detailed reviews of the components, applications and limitations of various types of geometric-optical, turbid-medium and simulation models for estimating plant structural characteristics. Franklin *et al.* (1993) applies geometric-optical models to estimate shrub canopy sizes, while Morris (1989) uses a turbid-medium model to examine light diffusion in the canopy of wetland grass.

The role of GIS in providing an environment for model development, testing, execution and display and analysis of results should also be established (Haines-Young *et al.* 1993). These roles include data storage and retrieval (graphic and database); functioning as a “repository” of knowledge, able to be continually updated; providing functional capabilities for executing models if operating on a raster cell or polygonal basis for computations (ie simple AML - C script). Specific advantages include their ability to implement spatially explicit dynamic models to examine spatial variations in model output, eg for sea-level rise, coastal subsidence and/or other ecosystem dynamics and to facilitate integration with other non-remotely sensed data sets.

To assess biophysical characteristics such as, height, density, cover, biomass and productivity, hand-held radiometers were initially used to determine spectral characteristics of vegetation and their controlling factors (Gross *et al.* 1989). Once the nature of these controls was established, empirical relationships at the scale of the radiometer footprint were established between a structural characteristic of the plant and its spectral reflectance characteristic (Drake 1976, Hardisky *et al.* 1983 a,b). Work by Hardisky established the main controls on wetland vegetation's spectral reflectance characteristics to be the amount of live and dead leaf area in the horizontal and vertical planes. Empirical relationships have been difficult to apply and obtain sound results due to complicating factors of: solar elevation; amount of live/dead plant matter; substrate type; standing water and wind stress (Bartlett *et al.* 1988). More success in providing stable estimates of biophysical parameters has come from use of deterministic approaches in canopy reflectance models for examining light decay in canopies (Morris 1989) and the leaf area and biomass in canopies (Jacquemond & Baret 1990), with limited application beyond plot scales. Although the majority of these modelling application have been in saltmarsh environments (forbs, grasses and shrubs) with passively data sets, results from radar based estimates of structural parameters in forestes suggest the range of forest environments may be monitored and modelled from remotely sensed data.

Table 6 Implementation of some landscape structure metrics using a general example

Guidelines	**Index class**	**Type of Indices**
General example landscape guidelines		
increases in forest cover overall by significant amount diverse	areal	area, core area, shape
age structure (Forest cover)	lineal / topological	interspersion / juxtaposition,
diverse physical structure (diversity)	lineal / topological	contagion, edge interspersion / juxtaposition,
diverse species composition (diversity)	lineal / topological	contagion, edge
large contiguous wooded areas (i.e. patches)	areal / topological	interspersion / juxtaposition, contagion, edge area, core shape, shape
curvy edges for edge habitat (e.g., for spp home range)	areal / lineal	contagion interspersion / juxtaposition,
non-geometric shapes inside forests (e.g., edges)	areal / lineal	edge shape, edge
some open spaces within forests (increase amenity/aesthetic value)	areal / topological	shape, edge
connectivity of patches (e.g., for spp. dispersal)	lineal / topological	area, core area, shape, contagion interspersion / juxtaposition
compact shapes (i.e, maximise interior habitat area)	areal / topological	shape, interspersion / juxtaposition, contagion, edge, connectivity, circuitry, area, core area, shape.

EVALUATION OF REMOTELY SENSED DATA AND PROCESSING APPROACHES FOR STATE OF THE WET TROPICS INDICATOR MONITORING

To arrive at a direct link between SoWT Indicators and suitable remote sensing data and processing approaches a three stage procedure was implemented. At the completion of this procedure **a clear link was established between each SoWT indicator and the remotely sensed variable it could be measured by** (Table 2). This linkage included specifications of the most appropriate remotely sensed data, image processing techniques, required personnel, hardware and software to complete the task . An estimated cost of mapping, verifying and monitoring the indicator was provided for each potentially suitable data type. A final assessment was then made for each data type and processing operation in terms of its “feasibility” for operational monitoring of select SoWT indicators.

The first stage of this process involved determining a direct link between environmental variables that could be mapped, measured and monitored from remotely sensed data and relevant SoWT environmental indicators. If an SoWT indicator could not be matched with a remotely sensed variable or surrogate it was removed from the evaluation process and considered to be in the “Impossible” category. An extensive review of past and current remote sensing applications in tropical forest environments from Phinn et al. (2000) and Lucas et al. (2001) was used as a basis for this evaluation. Example applications for each remotely sensed variable and indicator were presented in Table 2. This information was then condensed further into Table 7, where it became apparent that the information for several SoWT indicators matched up to one common remotely sensed variable. For example, processing of airborne or satellite image data sets to produce land cover maps provides the information required to assess several indicators, including land cover classes, extent of vegetation fragmentation, edge effects and extent of burnt areas. The only difference in extracting the different indicators relates to the type of land-cover classification developed and the spatial scale at which the information is required. WTMA should therefor devote specific attention to developing a suitable land-cover classification scheme (e.g. based on their broad habitat types) that could be used to address each of the indicators that are based on land cover or land cover change. Similar constraints also apply to developing mapping or monitoring approaches for the remaining remotely sensed variables (vegetation type, vegetation/soil index and structure/biomass index). Specific attention should be paid to the spatial scale(s) at which information and precise definition of the measurement approach required. Vegetation type was restricted to environmental weed species as general community type mapping was considered to be a component of land-cover mapping, and had a higher spatial resolution component

After establishing the link between remotely sensed variables and SoWT indicators, the next stage was to link “appropriate” remotely sensed data sets to each remotely sensed variable. This was achieved in Table 8 by taking all of the remotely sensed data types outlined in Table 4 and identifying the remotely sensed variable(s) they had been used to derive in an operational and test basis, and also specify the spatial and temporal scales at which these operations had been completed. By conducting this exhaustive evaluation the most “appropriate” remotely sensed data sets for deriving each type of remotely sensed variable were able to be identified.

