INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

**Bell & Howell Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600**

UMI[®]

**Monitoring Land-Cover Change: An Example of Forest
Change in Peninsular Malaysia**

by

GLEN HOHLMANN

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Arts
Department of Geography

Carleton University
Ottawa, Ontario

August 1999

© copyright

1999, Glen Hohlmann

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-48392-4

Canada

The undersigned recommend to the Faculty of Graduate
Studies and Research acceptance of the thesis

**Monitoring Land-Cover Change: An Example of Forest
Change in Peninsular Malaysia**

submitted by GLEN HOHLMANN

B.A.(Hons), Concordia University

in partial fulfilment of the requirements for
the degree of Master of Arts

THESIS SUPERVISOR

CHAIR, DEPARTMENT OF GEOGRAPHY

Carleton University

August 1999

ABSTRACT

The purpose of this research was to evaluate forest-cover change in and around the protected areas of Peninsular Malaysia between 1992 and 1996. To accomplish this a historical review of deforestation and conservation measures in Peninsular Malaysia was undertaken. Different change detection techniques were then applied to National Oceanographic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) imagery in order to create binary change/no-change maps. Results of an agreement assessment with other published maps show that combining change maps is more effective at identifying changes than simply using an individual technique. The application of fuzzy membership grades also provided increased amounts of useful information that could be incorporated in land-cover change studies. The findings of this study clearly demonstrate the usefulness of using remotely sensed data to monitor protected areas.

ACKNOWLEDGEMENTS

This research could not have been completed without the help of a number of people. First, thanks are extended to my supervisor at Carleton University, Professor Mike Fox and my advisor Dr. Doug King. Your advice and comments helped me tremendously. I would also like to thank every one else in the Geography Department who helped me along the way. Special thanks must go to Hazel Anderson, who always provided me with any information about school that I needed.

I received technical support and advice from a number of people as well. Without their help and advice I would not have been able to conduct this study. Special thanks go to Dan Auger, Jason Fournier, Kim Haddow, Pat Jordan and Rosa Tatasciore.

I would also like to express my appreciation to two former professors of mine at Concordia. These are Professor Robert Aiken and Dr. Jacqueline Anderson who both inspired me and made me want to learn more.

I wish to thank my family and friends who have stood by me since the beginning. Your encouragement and understanding have been extremely important. For my family in Germany, thank you for always being proud of me even when I did not

deserve it. I would especially like to express my thanks and heart felt gratitude to the three most important people in my life my mother and father and Heather. Mom and Dad you have always stood by me even during some pretty tough times. You will never know how much that meant to me. I would not be where I am today without the two of you. Heather, without you I would not have made it through these last few years and now that it is finally over we can move on with our lives.

Finally, I want to dedicate this thesis to my late grandmother, Hildegard Amalia Strenger, who passed away only two days after my defense and who will be sorely missed.

Table of Contents

Acceptance Sheet.....	ii
Abstract.....	iii
Acknowledgements.....	iv
Table of Contents.....	vi
List of Tables.....	viii
List of Figures.....	ix
List of Appendices.....	xiii
 CHAPTER 1: Introduction.....	 1
1.1 Introduction.....	1
1.2 Objectives.....	4
1.3 Study Rationale.....	5
1.3.1 Land-Cover Change Monitoring of Tropical Regions.....	5
1.3.2 Land-Cover Change and its Impact on Species.....	7
1.3.3 Parks and Protected Areas.....	10
1.3.4 Malaysia.....	15
1.3.5 Land-Cover Change Monitoring.....	20
1.3.6 Change Detection using Remote Rensing.....	22
1.4 Organization of the Thesis.....	24
 CHAPTER 2: Study Area: Peninsular Malaysia.....	 26
2.1 Introduction.....	26
2.2 Forest Formations.....	29
2.3 Extent and Rate of Change of Forest Cover.....	33
2.4 Causes of Deforestation and Forest Degradation...	36
2.4.1 Logging.....	37
2.4.2 Land Development Schemes.....	42
2.4.3 Other Causes.....	48
2.5 Conservation in Peninsular Malaysia.....	49
2.5.1 Parks and Protected Areas.....	49
2.5.2 Conservation Initiatives.....	55

CHAPTER 3: Digital Change Detection.....	61
3.1 Digital Change Detection.....	61
3.2 Image Algebra.....	64
3.3 Post-Classification Comparison.....	67
3.4 Vegetation Index Differencing.....	69
3.5 Principal Component Analysis.....	72
3.6 Fuzzy Membership Functions of Change.....	75
3.7 Change Detection using Spatial Information.....	78
3.8 An Alternative Approach that combines Change Images from Multiple Techniques.....	81
CHAPTER 4: Methodology.....	83
4.1 Data.....	83
4.2 Methods.....	89
4.2.1 Image-to-Image Registration.....	90
4.2.2 Creation of the Transformed Data.....	91
4.2.3 Change Mapping using Difference Images....	93
4.2.4 Change Mapping using Post-Classification Comparison.....	98
4.2.5 Change Mapping using Principal Component Analysis of Difference Images.....	99
4.2.6 Evaluation of Agreement of Change Mapping Techniques with Reference Data....	99
CHAPTER 5: Results and Discussion.....	105
5.1 Objectives.....	105
5.2 Creation of the Binary Change and Change Membership Images.....	105
5.3 Agreement Assessment of Binary Change Images....	109
5.4 Test Site Analysis.....	113
5.5 Fuzzy Membership Image.....	121
5.6 Changes Occurring in and around Protected Areas in Peninsular Malaysia.....	126
CHAPTER 6: Conclusion.....	130
6.1 Summary and Conclusions.....	130
6.2 Limitations.....	134
6.2 Future Research.....	135
References.....	137
Appendices.....	156

List of Tables

Table 2.1	Development land by state 1971-80.....	45
Table 2.2	Land Development by FELDA, 1956-1990.....	47
Table 3.1	Change detection studies used to formulate the methodology in this research.....	63
Table 4.1	Location of ground control points and errors for the image-to-image registration.....	92
Table 4.2	NOAA AVHRR sensor system characteristics.....	94
Table 4.3	Transformed images created from the five original AVHRR bands.....	95
Table 4.4	Various combinations of imagery analyzed.....	97
Table 5.1	Correlation coefficients of difference images.....	106
Table 5.2	Image statistics used for class thresholding.....	108
Table 5.3	Grey level brightness values for different forest type on the channel 2 difference image.....	118