The final stage of the evaluation process provided a complete specification of the resources required to map and monitor SoWT indicators from the most appropriate form of remotely sensed data. By combining this evaluation with reviews of previous remote sensing applications in tropical forest environments, a direct assessment of the feasibility and costs of remote sensing SoWT indicators was developed. Tables 9.1 –9.5 contain the results of the assessment process. The format of each table first specifies the relevant remotely sensed variable (land cover, land cover change, vegetation type, vegetation/soil index and structure biomass index) and its spatial and temporal dimensions.

Table 7: Listing of remotely sensed variables and the SoWT indicators they can be used to measure:

Remotely Sensed Variable	SoWT Indicator
Land-cover	-Land cover classes -Extent of vegetation fragmentation -Extent and severity of edge effects -Extent of burnt area by spatial unit and assemblage -Changes to drainage pattern
Land-cover change	-Extent of clearing by stratification -Extent of vegetation fragmentation -Extent of burnt area by spatial unit and assemblage -Changes to drainage pattern
Vegetation Type	-Extent of introduced environmental weed species by spatial unit and native plant assemblage
Vegetation Index	-Extent and severity of edge effects -Structural modifications forest health -Extent of burnt area by spatial unit and assemblage
Soil Index	-Erosion features
Structure/Biomass Index	-Structural modifications forest health

Table 8: Assessment of remotely sensed data sets suitability against the spatial, spectral and temporal scales of remotely-sensed variables that are linked to SoWT environmental indicators.

Data Type Sensor (platform)	Spatial Scale Extent	Spatial Scale Min.Map Unit	Spectral Scale	Temporal Scale Frequency	Remotely Sensed Variable
Field Spectometers	Site specific	Site specific	Very High	User defined	Veg. Type Structure / Biomass ndex
Aerial Photographs	Local - Province	Local - Province	Low	User defined Cloud restricted	Land cover Land cover change Veg. type Veg. structure Stanton & Stanton Veg. maps
Airborne multi-spectral	Local - Province	Local - Province	Moderate - High	User defined Cloud restricted	Land cover Land cover chang Veg. type Veg. index Soil index Structure / Biomass index

.....Table 8 continued overleaf

......Table 8 continued

Data Type Sensor (platform)	**Spatial Scale Extent**	**Spatial Scale Min.Map Unit**	**Spectral Scale**	**Temporal Scale Frequency**	**Remotely Sensed Variable**
Airborne Hyperspectral	Local - Province	Local - Province	Very High	User defined Cloud restricted	Land coverl Land cover change Veg. type Veg. index Soil index Structure / Biomass index
Satellite Multi-spectral Ikonos (Space Imaging) Quickbird (Earthwatch)	Local - Province	Local - Province	Low	At least 5 days Cloud restricted	Land cover Land cover change Veg. type Veg. index Soil index Structure / Biomass index
Landsat ETM Landsat TM SPOT XS IRS	Province - Region	Province - Region	Moderate	At least 5 days Cloud restricted	As above
SPOT VMI **Multi-spectral**	Region	Region	Low	Daily Cloud restricted	Land cover Land cover change Veg. index Soil index Biomass index
Satellite Hyperspectral MODIS (EOS-AM)	Region	Region	High	Daily Cloud restricted	Land cover Land cover chang Veg. type Veg. index Soil index Biomass index
Field Laser Ranging	Site specific	Site specific	N/A	User defined	Structure / Biomass index
Airborne Laser Altimeters	Local - Province	Local - Province	N/A	User defined	Structure / Biomass index
Satellite SAR	Province	Province	Low	Minimun of 5 days. No cloud or smoke restrictions	Land cover Land cover chang Veg. type Structure / Biomass index

The most appropriate data sets selected for each remotely sensed variable from Table 8 are then added, along with their dimensions and a listing of:

(1) Processing technique(s) required to convert remotely sensed data to the relevant environmental variable and SoWT indicator,

(2) Resources – includes specifications (and costs estimates) for the necessary data, hardware and software systems required to complete the processing of remotely sensed data to map or monitor the to the relevant environmental variable and SoWT indicator; and

(3) Equipment – identifies the type and level of skills required (along with time to complete the task) from staff completing the processing of remotely sensed data to map or monitor the to the relevant environmental variable and SoWT indicator.

Each table then provides a complete assessment of the types of remotely sensed data, accompanying resources, and costs of monitoring each of the SoWT indicators using remotely sensed data. The final assessment item within the table takes into account the review of Phinn et al. (1999) as well as the pre-eding information in the table to categorise each SoWT indicator's ability to be monitored from remote sensing approaches into the same classes used in Wallace and Campbell's (1999) National State of the Environment Report:

Operational

For indicators of this category, results have been or are being produced over broad areas relevant to the scales of the State of the Wet Tropics reporting process. The relevant data expertise and infrastructure are in place to continue of extend these operations.

Feasible

Present knowledge and case studies suggest that relevant information can be derived from available data, but large scale operational demonstrations have not been performed.

Likely/possible

This group includes indicators where present data are inadequate, but future studies are anticipated. It includes indicators where there is knowledge of relationships between the indicator and remotely sensed data, but further research is required to identify suitable processing for State of the Wet Tropics reporting.

Unlikely/ impossible

For these indicators, the assessment is that remote sensing is unlikely to deliver operational results, either because of lack of ability to measure the indicator of interest, or because the scale and logistics suggest that monitoring for State of the Environment reporting purposes would be impracticable.

Table 9.1: The remotely sensed variable LAND COVER (applies to SoWT indicators: Land cover classes, Extent of vegetation fragmentation, Extent and severity of edge effects, Extent of burnt area by spatial unit and assemblage, and -Changes to drainage pattern) and the listing of data types, processing requirements and costs for mapping and monitoring this variable using several suitable types of remotely sensed data (from Table 4).

LAND COVER	**Indicator attributes**	**Data type #1**	**Data type #2**	**Data type #3**
Spatial Scale	Regional	Landsat ETM	NOAA AVHRR	Radarsat
Extent	10, 000km^2	185km x 185km per scene	2500km swath width	100km x 100km per scene
MMU/GRE -Minimum Mapping Unit -Ground Resolution Element	1ha	15m panchromatic 30m multispectral 60m thermal	1.1km visible, Near infrared and thermal infrared	30m standard mode
Temporal	Annual eg by June for December delivery or event driven (WTMA Baseline data collection for land cover	Approx 9.45am every 16 days (archive from CRC Rainforest and ACRES)	Twice daily overpass	Morning overpass every 3- 5 days
Variable	Land-cover class (refer to Table 2 with list of indicators addressed by land-cover classes)	Reflectance in up to 7 spectral bands	Reflectance in red and NIR bands and surface temperature in two thermal bands.	Radar backscatter intensity on one wavelength
Processing technique		Image classification	Image classification	Image classification
(Output)		(Land-cover map)	(Land-cover, fire location)	(Land-cover map)
Resource – Equipment		PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)	PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)	PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)
Resource – Personnel		Trained in image classification Experience with Landsat data Knowledge of area to be mapped	Trained in image classification Knowledge of area to be mapped Experience with AVHRR reflected and thermal data	Trained in image classification Experience with Radarsat data Knowledge of area to be mapped

Estimated task and times		Image pre-processing (1 day) Image classification to Level 1 Broad habitat types, WTMA Annual Report 1998-1999: (15 days per scene) Field/Photo verification for a select number of sample sites: (10 days) Map output production: (2 days) Total = 28 days per scene	Image pre-processing (1 day) Image classification to Level 1 Broad habitat types, WTMA Annual Report 1998-1999: (4 days per scene) Field/Photo verification for a select number of sample sites: (5 days) Map output production: (2 days) Total = 12 days per scene	Image pre-processing (3 days) Image classification to Level 1 Broad habitat types, WTMA Annual Report 1998-1999: (10 days per scene) Field/Photo verification for a select number of sample sites: (8 days) Map output production: (2 days) Total = 23 days per scene
Estimated Cost Note that these are estimates are flexible		Data acquisition: Image data = $1950 Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 28 days of technical officer @ $150/day = $4200 Total = $7250 Note: This assumes software have been purchased	Data acquisition: Image data = < $500 scene Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 12 days of technical officer @ $150/day = $1800 Total = $2400 Note: This assumes software have been purchased	Data acquisition: Image data = US$3500 ($6400) Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 23 days of technical officer @ $150/day = $3450 Total = $10450 Note: This assumes software have been purchased
Evaluation Result		**Operational**	**Operational**	**Feasible**

Table 9.2: The remotely sensed variable LAND COVER CHANGE (applies to SoWT indicators: Extent of clearing by stratification, Extent of vegetation fragmentation, Extent of burnt area by spatial unit and assemblage, and Changes to drainage pattern) and the listing of data types, processing requirements and costs for mapping and monitoring this variable using several suitable types of remotely sensed data (from Table 4).

LAND COVER CHANGE	**Indicator attributes**	**Data type #1**	**Data type #2**	**Data type #3**
Spatial Scale	Regional	Landsat ETM	NOAA AVHRR	Radarsat
Extent	10, 000km^2	185km x 185km per scene	2500km swath width	100km x 100km per scene
MMU/GRE	1ha	15m panchromatic 30m multispectral 60m thermal	1.1km visible, Near infrared and thermal infrared	30m standard mode
Temporal	Annual eg by June for December delivery or event driven (WTMA Baseline data collection for land cover	Approx 9.45am every 16 days (archive from CRC Rainforest and ACRES)	Twice daily overpass	Morning overpass every 3- 5 days
Variable	Land-cover class change (refer to Table 2 with list of indicators addressed by land-cover classes)	Reflectance in up to 7 spectral bands	Reflectance in red and NIR bands and surface temperature in two thermal bands.	Radar backscatter intensity on one wavelength
Processing technique		Image classification followed by change detection (post-classification comparison)	Image classification followed by change detection (post-classification comparison)	Image classification followed by change detection (post-classification comparison)
(Output)		(Land-cover map, Land-cover change map show areas of change and no change)	(Land-cover map, Land-cover change map show areas of change and no change)	(Land-cover map, Land-cover change map show areas of change and no change)
Resource – Equipment		PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)	PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)	PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)
Resource – Personnel		Trained in image classification Experience with Landsat data Knowledge of area to be mapped	Trained in image classification Knowledge of area to be mapped Experience with AVHRR reflected	Trained in image classification Experience with Radarsat data Knowledge of area to be mapped

			and thermal data	
Estimated task and times		Image pre-processing (2 days) Image classification to Level 1 Broad habitat types, WTMA Annual Report 1998-1999 and change detection: (15 days per scene – 30 days) Field/Photo verification for a select number of sample sites: (20 days) Map output production: (4 days) Total = 56 days per scene	Image pre-processing (2 day) Image classification to Level 1 Broad habitat types, WTMA Annual Report 1998-1999 and change detection: (4 days per scene - 8 days) Field/Photo verification for a select number of sample sites: (20 days) Map output production: (4 days) Total = 34 days per scene	Image pre-processing (6 days) Image classification to Level 1 Broad habitat types, WTMA Annual Report 1998-1999 and change detection: (10 days per scene – 20 days) Field/Photo verification for a select number of sample sites: (16 days) Map output production: (4 days) Total = 46 days per scene
Estimated Cost Note that these are estimates are flexible		Data acquisition: Image data = 2 x $1950 Aerial Photos (20) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 56 days of technical officer @ $150/day = $8400 Total = $14300 Note: This assumes software have been purchased	Data acquisition: Image data = 2 x < $500 scene Aerial Photos (20) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 34 days of technical officer @ $150/day = $1800 Total = $8100 Note: This assumes software have been purchased	Data acquisition: Image data = 2 x US$3500 ($6400) Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 46 days of technical officer @ $150/day = $6900 Total = $21700 Note: This assumes software have been purchased
Evaluation Result		**Operational**	**Operational**	**Feasible**

Table 9.3 The remotely sensed variable VEGETATION TYPE (applies to SoWT indicators: Extent of introduced environmental weed species by spatial unit and native plant assemblage) and the listing of data types, processing requirements and costs for mapping and monitoring this variable using several suitable types of remotely sensed data (from Table 4).