List of Figures

Figure 1.1	Map of Peninsular Malaysia indicating land above 300 metres, international boundaries, state boundaries, with inset showing regional situation.....	16
Figure 2.1	Regional development schemes in Peninsular Malaysia	43
Figure 2.2	Map of Peninsular Malaysia showing protected areas of at least 50 square kilometres in size.....	51
Figure 2.3	Map of Peninsular Malaysia showing the Permanent Forest Estate (1995).....	54
Figure 3.1	Diagram of image algebra change detection....	65
Figure 3.2	Diagram of multi-date post-classification Comparison change detection.....	68
Figure 3.3	Typical spectral reflectance characteristics for healthy green grass, dead or senescing grass, and bare dry soil.....	70
Figure 3.4	Diagrammatic representation of the spatial relationship between the first two principal components.....	74
Figure 3.5	An example fuzzy membership function of change.....	76
Figure 4.1	Geographical extent of NOAA AVHRR images.....	88
Figure 4.2	Unsupervised classification of AVHRR channel 3.....	100
Figure 4.3	Unsupervised classification of AVHRR channels 1, 2, and 3.....	101
Figure 4.4	Forest cover in Peninsular Malaysia.....	100

Figure 5.1	Number of pixels classified as change.....	110
Figure 5.2	Comparison of similarity between various change detection procedures and a reference map.....	112
Figure 5.3	Test sites used in the second accuracy assessment.....	115
Figure 5.4	Grey-level brightness values for different forest classes.....	119
Figure 5.5	Number of pixels at each change membership grade on the combination 6 image.....	122
Figure 5.6	Factor map that shows the number of bands classifying pixels as having undergone change.....	124
Figure 5.7	A possible design for a bivariate change map legend	125
Figure 5.8	Change membership images showing changes to Peninsular Malaysia's forest cover.....	127
Figure A-1	NOAA AVHRR channel 1.....	157
Figure A-2	NOAA AVHRR channel 2.....	158
Figure A-3	NOAA AVHRR channel 3.....	159
Figure A-4	NOAA AVHRR channel 4.....	160
Figure A-5	NOAA AVHRR channel 5.....	161
Figure B-1	NDVI image.....	163
Figure B-2	Surface temperature brightness (Ts) image....	164
Figure B-3	Ts/NDVI.....	165
Figure B-4	Contrast texture measure applied to NDVI image.....	166

Figure B-5	Entropy texture measure applied to NDVI image.....	167
Figure B-6	Contrast texture measure applied to band 3 image.....	168
Figure B-7	Entropy texture measure applied to band 3 image.....	169
Figure C-1	Channel 1 difference image.....	171
Figure C-2	Channel 2 difference image.....	171
Figure C-3	Channel 3 difference image.....	172
Figure C-4	Channel 4 difference image.....	172
Figure C-5	Channel 5 difference image.....	173
Figure C-6	NDVI difference image.....	173
Figure C-7	Surface temperature brightness (Ts) difference image.....	174
Figure C-8	Ts/NDVI difference image.....	174
Figure C-9	Contrast texture measure (NDVI) difference image.....	175
Figure C-10	Entropy texture measure (NDVI) difference image.....	175
Figure C-11	Contrast texture measure (band 3) difference image.....	176
Figure C-12	Entropy texture measure (band 3) difference image.....	176
Figure D-1	Channel 3 post-classification change image.....	178
Figure D-2	Multi-spectral post-classification change image.....	178
Figure D-3	Channel 1 (RED) change image.....	179

Figure D-4	Channel 2 (NIR) change image.....	179
Figure D-5	Channel 3 change image.....	180
Figure D-6	NDVI differencing change image.....	180
Figure D-7	Surface temperature brightness (Ts) change image.....	181
Figure D-8	Ts/NDVI change image.....	181
Figure D-9	Contrast texture measure (NDVI) change image.....	182
Figure D-10	Entropy texture measure (NDVI) change image.....	182
Figure D-11	Contrast texture measure (band 3) change image.....	183
Figure D-12	Entropy texture measure (band 3) change image.....	183
Figure D-13	Principal component difference change image.....	184
Figure D-14	Combination 1 change image.....	184
Figure D-15	Combination 2 change image.....	185
Figure D-16	Combination 3 change image.....	185
Figure D-17	Combination 4 change image.....	186
Figure D-18	Combination 5 change image.....	186
Figure D-19	Combination 6 change image.....	187

List of Appendices

Appendix A.....	156
Appendix B.....	162
Appendix C.....	170
Appendix D.....	177

CHAPTER 1

INTRODUCTION

From space, we see a small and fragile ball dominated not by human activity and edifice but by a pattern of clouds, oceans, greenery, and soils. Humanity's inability to fit its doings into that pattern is changing planetary systems fundamentally. Many such changes are accompanied by life-threatening hazards. This new reality, from which there is no escape, must be recognized and managed (WCED 1987, p.1).

1.1 Introduction

Human survival depends on conserving a wide range of living resources and the diversity of life on Earth. It is therefore essential that ecosystems and their biotic components be protected. In addition to maintaining a reservoir of genetic information, natural areas perform a number of other functions crucial to our well being. These functions include regulating climate, maintaining the quality of the atmosphere and freshwater supplies, cycling of nutrients, disposing of waste, producing and maintaining soils, pollinating crops, and controlling pests and disease (Ehrlich 1980). However, many ecosystems have been altered

with the most noticeable changes taking place to the terrestrial environment which include biota, soil, surface and groundwater, and topography (Turner et al. 1995). This process of transforming the terrestrial environment has come to be known as land-cover change.

Some land-cover changes such as deforestation are obvious, converting cover of extensive areas from one type to another, for example from forest to grassland, pasture or settlement. More subtle forms of land-cover alterations are associated with activities such as selective logging, and result in within-type transformations. These changes can lead to degraded ecosystems with altered biomass content or net primary productivity (IGBP 1992).

Historically, most land-cover changes were caused by natural processes including such events as climatic variations, volcanic eruptions, or fires. These types of changes have always occurred, and will continue to take place. However, contemporary land-cover changes, and those of the recent past, are overwhelmingly the result of human activities.