VEGETATION TYPE	**Indicator attributes**	**Data type #1**	**Data type #2**	**Data type #3**
Spatial Scale	Regional - Local	Landsat ETM	Airborne Hyperspectral	Aerial Photographs
Extent	10,000km^2 - 100km^2	185km x 185km per scene	Up to 100km^2	1.3 – 33km^2
MMU/GRE	1ha - 100 m^2	15m panchromatic 30m multispectral 60m thermal	0.5 – 10m	5m – 250m
Temporal	Annual eg by June for December delivery or event driven (WTMA Baseline data collection for land cover	Approx 9.45am every 16 days (archive from CRC Rainforest and ACRES)	User controlled (subject to weather and aircraft availability)	User controlled (subject to weather and aircraft availability)
Variable	Land-cover class (refer to Table 2 with list of indicators addressed by land-cover classes)	Reflectance in up to 7 spectral bands	Reflectance in up to 126 spectral bands	Contact prints (23cm x 23cm) requiring scanning and orthocorrection to produce a digital mosaic
Processing technique		Image classification or feature detection	Image classification or (hyperspectral) feature detection	Manual delineation of vegetation types either on hard-copy photographs or on-screen digitizing.
(Output)		(Vegetation type map and target features) Note: The ability to map specific targets will depend on their growth form and extent.	(Vegetation type map and target features) Note: The ability to map specific targets will depend on their growth form and extent.	(Vegetation type map)
Resource – Equipment		PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)	PC Image processing software capable of hyperspectral data processing.	PC A3 size or larger Scanner Softcopy photogrammetry software Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)

Resource – Personnel		Trained in image classification Experience with Landsat data Knowledge of area to be mapped	Trained in image classification and spectral unmixing or matching. Experience with Hyperspectral data Knowledge of area to be mapped	Training in softcopy photogrammetry and image processing. Extensive knowledge of area to be mapped
Estimated task and times		Image pre-processing (1 day) Image classification to, WTMA Broad Habitat Types Annual Report 1998-1999(p.26): (15 days per scene) Field/Photo verification for a select number of sample sites: (8 days) Map output production: (2 days) Total = 26 days per scene	Note: This estimate is for a 10km x 10km area Image pre-processing (2 days) Image analysis using classification, un-mixing or matching to define WTMA Broad Habitat Types Annual Report 1998-1999(p.26) and target features: (8 days per area) Field/Photo verification for a select number of sample sites: (3 days) Map output production: (1 days) Total = 14 days per 10km x 10km scene	Note: This estimate is for a 20km x 20km area (10 x 10 photos) Aerial Photograph Scanning (1 day) Digital photographs ortho-correction (5 days) Photograph interpretation and digitizing boundaries (25 days) Build and clean up vegetation type layer Map output production: (2 days) Total = 33 days per 20km x 20km scene
Estimated Cost Note that these are estimates are flexible		Data acquisition: Image data = $1950 Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 28 days of technical officer @ $150/day = $4200 Total = $7250 Note: This assumes software have been purchased	Data acquisition: Image data = $15000 Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 14 days of technical officer @ $150/day = $1700 Total = $16900 Note: This assumes software have been purchased	Data acquisition: Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources = $9000 Ancillary data (topo sheets)= $200 Processing = 33 days of technical officer @ $150/day = $4950 Total = $14150 Note: This assumes software have been purchased
Evaluation Result		**Operational**	**Feasible**	**Operational**

Table 9.4 The remotely sensed variable VEGETATION INDEX + SOIL INDEX (applies to SoWT indicators: Extent and severity of edge effects, Structural modifications forest health, Extent of burnt area by spatial unit and assemblage, and Erosion effects) and the listing of data types, processing requirements and costs for mapping and monitoring this variable using several suitable types of remotely sensed data (from Table 4).

VEGETATION INDEX ***SOIL INDEX***	**Indicator attributes**	**Data type #1**	**Data type #2**	**Data type #3**
Spatial Scale	Regional - Province	Landsat ETM	NOAA AVHRR	
Extent	10 000km^2 -1000km^2	185km x 185km per scene	2500km swath width	
MMU/GRE	1ha or smaller	15m panchromatic 30m multispectral 60m thermal	1.1km visible, Near infrared and thermal infrared	
Temporal	Annual eg by June for December delivery or event driven (WTMA Baseline data collection for land cover	Approx 9.45am every 16 days (archive from CRC Rainforest and ACRES)	Twice daily overpass	
Variable	Land-cover class (refer to Table 2 with list of indicators addressed by land-cover classes)	Reflectance in up to 7 spectral bands	Reflectance in red and NIR bands and surface temperature in two thermal bands.	
Processing technique **(Output)**		Image algebra to produce an appropriate vegetation or soil exposure index: Define each of these NDVI IRI GEMI Soil Exp (Vegetation or Soil Index Map relating directly to biomass, canopy cover and soil exposure)	Image algebra to produce an appropriate vegetation or soil exposure index: Define each of these NDVI IRI GEMI Soil Exp (Vegetation or Soil Index Map relating directly to biomass, canopy cover and soil exposure)	Image algebra NDVI IRI GEMI Soil Exp (Vegetation or Soil Index Map relating directly to biomass, canopy cover and soil exposure)

Resource – Equipment		PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)	PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)	
Resource – Personnel		Trained in image classification Experience with Landsat data Knowledge of area to be mapped	Trained in image classification Knowledge of area to be mapped Experience with AVHRR reflected and thermal data	
Estimated task and times		Image pre-processing (1 day) Image algebra application of model and model refinement based on field data: (5 days per scene) Field/Photo verification for a select number of sample sites: (5 days) Map output production: (2 days) Total = 13 days per scene	Image pre-processing (1 day) Image algebra application of model and model refinement based on field data: (5 days per scene) Field/Photo verification for a select number of sample sites: (5 days) Map output production: (2 days) Total = 13 days per scene	
Estimated Cost Note that these are estimates are flexible		Data acquisition: Image data = $1950 Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 13 days of technical officer @ $150/day = $1950 Total = $5000 Note: This assumes software have been purchased	Data acquisition: Image data = < $500 scene Aerial Photos (10) = $90/frame to acquire or less to hire from Dept. of Natural Resources Ancillary data (topo sheets)= $200 Processing = 13 days of technical officer @ $150/day = $1950 Total = $3550 Note: This assumes software have been purchased	
Evaluation Result		**Operational**	**Operational**	

Table 9.5 The remotely sensed variable STRUCTURE & BIOMASS INDEX (applies to SoWT indicators: Structural modification of forest health) and the listing of data types, processing requirements and costs for mapping and monitoring this variable using several suitable types of remotely sensed data (from Table 4).