Human-induced change has taken place at least since the use of fire by man and the advent of plant and animal domestication (Thomas 1956). Yet, these changes were still relatively minor in spatial scale, magnitude, and pace

through the agricultural phase of our history (Wolman and Fournier 1987). Since the beginning of the industrial age, however, the spatial scale, pace, and magnitude of human-induced change has increased exponentially (Turner et al. 1995). According to Turner et al. (1994) anthropogenic land-cover changes are occurring at unprecedented magnitudes, rates and spatial scales. For example, half of the ice-free surface of the Earth has been altered for human uses (Kates et al. 1990) and the annual diversion of water by human beings is about a quarter of the total yearly stable runoff on all the world's lands (Rogers 1994).

Unfortunately, the consumption requirements of today's society cannot be met without converting and altering the land environment. The most important human uses of land, both economically and in terms of spatial extent, include cultivation, livestock production, forestry, mining, settlement and associated infrastructure, recreation, and conservation (Turner et al. 1994; Turner et al. 1995). By 1992, according to the International Geosphere Biosphere Project (IGBP), humankind had ploughed 15 million square kilometres, used 32 million square kilometres as pasture for grazing animals, extracted timber from around 10 million square kilometres and has "left only the most inaccessible, unproductive and inhospitable parts of the remaining 90

million km squared in a pristine state" (IGBP 1992, p.11).

It is now generally recognized that a balance must be met between consumption and conservation. This way of thinking has led to the idea of sustainable development. As a result, many countries have begun to develop conservation strategies centred around this concept in addition to the establishment of more protected areas. While this is a step in the right direction there remains a need to monitor land-cover changes in environmentally sensitive areas which include parks and reserves to ensure that these initiatives are in fact meeting their objectives and succeeding at protecting natural resources and the diversity of life on Earth. If in fact they are not working, other actions must be taken because, as Lovejoy (1989) suggests, the measure of how we have managed our global resources will be judged on how much biological diversity has survived.

1.2 Objectives

This research has three primary objectives: (1) to conduct a historical review of deforestation in Peninsular Malaysia, its causes, and the measures employed by the government to control it; (2) to develop and test the effectiveness of a new methodology for change studies at regional scales that combines the resultant images from different digital change

detection techniques; and (3) to evaluate the usefulness of using remotely sensed data such as that obtained from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) sensor and fuzzy membership functions to monitor forest cover change in and around the protected areas of Peninsular Malaysia.

To accomplish these objectives composited AVHRR images of Peninsular Malaysia from 1992 and 1996 were obtained. New image bands were created by transforming the original image channels. Binary change/no-change images were produced. The resultant change images were then used in various combinations. All of the change images were compared to maps of Peninsular Malaysia from 1991 and 1996. The most suitable image obtained was then reclassified using fuzzy membership functions and analyzed to evaluate the effectiveness of using this technique with remotely sensed data for monitoring protected areas.

1.3 Study Rationale

1.3.1 Land-Cover Change Monitoring of Tropical Regions

Land-cover change monitoring is essential for a better understanding of the relationship between physical and human processes (Estes 1992; Jensen and Narumalani 1992).

However, at the end of the twentieth century uncertainty and

error remain relatively high concerning rates, magnitudes and spatial scales of this process. Estimates of the amounts of land-cover change from different sources can vary dramatically and have become controversial issues. According to Tucker et al. (1984, p.255) "the lack of any systematic data on the subject [i.e., estimates] has hampered discussion of what many scientists feel to be a major ecological crisis with serious biological, climatic, and political ramifications".

Accurate measurements of land-cover change are also needed for the development of predictive models. For example, the latest IPCC (WMO/UNEP-Intergovernmental Panel on Climate Change) report still considers the rate of tropical deforestation one of the key unknowns in global change climate assessment models (Turner et al. 1995). Consequently, these models have been fraught with uncertainties.

The need to monitor and quantify the rate, spatial pattern, and temporal characteristics of forest change at a sufficiently high frequency has been recognized by numerous organizations such as the International Geosphere Biosphere Project (IGBP), which has identified change detection as a key objective in their research programme. In addition to providing a foundation upon which a range of models can be

calibrated and validated they can provide supplementary information on the spatial relationships between land-use and land-cover change, landscape fragmentation, spatial trends and spatial diffusion (Turner et al. 1995). An accurate assessment of change is also needed in order to evaluate and correct national resource policies if need be. This is especially true of the situation in developing countries which are struggling to conserve their natural resources while at the same time expanding their economies.

1.3.2 Land-Cover Change and its Impact on Species

Changes in species, numbers and diversity are associated with land-cover changes at both the global and local level. There is still a great deal of uncertainty concerning the cumulative impact of land-cover changes at the global scale (IGBP 1992). This uncertainty results in part from a lack of accurate knowledge of the geographic extent and spatial pattern of land-cover change (Turner et al. 1995). At the local level it is known that soil erosion, surface run off from precipitation, and a decline in precipitation from changes in local climates are known to be associated with land-cover change. However,

"... the greatest irreversible change associated with land-cover change is the loss of biodiversity from habitat destruction and fragmentation. Some estimates suggest that at current global rates it could result in the loss of up to half of the world stock of

genes, which would drastically reduce the biological diversity of plant and animal species and severely limit the future of genetic stocks for biotechnology development (Turner et al. 1995, p.74).

According to Wilson (1992) the loss in the number of species and varieties in tropical forest alone is in the order of 27000 species annually, although much higher estimates exist (Ehrlich and Ehrlich 1981). This translates into an extinction rate approximately four hundred times normal (Wilson 1985). Many of these species will still not have been discovered and catalogued by the time they are gone. Given humankind's interest in the biological sciences, Lovejoy (1989) has stated that our heedless discard of species is perhaps the greatest anti-intellectual act of our history.

Since the start of this century, and particularly the latter half, it has been in the tropical realm that most of the major land-cover changes have occurred (US Interagency Task Force on Tropical Forests 1980; Allen and Barnes 1985; Brookfield et al. 1990; Thapa and Weber 1990; Myers 1993). Although naturally occurring fires have played a significant role in changing the landscape (Turner et al. 1995), as was witnessed in Indonesia during 1982 and 83, most of the changes to forest cover have been the result of human actions.

The pressure upon the poor to fulfil their essential need for cereals, fuel-wood and fodder, and the élite's desire to accumulate more and more wealth e.g. to maintain or consolidate socio-political power, have been the two major factors causing continuous destruction of forests (Thapa and Weber 1990, p.26).