STRUCTURE BIOMASS INDEX	**Indicator attributes**	**Data type #1**	**Data type #2**	**Data type #3**
Spatial Scale	Regional	Landsat ETM	NOAA AVHRR	Radarsat/AirSAR
Extent	10, 000km^2	185km x 185km per scene	2500km swath width	100km x 100km per scene
MMU/GRE	1ha	15m panchromatic 30m multispectral 60m thermal	1.1km visible, Near infrared and thermal infrared	30m standard mode (also other modes possible)
Temporal	Annual eg by June for December delivery or event driven	Approx 9.45am every 16 days (archive from CRC Rainforest and ACRES)	Twice daily overpass	Morning overpass every ~3- 5 days
Variable	Land-cover class (refer to Table 2 with list of indicators addressed by land-cover classes)	Reflectance in up to 7 spectral bands	Reflectance in red and NIR bands and surface temperature in two thermal bands.	Radar backscatter intensity on one wavelength
Processing technique		Image models based on field calibration.	Image models based on field calibration	Image models based on field calibration
(Output)		(Biomass estimate map, Forest structural class estimate map)	(Biomass estimate map, Forest structural class estimate map)	(Biomass estimate map, Forest structural class estimate map)
Resource – Equipment		PC Image processing software GIS with image classification module (e.g. Arc-View Image Analyst)	PC Image processing software with modeling/programming capabilities	PC Image processing software with radar and image modeling/programming capabilities
Resource – Personnel		Trained in image based modeling and programming, and experience linking field and image data. Experience with Landsat data Knowledge of area to be mapped	Trained in image based modeling and programming, and experience linking field and image data. Knowledge of area to be mapped Experience with AVHRR reflected and thermal data	Trained in image based modeling and programming, and experience linking field and image data. Experience with Radarsat data Knowledge of area to be mapped

Estimated task and times		Image pre-processing (1 day) Field sampling for collection of model calibration and validation data. (10 days) Image and field data integration and modeling to estimate biophysical variable, includes calibration and validation: (15 days per scene) Map output production: (2 days) Total = 28 days per scene	Image pre-processing (1 day) Field sampling for collection of model calibration and validation data. (6 days) Image and field data integration and modeling to estimate biophysical variable, includes calibration and validation: (10 days per scene) Map output production: (2 days) Total = 19 days per scene	Image pre-processing (1 day) Field sampling for collection of model calibration and validation data. (10 days) Image and field data integration and modeling to estimate biophysical variable, includes calibration and validation: (15 days per scene) Map output production: (2 days) Total = 28 days per scene
Estimated Cost Note that these are estimates are flexible		Data acquisition: Image data = $1950 Ancillary data (topo sheets)= $200 Processing = 28 days of technical officer @ $150/day = $4200 Total = $6350 Note: This assumes software have been purchased	Data acquisition: Image data = < $500 scene Ancillary data (topo sheets)= $200 Processing = 19 days of technical officer @ $150/day = $2850 Total = $3550 Note: This assumes software have been purchased	Data acquisition: Image data = US$3500 ($6400) Ancillary data (topo sheets)= $200 Processing = 28 days of technical officer @ $150/day = $4200 Total = $10800 Note: This assumes software have been purchased
Evaluation Result		**Feasible**	**Feasible**	**Feasible**

OPTIMAL REMOTELY SENSED DATA AND PROCESSING APPROACHES FOR STATE OF THE WET TROPICS MONITORING

To complete the assessment process the results from the preceding sections are integrated with findings from the evaluation of remote sensing for monitoring National State of The Environment Indicators (Wallace and Campbell 1998), and considerations for implementing remote sensing of SoWT indicators. A common finding to this study and Wallace and Campbell (1998) was the need for a clear link between the type of indicator to be monitored, an environmental variable able to be detected from remotely sensed data, and the spatial and temporal scale(s) at which the information is required.

To review, the process and information used to evaluate remote sensing for SoWT indicators included:

- Identifying the spatial and temporal characteristics of each SoWT indicator, along with the remotely sensed variable capable of representing the indicator or a surrogate (Table2);
- Reviewing the dimensions, costs and availability of all current forms of remotely sensed data (Table 4);
- Identifying the remotely sensed variables capable of being used to monitor SoWT indicators (Table 7);
- Assessing the “appropriateness” of each type of remotely sensed data to deriving the remotely sensed variables matched to each SoWT indicator (Table 8); and
- Specifying the type and costs of data, personnel, experience, hardware and software to be able to map SoWT indicators from the most appropriate form of remotely sensed data (Tables 9.1 – 9.5).

Results from Wallace and Campbell’s (1998) Report identified several types of environmental indicator data that could estimated from remotely sensed data:

“Operational remote sensing applications” for mapping indicators that could apply to tropical rainforest environments include:

- Vegetation (remnant or woody vegetation)
- Burnt area by spatial unit and assemblage
- Mangroves
- Land -use categories

“Feasible [not yet subject to large scale operational demonstrations] remote sensing applications” for mapping indicators that could apply to tropical rainforest environments include:

- Extent of vegetation fragmentation
- Structural classes of vegetation (from stereophotos)
- Sediment plumes in estuaries
- Algal blooms
- Trends in vegetation cover
- Urban Land use
- Land surface temperature

“Likely/possible [in context of SoE reporting] remote sensing applications” for mapping indicators that could apply to tropical rainforest environments include:

⇑ Introduced floral species (Except in specific circumstances)

Integrating the results contained in Tables 2 – 7.5 enabled each of the SoWT to be evaluated in the same context as the National State of the Environment Indicators (Table 10). Operational applications included those with established monitoring programs, accessible data and commonly available processing tools in image processing or GIS systems. Applications had been developed for these indicators in Australia and overseas and a significant body of scientific literature supported the application. The majority of these applications were concerned with mapping land cover types, ranging from broad habitat or land-use categories, to specific vegetation communities and types of land cover (e.g., burnt and cleared areas). Interestingly, these applications also spanned a range of spatial scales from local to regional scale and had suitable data and processing techniques at each scale.

Feasible applications (Extent and severity of edge effects, Structural modifications forest health, Change in drainage patterns) were not being measured as part of ongoing monitoring programs. Data sets for these applications are commonly available as are the necessary image processing tools. These applications require significant investment in calibration and validation programs to be established as operational monitoring programs. There is a significant body of scientific literature supporting these applications, mainly in terms of experimental development.

Table 10: Assessment of operational status of remote sensing for monitoring selected State of the Wet Tropics Indicators

Indicator (Surrogate)	Status
Land cover classes	Operational
Extent of clearing by stratification (within land cover types: linear service corridors, inundation, spot clearings, boundary anomalies)	Operational
Extent of vegetation fragmentation (area of powerlines, roads)	Operational
Extent and severity of edge effects	Feasible
Structural modifications forest health	Feasible
Extent of burnt area by spatial unit and assemblage (within Webb-Tracy Communities and landcover types)	Operational
Extent of introduced environmental weed species by spatial unit and native plant assemblage	Likely/Possible (dependent on scale of feature)
Erosion features (exposed soil)	Feasible (dependent on scale of feature)
Changes to drainage pattern (dams, stream geometry)	Feasible (dependent on scale of feature)

The likely or possible application (Extent of introduced environmental weed species by spatial unit and native plant assemblage) is a difficult case due to the nature of the feature to be mapped. There are ongoing weeds monitoring programs in other environments where the weeds cover large areas and occur on the tops of canopies, in water bodies and in open woodland and grassland. Weeds in tropical forests are problematic due to their location and size, both of which make hem difficult to detect from remotely sensed data. This indicator requires further assessment on a case by case basis to identify priority weeds and those the have a suitable spatial scale and distribution to be monitored using remotely sensed data.

To move on from the findings of this report and implement remote sensing techniques as an integral part of SoWT monitoring a number of actions need to be taken:

(1) the remote sensing approaches evaluated as operational for monitoring SoWT indicators need to considered by WTMA and set up as part of their monitoring program where possible,

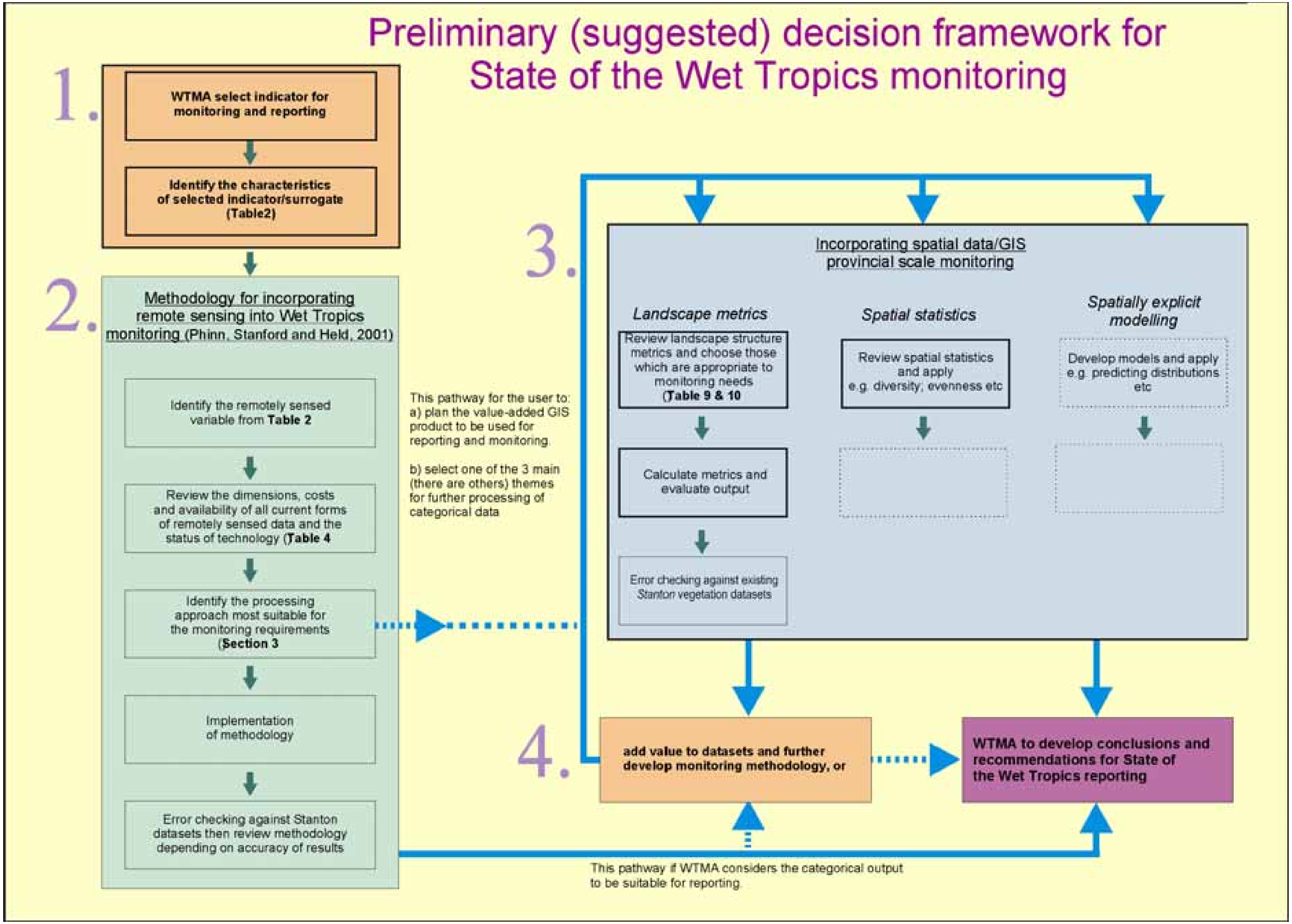
(2) jointly run projects between the Rainforest CRC and WTMA should be use to "operationalise" the procedures and transfer skills and knowledge for completing these tasks to WTMA;

(3) Figure 2 provides a schematic outline for applying the knowledge and procedures developed in this report,

(4) the acquisition, storage, meta-data, intellectual property and data distribution procedures for using remotely sensed data within the monitoring program need to be set up, and

(5) further work is required to complete validation and cost assessment work on remotely sensed data sets that were considered feasible for monitoring specific indicators.