The loss and degradation of tropical forest has affected numerous species of flora and fauna. At least half the Earth's species of organisms live in this region even though tropical forests cover only approximately five per cent of the total land surface of the planet (Wilson 1988; Soulé 1991). According to previous studies, forest fragmentation caused by human-induced land-cover changes poses the greatest threat to forest wildlife and is now the considered the main cause of species extinctions. It has been estimated that from 25 to 50 per cent or more of tropical species will vanish in the next century or sooner due simply to loss of habitat (Simberloff 1986; Wilson 1988; Reid and Miller 1989). The loss of a species, although in itself a cause for concern, may not be the most troublesome aspect of extinctions. Some researchers believe that the most serious consequence of species extinctions is that fewer genetic materials will be available for speciation processes, leading to a disruption of evolutionary courses (Myers 1989b). Lovejoy (1989) has stated that the Earth is

already in the initial stages of a biological transformation caused by a major loss of biological diversity.

Research during the late 1980s and early 1990s showed that tropical forests were being eliminated at ever increasing rates (Myers 1984; Lovejoy 1989; FAO/UNEP 1993). According to the FAO/UNEP (1993), the annual deforestation rate of tropical forests between 1980 and 1990 was 15.4 million hectares per annum which is more than double the rate of 7.3 million hectares per annum for the period 1970 to 1980 (Lanly 1981). It has been estimated that if deforestation continues at the same pace as in the 1980s only a few isolated patches of primary rain forest will remain by the middle of the next century (Myers 1993). Furthermore, by the year 2100, it is expected that almost all of the tropical forests outside of protected areas will be eliminated (Houghton 1990; Soulé 1991).

1.3.3 Parks and Protected Areas

The loss of tropical forest species and biodiversity has led to increased concern on the part of scientists and the public in general (Prins and Wind 1993). A survey conducted by Dixon and Sherman (1991) found that there is now a global consensus to protect natural forests for future generations. In addition to preserving biological diversity for the future, there are economic, scientific, and ethical reasons

for conservation (Ledec and Goodland 1988; Weston and Pearl 1989; Munasinghe 1992). Furthermore, many people simply "...feel a moral obligation to protect our only known living companions in the universe - many of which provide us with pleasure through the mere knowledge of their existence" (Munasinghe 1992, p.228).

Historically, the prime response on the part of countries and governments worldwide to safeguard ecosystems has been the creation of parks and protected areas. Therefore, at the end of the 1980s these entities represented the single most important method of conserving biological diversity worldwide (Brandon and Wells 1992). In 1989, approximately 4500 sites covering 4.8 million square kilometres, about 3.2 per cent of the Earth's land surface, had been designated as protected, half of which were located in the tropics (Reid and Miller 1989). By 1997, of the approximately 40 million square kilometres of forest in the world, just over three million were in protected areas (Iremonger et al. 1997). This represents eight per cent of the world's forests. The importance of protected areas in the tropics for conservation cannot be understated. These areas protect over two-thirds of the world's species, they are genetic libraries and serve as laboratories for research (Thorsell 1990). Parks and protected areas have also become

popular tourist destinations making substantial contributions to the economy of many tropical countries (Rubeli 1989; Malaysia 1991; ANON 1996).

All protected areas are by definition "lands or waters which we would presume would be threatened now or in the future by ill-conceived human activities were it not for their legal status" (Ham et al. 1993, p.233). For a time parks and protected areas were considered the ideal tool to promote conservation. M.A. Badshah (1962, p.24), the former wildlife officer of the State of Madras, India, stated in 1962 at the First World Conference on National Parks held in Seattle:

So far as I can visualize, the nearest approach to a paradise on earth - short of a fabled land with milk and honey flowing and angels and fairies in attendance - is a... park, a combination of some or all of the ingredients: forested hills and valleys, sparkling multicolored lakes, crystal clear streams, rippling brooks, placid rivers, silvery beaches, scented flowers, luscious fruits, sweet berries, snow-clad mountains, and wildlife. In the parks coexistence, tolerance, goodness, love, and attention prevail, and both man and beast can go each his own way and wander freely.

Unfortunately, most protected areas in developing countries have not lived up to this vision. Uncontrolled burning, fuelwood collection, illegal logging and hunting, the expansion of agricultural frontiers and development projects are posing major threats to the integrity of protected areas

(Brandon and Wells 1992). As a result, legally designated protected areas do not always provide forests with actual protection on the ground.

The governments and citizens of many tropical countries often cannot forego the economic opportunities that exist within parks and protected areas or on the land they occupy (Aiken 1994). This is because forest resources contribute in a wealth of ways to the economies of many countries and the daily lives of many of their citizens. As a result Johns (1985) has found that plans developed by economic and trade agencies usually take precedence over the initiatives of conservation departments. Illegal logging practices and poaching are also taking their toll. Unfortunately, many governments often turn a blind eye toward such activities for a number of reasons not the least of which are greed and corruption (Thapa and Weber 1990; see also Chin 1990, p.6). For example, on the Malaysian island state of Sarawak, it has been shown that timber extraction is being conducted in an unsustainable manner by many companies financially linked to several politicians in the ruling parties (Hanbury-Tenison 1990).

Studies of parks in the tropics found that rural people with few opportunities living in close proximity also pose serious threats to a park's security (Arnold and Minzava

1985; Brandon and Wells 1992; Kremen et al 1994). Generally people living in these areas rely on locally available forest resources for fuel and other essentials. The people in these areas often do not have access to government services and, because of their poverty, have no commercial alternatives. With virtually no political power there is little they can do and must resort to illegally entering protected areas (Brandon and Wells 1992).

The creation of parks and the subsequent loss of access to resources means that adjacent communities must bear substantial costs while receiving few benefits. These costs include both opportunity costs-- for example increased time resulting from loss of access to resources, such as fuel wood, and the need to collect it elsewhere-- and negative externalities, such as more tourists and cultural conflicts, associated with parks (Brandon and Wells 1992). For instance Kremen et al (1994, p.391) found that "in the Ranomafana National Park in Madagascar, short-term benefits available from slash-and-burn farming are more important to local residents than the long term benefits available from conservation...". Therefore, Pimentel et al. (1992) have suggested that whether or not a park will meet its objectives is largely dependent on socio-political factors in the surrounding area.

As a result of human activities, parks and protected areas are beginning to look like islands in seas of development (Harris 1984; Aiken and Leigh 1992; Kremen et al. 1994). As more and more land is cleared around parks they will increasingly suffer from 'edge effects' and become more "susceptible to invasions by exotic sun-loving species that normally live in open fields or the forest canopy" (Grainger 1993a, p.206). Therefore, conservation strategies are needed to safeguard the integrity of protected areas by ensuring that there are forests remaining directly outside protected areas which can serve as buffer zones against these negative effects.

1.3.4 Malaysia

There are many examples of countries struggling to protect their forests and the associated biodiversity. Malaysia, the area of study in this research, is one country facing this problem. Since about 1957, Malaysia has been faced with significant changes to its environment, and according to Aiken and Leigh (1992) is in the midst of an ecological transition.

Malaysia, a country in Southeast Asia, comprises the former federation of Malaya, the eleven states of Peninsular Malaysia, with the former British colonies of Sabah and Sarawak (Figure 1.1). Since the end of the nineteenth

Figure 1.1

Map of Peninsular Malaysia indicating land above 300 metres, international boundaries, and state boundaries, with inset showing regional situation.

Source: Aiken 1994, p.50.

century Malaysia has changed considerably as a nation.

After 1874 the colonial government began to establish the framework for a profitable export economy based on tin and plantation agriculture: an efficient legal and administrative apparatus was established, a modern system of communications was laid down, the Torrens system of land tenure was adopted (this providing undisputed title to land, thereby stimulating land development and resource exploitation), liberal taxation policies were implemented, a trigonometrical land survey was started, cheap labour was made available to planters and miners, and law and order were upheld (Aiken and Leigh 1992, p.49-50).

In 1957 Malaysia achieved independence which set the stage for even more changes. Many of these changes were linked to a set of government programmes which sought to restructure society and eradicate poverty among all Malaysians. Through a series of Five-Year Plans starting in 1961 the Malaysian economy has greatly expanded. The country's success in stimulating economic growth has been noted by numerous researchers (Cleary and Shaw 1994; Ghaffar 1994; Voon 1994) and can most clearly be seen by the fact that between the 1960s and the late 1980s its Gross Domestic Product (GDP) growth rate was amongst the eight most rapidly growing economies in the developing world (World Bank 1988). The strong performance of the Malaysian economy has continued and real GDP grew at 8.7 per cent between 1991 and 1995 (Malaysia 1996). It is expected that if economic development

continues at the same pace Malaysia will attain developed nation status by the year 2020 (Voon 1994).

Although Malaysia's development achievements over the last twenty-five years have been creditable and impressive, the environment has suffered as a result (Sham-Sani 1993). Negative effects to the environment include: soil erosion (Department of Environment 1991); water pollution (DoE 1991); air pollution (DoE 1991; Sham-Sani et al. 1991); and acid rain (Leong et al. 1988; Myers 1993). However, the most notable consequence of development has been the loss of forest cover due to land development programmes, commercial logging, shifting cultivation, urbanization and dam construction (Sham-Sani 1993).

The FAO/UNEP (1993) recently estimated that forest cover in Malaysia is decreasing by two per cent each year. Much of the deforestation has taken place on the Peninsula. According to Aiken and Leigh (1992), from 1958 to 1990 the proportion of the total land area covered with lowland forests in the Peninsula declined from seventy-four to about forty per cent. It is suspected that where there are forests still left, deforestation continues at a rapid pace today although somewhat slower when compared to the past. As a result of deforestation and habitat loss, many species of plants and animals have become either endangered or extinct.

For example, the Malaysian tiger thought to number 3500 in the early 1950s has dwindled to about 250 and is now confined to a few isolated areas. The Javan rhinoceros became extinct in 1932 (Collins *et al.* 1991).

In order to safeguard some of Malaysia's natural resources, British administrators and successive Malaysian governments have been setting aside land in protected areas since 1903. On the Peninsula where deforestation and forest degradation have been most widespread, protected areas account for 4641 square kilometres or about 9.9 per cent of the forest area still remaining. In an attempt to further conserve forests and safeguard the integrity of the protected areas already established, the Malaysian government has outlined programmes and initiatives in the Sixth Malaysian Plan (SMP) (1991-1995) that specifically addressed environmental issues.

There has been no published study quantifying changes in forest cover in and around protected areas in Peninsular Malaysia since Stevens (1968) raised the matter in the late sixties. Much of what has been reported in terms of the integrity of the protected area system is based on speculation and the informed opinions of experts. While these opinions are most likely correct, a quantitative study of protected areas is needed to set the record straight

(Thorsell 1990; Sawada et al. 1991; Aiken 1994). As Woodley (1990, p.50) states, "if parks and protected areas are to play their critical role in protecting biodiversity and ecological integrity, there must be an ongoing assessment of the state of the ecosystem under stewardship". This will allow for review and amendment of programmes and initiatives already established by the government, such as those outlined in the Sixth Malaysian Plan. With this type of information, new and more direct initiatives could then be included in future Malaysian development plans.

1.3.5 Land-Cover Change Monitoring

Monitoring land-cover changes have traditionally been done by conducting land-inventories through field work. Unfortunately, in general the collection of such information *in situ* is costly, time consuming, labour intensive and often virtually impossible because of the difficult terrain, uncomfortable climate and near impenetrable nature of tropical forests (Woodwell et al. 1987; Eastman and Fulk 1993; Jusoff and D'Souza 1996). Furthermore, political agendas and economic considerations have hampered the development of accurate estimates (Woodwell et al. 1987). Many countries, including Malaysia, also have a restricted status on maps and aerial photographs and access to them is difficult. Thus, information about deforestation is only

available from national agencies, a situation that leads to two problems. First, because of the cost and time needed to conduct them, national forest surveys have taken place rather infrequently, often more than ten years apart (Lovejoy 1989; Grainger 1993a,b). Furthermore, the minimum mapping unit often employed in most nation-wide forest classifications is too large to depict accurately all of the areas suffering from localized deforestation. As a result, deforestation of only a few square kilometres will not be included on smaller scale nation wide maps.

Second, countries are often hesitant to report the correct amount of deforestation. Many of these nations feel the need to cover up the true extent of deforestation because they cannot afford to be sanctioned by countries or development agencies which help finance many projects. For example, in the Philippines in 1977, a survey showed that the actual forest cover of that country was twenty-four thousand kilometres squared less than reported (General Electric and Department of Natural Resources 1977). Initially, it was thought that the Philippine government was not aware of the severity of deforestation within the country (Myers 1988). However, it was later revealed that :

the Philippine government, on the basis of previous national forest inventories, knew that forest cover was less than the fifty-seven per cent it had been reporting, but

continued to hold on to this figure as part of its deliberate cover-up of the rate and extent of deforestation (Kummer 1992, p.1469).

In some cases countries just simply do not want to be told what to do about their resources.