The framework (Figure 2) requires decision-making by the WTMA at various levels, in terms of defining the extent of the region being examined and the main target of monitoring. To use the framework you must first select a relevant indicator to work with and then follow it through the whole process. **Step 1** requires WTMA to select the indicator, and define the extent of the area to be monitored and how frequently to monitor it. In **Step 2** the indicator is matched up to a variable able to be measured from remotely sensed data. Specific details on the costs and availability of image data sets can also be identified at this stage. In **Step 3** the combination of selected indicator and relevant remotely sensed variable for that indicator is used to select a processing methodology from Tables 9.1 – 9.5. Each table contains complete specifications of the data requirements, processing requirements (hardware, software and personnel), time and cost requirements for using selected forms of remotely sensed data to monitor remotely sensed variables. Separate tables are provided for land cover, land cover change, vegetation type, vegetation and soil indices and structure/biomass indices. The final step represents a direction for joint research between the Rainforest CRC and WTMA to implement monitoring of one or more SoWT indicators using remotely sensed data, and is intended to establish an operational capability for WTMA in this area.



Preliminary (suggested) decision framework for State of the Wet Tropics monitoring

DATA OWNERSHIP AND INTELLECTUAL PROPERTY ISSUES

There are two main issues associated with intellectual property and ownership of remotely sensed data sets and their processing routines that need to be considered. The first relates to the data sets themselves (and their derived products) and the second to the procedures used to transform the image data to maps of biophysical information. There needs to be a system set-up to record exchange of image data sets and a record of the processing operations completed. In relation to data ownership there are two types:

(1) For all aerial photography and Landsat images Thematic Mapper or Multispectral Scanner copyright and ownership rests with the purchaser or owner of the data. In these cases the Australian Centre for Remote Sensing Purchase Agreements restrict the use or distribution of the data sets to any other groups beyond that they were originally purchased. The data owners also have rights on controlling the distribution of products derived from their image data sets.

(2) For Landsat data sets purchased from Landsat 7 (1999 onwards) these copyright restrictions do not apply and the data purchasers are free to distribute the data without restriction.

An agreement has been signed between the Rainforest CRC and the Australian Centre for Remote Sensing to access a historic set of Landsat Thematic Mapper images covering the Wet Tropics and spanning the three decades 1970, 1980, and 1990 to 2000. All CRC partners will have access to these data and their derived products.Other image data sets purchased as part of the CRC project will be available to researchers or partners within the CRC. This covers a number of airborne multi and hyperspectral data sets along with some imaging radar and other satellite data.

Intellectual property is a slightly different issue, and can be considered in relation to our assessment of SoWT indicator monitoring as operational, feasible, or likely/possible. For operational remote sensing applications the necessary image processing sequence and codes are publicly available on commercial image processing and GIS systems, as well as being documented in peer-reviewed scientific literature. Processing approached will be developed to address those indicators considered feasible and likely/possible. Under the current agreement set up by the CRC, these procedures are then part of the CRC’s intellectual property, for use by partner organisations. A complicating factors here is that both CSIRO Land and Water and the Biophysical Remote Sensing Group (University of Queensland) have defined a significant amount of background intellectual property that they are bring to the CRC project (see Appendix 2). These procedures will remain the property of CSIRO and University of Queensland, and shared Intellectual Property arrangements will be set up to incorporate these issues.

The original and continuing objectives of Project 1.2 in the Rainforest CRC “Monitoring changes in rainforest vegetation structure and condition and their drainage systems” were established and have been refined to meet a number of these needs. This project will deliver operational, accurate and cost-effective environmental monitoring solutions for tropical rainforest environments from remotely sensed data.
Of particular relevance to this report are several of the ongoing components of project 1.2:

- development of a historic multi-date Landsat Thematic Mapper and Multi-Spectral Scanner image archive for the wet tropics for 1970s, 1980s, 1990s and 2000 for use by CRC partners;

- construction of ANZLIC standard metadata records for all image data sets collected as part of the project;

- conducting detailed assessments of the types of biophysical information able to be extracted on tropical rainforests, along with its level of accuracy and costs from remotely sensed data sets considered as “feasible” for a number of SoWT indicators (e.g. airborne hyperspectral images and synthetic aperture radar systems); and

- assessment of the capabilities of new remote sensing technologies, such as airborne lser scanning for addressing SoWT indicator monitoring needs.

We have used the results of this report to further fine-tune the goals of our projects, which were previously focussed on evaluation of the capabilities of the full range of current and future remote sensing technologies. The review process completed here as identified key environmenta indicators, which will now act as driving factors in our evaluation process, especially for indicators such as structure and biomass and invasive weeds. The results from our ongoing work will now be presented in the context of their relevance to addressing select indicators and as a full assessment of the techniques an costs required to implement such approaches. Hopefully this approach will ensure a transition to operational, accurate and cost effective remote sensing applications within WTMA’s monitoring program, and also provide guidance/example for other agencies responsible for tropical forest monitoring.

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Appendix 8.1 Select articles from the rainforest remote sensing review.