1.3.6 Change Detection using Remote Sensing

Due to scepticism surrounding official national figures the scientific community is continually searching for new and innovative ways to measure ecological changes that are occurring quickly and at a variety of scales (Greigor Jr. 1986) without governmental aid or interference. With advances in technology at the beginning of the 1970s it was hoped that remote sensing from space "... would offer the possibility of evaluating forest and other vegetative cover over large areas on a repetitive basis and at low cost per unit area covered" (Kummer 1992, p.1469). Remote sensing potentially offers researchers the ability to monitor, effectively and objectively, tropical forests and protected areas without undertaking a massive study in the field (Waring et al. 1986; Woodwell et al. 1987; Malingreau and Tucker 1988; Sader et al. 1990; Sawada et al. 1991; Malingreau et al. 1992; Grainger 1993a). In fact, according to Christenson et al., (1988) recording land-cover changes over time is perhaps one of the most important applications

of remote sensing data.

Thanks to a multitude of new imaging systems and advances in computing technologies, scientists and researchers now have an abundance of data and information available to them for land-cover change research. This has led to the establishment of a number of methodologies capable of detecting land-cover changes on digital images (Tucker et al. 1984; Malingreau and Tucker 1988; Belward 1992; Gong 1993; Lambin and Strahler 1994a, 1994b; Lambin and Ehrlich 1995, 1996, 1997; Mantovani and Setzer 1997; Nemani and Running 1997; Riou and Seyler 1997). However, to my knowledge, although comparisons have been made between change detection methodologies, no one has attempted to test the feasibility of combining different forms of imagery in the same study. Undoubtedly, an approach making use of more than just the original bands of imagery from a sensor would yield greater amounts of information especially with respect to subtle changes that may not always be apparent with individual methods. It is possible that such a method would be more reliable than any one method on its own especially when no training data are available. Another area of research that has been lacking is the use of remotely sensed data to analyze changes occurring within and around protected areas. This is unfortunate because remote sensing

could be an effective tool for monitoring such changes in near real time. This capability would provide resource managers with the opportunity to alter or modify forest management policies and conservation strategies in between more detailed *in situ* studies (see Dinerstein and Wikramanayake 1993).

1.4 Organization of the Thesis

The thesis is organized into six chapters. The present chapter, CHAPTER 1, is an introduction to the topic and describes the rationale behind the thesis. CHAPTER 2 is devoted to a brief description of Peninsular Malaysia. Much of the literature specifically devoted to conservation in Peninsular Malaysia has been published by Aiken (1994) and Aiken and Leigh (1992). As a result, Aiken's work forms a major component of the literature reviewed in this chapter. In addition, major studies of deforestation in Malaysia are reviewed individually as they cover different time periods and use different methodologies. CHAPTER 3 briefly reviews the various digital change detection techniques used in this research. A description of the source data and the methodology employed follows in CHAPTER 4. A new approach combining various proven change detection techniques is outlined and forms the basis of the methodology employed

here. CHAPTER 5 presents the analysis and results of the research. CHAPTER 6 is the conclusion and outlines areas of future research.

CHAPTER 2

STUDY AREA

Peninsular Malaysia

Malaysia is being transformed. Here, as elsewhere in the humid tropics, the clearest expression of ecological change is the demise of large tracts of tropical rain forest. Behind the now familiar images of the throbbing chain-saw, the toppling forest giants, and the relentless march of monocultures are national planning goals and policies, promises of future rewards that fuel rising expectations, more complex networks of communication and the demands of distant markets, the ever-present jockeying for control over natural resources, and a set of Western-style attitudes and values that reveal a desire to shape and control the natural world solely for the benefit of humans (Aiken and Leigh 1992, p.79).

2.1 Introduction

Peninsular Malaysia is located between latitudes 1° 20' and 6° 45' North and between longitudes 99° 40' and 104° 20' East (see Figure 1.1). The peninsula extends from the Isthmus of Kra to the Singapore Strait. The total land area of Peninsular Malaysia is approximately 132,000 square kilometres. The temperature generally remains the same

throughout the year. The mean temperatures during the day and night are 32° C and 22° C respectively. The average monthly temperature variation is about 2° C. There are two wet seasons which occur from November to February and August to October with an average annual rainfall of about 2540 mm. Precipitation occurs mostly in the afternoon. Humidity is always high and ranges from 70 to 98 per cent. The sky is cloudy most of the day, especially during the monsoon months. The relief is diversified with east and west coast plains and a central mountain range (Korbu Range) running north to south. Most development has occurred along the west coast. The east coast is much less developed by comparison. However, the construction of more roads linking the west and east coasts will surely increase development along the latter. Thanks to these new transportation networks even the most remote areas will soon become accessible.

The characteristic natural vegetation of Peninsular Malaysia is tropical rain forest whose distinctive flora are part of a botanical region called Malesia. Malesia is a botanical term used to designate the vegetation of the Malay archipelago and Peninsular Malaysia (Collins et al. 1991). Within the Malesian region is found the greatest floristic variety of any forest region on Earth (Whitmore 1984a,b). According to Steenis (1971; see also Whitmore 1984a), the

flora of the Malesian region as a whole includes at least 25,000 species of flowering plants, or about 10 per cent of the world's flora species. This region can be divided into three floristic provinces: South Malesia; East Malesia; and West Malesia which contains Peninsular Malaysia (Steenis 1950, 1979). The main difference between West Malesia and the other two provinces is that the former region has a greater abundance of the timber-rich, commercially valuable tree family Dipterocarpaceae (Whitmore 1988; Aiken and Leigh 1992). According to Whitmore (1988) no other forests in the world have such an abundance of species and genera of this commercially valuable tree family growing together in the same place.

Within Peninsular Malaysia itself, there are many different forest formations, depending on factors such as migrational history of the flora, variations in lithology, soils, topography, drainage, and altitude (Whitmore 1984a). Generally, however:

below an elevation of about 750m there are species-rich lowland and hill dipterocarp-dominated forests in dryland areas, and mangrove, peat swamp and freshwater-swamp forests in wetland areas. Lower montane and upper montane rain forest formations occur above 750m and 1500m respectively (Aiken and Leigh 1992, p.xv).

What follows describes the distribution of the various

forest formations in Peninsular Malaysia. More detailed description can be found elsewhere (see for example, Whitmore 1984a and 1988).

2.2 Forest Formations

Lowland evergreen rain forest is the most extensive forest formation on the Peninsula. At one time lowland evergreen rain forest covered almost the entire Peninsula in lowland areas and hill areas below 750 metres with no limiting factor (Whitmore 1988). Now, because of land development and logging, only a few patches of undisturbed primary forest remain, mainly in Northern Kelantan, in Pahang's Kerau Wildlife Reserve, in part of Taman Negara National Park and in Endau-Rompin (Aiken 1993). Except for a few emergent trees which can reach heights of 60 metres, the trees form a continuous canopy. Below the canopy there are saplings and a layer of shrubs. Generally this formation is located on the most productive land and is consequently the most species-rich. According to Aiken and Leigh (1992) virtually all of the lowland forests in their original climax state are now gone however.

Heath forest occurs mostly along the east coast. The Perak coast of Tanjung Hantu also contains minor amounts (Whitmore 1988). A patch of forest allied to heath forest

occurs on the summit of the plateau in the Endau-Rompin area. Heath forest has been known to replace lowland evergreen forest on free draining podzolic soils derived from siliceous parent materials (Whitmore 1984a). They generally contain trees of poor form and small size.

Three types of wetland forest formations occur in the Peninsula: freshwater-swamp forests, peat-swamp forest, and mangroves. These forests occur mostly along the west coast and to a lesser extent on the east coast, with a few patches of swamp forest inland (Aiken and Leigh 1992).

Freshwater-swamp forest forms over soils that are inundated with fresh water either permanently or periodically (Whitmore 1988). According to Whitmore (1988), this forest formation once occurred in all parts of Peninsular Malaysia. Unfortunately, most of Peninsular Malaysia's freshwater swamp forests have been cleared for agriculture and are now confined to a few isolated areas.

Peat-swamp forest can be found along the edges of both coasts of the Peninsula especially in the south east (Whitmore 1988), mostly along the coasts of Selangor, Pahang, and Johor (Figure 1.1). Many of the shallow peat-swamp areas have been converted to rubber, oil palm or pineapple plantations (Whitmore 1988).

Mangrove forests are the only wetland forests that can

grow in saline water. They are only found along tidal estuaries lagoons and the muddy shores of the west coast (Whitmore 1988). The trees range in height from 6 metres to 25 metres with an unbroken canopy. The north-east monsoon prevents these forests from forming along the more exposed east coast. In 1988, according to Whitmore (1988), out of a total coverage of 140,000 ha, 51,200 ha were found in Perak. Selangor and Johor also have large areas. These forests are utilized for poles, firewood and charcoal. In recent years, the mangrove forests have also been cleared for land uses such as agriculture, industry, airport and port development, salt-pans, and aquaculture ponds (Aiken and Leigh 1992; Whitmore 1988). As a result by the end of the century there will be little of this formation left (Aiken and Leigh 1992).

Montane forests occur above about 750 metres and can be found along the Main Range and its peaks (Collins et al. 1991). At approximately 750 metres lowland rain forest merges gradually with lower montane rain forest. At about 1500 metres lower montane rain forest is replaced by upper montane forest (Whitmore 1988). The trees here are less tall than in lowland forests and have an even canopy. There are also fewer species of the valuable Dipterocarpaceae. This fact, in addition to the often steep and difficult relief,

has spared a greater proportion of this forest type from logging activities and development projects. However, road construction is threatening this forest formation (Aiken and Leigh 1992) and according to Rubeli (1989) loggers are also beginning to harvest lumber in mountainous areas at altitudes of 800 metres or higher.

The importance of the forest cover for the flora and fauna can hardly be overstated because the overwhelming majority of the Peninsula's wild species are forest dwelling (Cranbrook 1988). In Peninsular Malaysia, it is estimated that there are about 8,000 species of flowering plants, 2,600 of which are trees; 370 species of birds (Wells 1988); 203 species of mammals including 83 species of bats (Cranbrook 1988); 110 species of snakes and thousands of insect species (Cranbrook 1988). Undoubtedly, there are many more species in Peninsular Malaysia that still await discovery. Estimates of endemism have been made for Malaysian plants and studies suggest that 33 per cent of tree species (Ng and Low 1982), 90 per cent of the Begoniaceae, 80 per cent of the Gesneriaceae (Kiew 1983) and 50 per cent of orchids are endemic.

Tropical forests also possess great real and potential value to Malaysia because they help to conserve soil, maintain environmental stability, minimize damage to rivers

and agricultural land by floods, and safeguard water supplies (Thang 1995). Furthermore, forests

...constitute a potentially renewable source of many economically valuable products (of which timber is only one); they carry scientific, educational, genetic, aesthetic, recreational, and intrinsic values; and they are the ancestral home of several forest-dwelling peoples (Aiken and Leigh 1992, p.45).

The importance of the forest, however, has not stopped people from destroying it.

2.3 Extent and Rate of Change of Forest Cover

There have been many studies of deforestation covering many different time periods in Malaysia (Sommer 1976; Myers 1980, 1989; Lanly 1981; Grainger 1983; FAO 1987; Salleh 1988). Although the results published in these studies are often quite different, it has been established that when the problems of definitions and assumptions are cleared up most estimates are similar (Melillo et al. 1985). All of the studies have found that the extent of Peninsular Malaysia's forest cover has steadily decreased since the end of the nineteenth century. Four studies, however, deserve particular attention.

The FAO/UNEP (1993) recently estimated that forest cover was decreasing by two per cent each year between 1980 and 1990 in all of Malaysia. The FAO/UNEP arrived at this

figure through both classification of various remotely sensed images and national forest surveys. The FAO's 1993 estimate is singled out because it is considered authoritative (Grainger 1996). However, many researchers such as Myers (1984) contend that the FAO's estimates are too low because in their analysis they do not consider forest degradation. For example, according to the FAO/UNEP (1993, p.10):

Deforestation refers to change of land use with the depletion of tree crown cover to less than 10 per cent. Changes within the forest class (from closed to open forest) which negatively affect the stand or site and capacity are termed forest degradation.

Therefore, under this definition, deforestation only takes place when forest is replaced by another land use, which includes different types of shifting and permanent agriculture as well as non-agricultural uses such as mining. Selective logging is not included even though it has been shown to cause significant damage and also severely alter the composition of the residual stand.

Brookfield et al. (1990) have also conducted a detailed study of Peninsular Malaysia. Based on post classification analysis of land-use maps, they found that 64 per cent of the land area of the Peninsula was still under forest in 1966, and this after already more than a decade of rapid conversion. The proportion of land covered with forest was

reduced to 59 per cent by 1974 and then to only 51 per cent by 1982.