Sensor type	Monitoring application	Location	Area (sq km)	Parameters	Accuracy	References	Notes (procedure, ancillary data etc) * = pdf available
TM/MSS	Deforestation	Ivory Coast	10000	Landcover	Local scale classification(n=128 ,86%)	(Chatelain, Gautier and Spichiger 1996)	MSS 74,84 TM90, RegionalDensity slicing, superv class,filtered: local, (36x27km)
NOAA/MSS/TM/ SPOT	Land-use change	Indonesia	4798630ha	Landcover change/carbon release/above ground biomass	—	(Murdiyarso and Wasrin 1995)	Manual interp. of colour composite
AVHRR/MS/TM	Deforestation	Ghana	1700000ha	Cover	—	(Foody and Curran 1994)	Some existing ground data –floristics but small plots(29x1ha)also cf to old classified images
API/TM	Deforestation	Mexico	850	Cover esp forest	—	(Dirzo and Garcia 1992)	Assumed 100% cover at start, 67,76,86 years. Used some field checking. Delin then used GIS to work out areas changed.
TM/SPOT/AVHRR	Cover/ deforestation	Mexico/ central America	c.10000	Cover esp forest	only qualitative	(Eggen, Lannom and Jacobs 1994; Lannom and Evans 1995)	Checking with video GPS aerial photography; 5 forest cover types only
AVHRR/ATSR-1	Deforestation	Brazil	190x205	Non-forested	—	(Eva, Conway and D'Souza 1995)	Accuracy wasn't checked
SIR-C cf AIRSAR	Veg cover	NL/Brazil	—	Veg cover	—	(Freeman 1995)	
AVHRR	Forest cover/change	Sumatra	476000	Cover forest	70%	(Gastellu-Etchegorry, Estreguil, Mougin and Laumonier 1993)	Defor c. 9.4% per year
TM	Cover esp forest	phillipines	85795ha	Forest cover	~90%	(Apan 1997)	Ancillary = existing maps etc also was ground truthed to some extent *
AVHRR	Cover	Cameroon	50000	Biomass	High accuracy	(Boyd, Foody and Curran 1999)	Biophysical measurements at 61 * 1ha plots
AVHRR/TM	Cover	Brazil		Cover change	~55% for TM; >80% for AVHRR	(Di-Maio-Mantovani and Setzer 1997)	*
Space SAR	Cover	Brazil	250	Biomass/regen	High correlations for backscatter ratios	(Foody, Green, Lucas, Curran, Honzak and Amaral 1997a)	*

Sensor type	Monitoring application	Location	Area (sq km)	Parameters	Accuracy	References	Notes (procedure, ancillary data etc) * = pdf available
TM/IR photography	Cover	Venezuela	~150	Vegetation change - deforestation	—	(Guerra, Puig and Chaume 1998)	*
TM	Cover	Amazon		Vegetation change	~90%	(Hill 1999)	*
TM/MSS/AVHRR/ SPOT	Deforestation	Vietnam	1200	Cover/deforestation	High correlations	(Jeanjean and Achard 1997)	*
ERS1/2	Land use and deforestation	Indonesia	4800	Deforestation	Only qualitative (~80%)	(Kuntz and Siegert 1999)	Truthed with Landsat and ground
						(Lambin and Ehrlich 1997)	*
SAR (Convair 580)	Cover	Brazil	576		—	(Luckman, Frery, Yanasse and Groom 1997b)	*
						(Paradella, Bignelli, Veneziani, Pietsch and Toutin 1997)	*
						(Raucoules and Thomson 1999)	*
TM/aerial photos	Land cover change	Nigeria	100	Land cover	—	(Salami 1999)	Ancillary-air photos inc multi-temporal
MSS/TM multidate	Cover/ Deforestation	Costa Rica	986	Cover including change	—	(Sanchez Azofeifa, Quesada Mateo, Gonzalez Quesada, Dayanandan and Bawa Kamaljit 1999)	*forest including successional stages etc
TM	Cover/Deforestation	Madagascar	88	Cover	—	(Kramer, Richter, Pattanayak and Sharma 1997)	*historical forest maps(photo interp.)
TM	Cover/Deforestation	Guatamala	100	Cover	planned AP's and ground	(Sader, Sever, Smoot and Richards 1994)	*generated a grid over the whole of the site @100sq km also CAMS airborne airborne CIR ap's
Aerial photography (BW/Col/CIR)	Land use	West Africa	60	Cover	—	Gilruth, 1995	*ancillary DEM
TM	Diversity (esp landscape)	Guatamala	5000	Cover	Qualitative	(Rey Benayas Jose and Pope Kevin 1995)	Topo maps: Used PCA + cluster analysis (incorp Shannon-Weaver index)
AVHRR	Mapping cover	Se Asia	>2000000	Cover	Cf existing veg maps and TM class	(Achard and Estreguil 1995)	

Sensor type	Monitoring application	Location	Area (sq km)	Parameters	Accuracy	References	Notes (procedure, ancillary data etc) * = pdf available
MSS/TM	Deforestation	Amazon	14400	Cover	73%	(Foody Giles, Palubinskas, Lucas Richard, Curran Paul and Honzak 1996)	
TM/ERS1/JERS1/SIR-C	Forest regeneration	Amazon	5000	Biomass	High	(Luckman, Baker, Kuplich Tatiana, Yanasse Corona Da and Frery Alejandro 1997a)	
JERS1	Forest regeneration	Amazon	~5000	Biomass	High	(Luckman, Baker, Honzak and Lucas 1998)	
TM/AVHRR	Forest cover	TREES	—	Cover	High	(Mayaux and Lambin 1995)	
TM/AVHRR	Forest cover	TREES	—	Cover	>70%	(Mayaux and Lambin Eric 1997)	
Airborne laser	Forest cover	Costa Rica	—	Basal area, volume, biomass	High	(Nelson, Oderwald and Gregoire Timothy 1997)	
SIR-C/TM/JERS1/SPOT XS	Deforestation/ change	Brazil	525	Cover	Mixed results	(Rignot, Salas William and Skole David 1997)	Compared two optical and two radar sensors
AIRSAR(X,C,L & P)	Deforestation	Colombia	—	Cover	—	(van der Sanden Joost and Hoekman Dirk 1999)	Note: texture applications
AIRSAR	Deforestation/ land use	Brazil	2400	Cover	<60%	(Saatchi Sasan, Soares Joao and Alves Diogenes 1997)	