Bernard and DeKoninck (1997), who used maps from the National Forest Inventory of Peninsular Malaysia (1972,1982,1992), similarly found that forest cover had been reduced to 53 per cent by 1982. By 1992 the extent was reduced to less than 47 per cent. Their figures indicate that the average annual deforestation was less during the 1980s (1.06 per cent) compared to the previous decade (1.94 per cent). However, the rate of retreat of undisturbed forest alone accelerated during the second decade from 2.75 per cent to 4.48 per cent. According to Bernard and DeKoninck (1997, p.3) "...more than half of the undisturbed forest of 1972 had been lost or down graded by 1992".

The Malaysian government has also been monitoring forest resources. The forestry department is currently charged with this task. Up to now there have been three forest inventories carried out in Peninsular Malaysia, all of which have been conducted by the Malaysian Forestry Department in conjunction with the UNDP/FAO project.

The objective of these inventories was to enable the forestry department to review and/or update the various policies and strategies that had been formulated for the development of the forestry sector in terms of the ability of the forest resource base to support the wood-based industries and in the formulation of more effective forest

management systems in accordance with the principle of sustained yield (Thang 1995, p.14).

The latest forest inventory (1991-1993) shows that 45.3 per cent of the Peninsula was covered with forest in 1993. The monitoring of changes in forest cover was done through post-classification analysis of satellite images and forest cover maps along with *in situ* information. Findings showed that for the period 1983 to 1993 a total of 580,000 hectares of forest, or 8.9 per cent of the total forested areas in Peninsular Malaysia, had been converted to non-forestry uses. The forest resource data obtained in this latest inventory have also been entered into a GIS to allow for continuous updating through ground sampling and the analysis of geocoded Landsat TM imageries (Thang 1993). However, no new findings have yet been published.

2.4 Causes of Deforestation and Forest Degradation

Forests have always been a resource exploited by people all over the world. Peninsular Malaysia's forests are no exception. They have been used for centuries by the Orang Asli (aborigines). According to Barlow (1978), however, only approximately two per cent of Peninsular Malaysia's forest had been cleared by people in 1876. The scale and pace of change began to increase dramatically during the late

nineteenth century, when British colonialism and the expansion of the world economy exerted increasing pressure on the forests. At that time the forest was just regarded by many officials as an unproductive liability (Hurst 1987). The land on which forest grew, however, was recognized as an opportunity for development. Consequently, forests were cleared for other land uses.

The colonial economy was based mainly on tin and rubber, the latter requiring large amounts of land. Most of the deforestation during the colonial era was confined to the west coast. The east coast remained relatively untouched. By the end of the colonial period, only one-quarter of the Peninsula was no longer covered with forest (Aiken and Leigh 1992).

In recent decades the pace and scale of forest clearance have increased dramatically. Most of the deforestation and forest degradation has taken place since Peninsular Malaysia achieved independence in 1957. Two processes have been mainly responsible: logging and land development for cash crops.

2.4.1 Logging

Timber has been a major source of revenue for Malaysia in the last few decades; consequently, it has been heavily exploited. According to Aiken and Leigh (1992, p.68) "prior

to the 1950s, the timber industries of Malaya [Peninsular Malaysia] and Sarawak were mainly geared to meeting local demand". Since the 1960s, the importance of timber has increased and is now Malaysia's third-largest foreign-exchange earner after manufacturing and cash crop exports (Malaysia 1991). In 1993 the value of timber exports was 12.5 billion RM which is 10.3 per cent of the country's total export earnings. Furthermore, the forestry sector accounted for 4.6 per cent of the country's GDP and employed about three per cent of the country's labour force.

However, because of political factors and greed many impartial observers suggest that the forestry industry in Malaysia is operating at unsustainable levels. According to Ngau et al., (1987, p.177) "forests provide ready easy wealth for those in power and huge forest concessions have been issued to timber companies often owned by Malaysian politicians or those related by blood or money to them". Not surprisingly, it has been found that extraction rates increase just before elections (Hurst 1987).

Many Malaysian politicians argue that forestry is too important to the economy to drastically cut back the amount of timber harvested. For example, in 1987 Sarawak Environment and Tourism Minister Datuk Amar James Wong, who also happens to own a large logging concession, was quoted

as saying that "logging is important, without it Sarawak cannot have the revenue to improve the standard of living of the people" (ANON, 1987). Yet, many of the people he is talking about are themselves actively protesting against logging operations which are affecting their lives in a multitude of negative ways (see for example Pearce 1990 and Rubeli 1987). Furthermore, as Hurst (1987, p.174) points out:

If an attempt is made to assess the cultural costs (of the logging industry), the lost potential for development and for secondary industries once the timber has been removed, and the cost of rehabilitating and maintaining the resident population, it may well be found that far from bringing benefits to the people, the eventual effect of the lumber business has been to lower the standard of living and remove their ability to be self-supporting.

Although not all trees in a concession are removed in selective logging operations in Malaysia, this form of timber harvesting has still had a major impact on the forest. According to Ngau et al. (1987) the amount of timber extracted per hectare in Malaysia is among the highest in the world. This is due to damage inflicted on non-commercial trees in the logged areas. It has been shown that selective logging damages as much as forty per cent of the surrounding trees in a logging area during extraction (Kartawinata et al. 1981). Many of the damaged trees eventually die.

Consequently, susceptibility to fire increases because of the large amounts of dead wood left in the area. Soils are also compacted by heavy machinery often used to drag the logs out of the area.

Many of the guidelines designed to limit the amount of residual damage are ignored because concessions usually run out before forests can regenerate. As a result, there is little incentive for logging companies to be careful during the extraction process. According to Collins et al. (1991) and Brookfield and Byron (1990) it was clear that by the late 1970s, the rates of logging in Malaysia were not sustainable.

It is expected that the Peninsula will become a net importer of logs by the turn of the next century (Thang 1995) due to supply shortages of certain species. Some sawmills were already experiencing shortages in the late 1980s (Rachagan and Bahrin 1983; Aiken and Leigh 1992) and logs of certain species were already being imported to the Peninsula from East Malaysia and Indonesia as early as 1981 (Ngau et al. 1987).

The view among many foresters in Malaysia is that the industry is operating sustainably and that forests will recover naturally after selective logging no matter what the damage done during the extraction process. Datuk Amar Wong

is even quoted as saying that "...five years after an area is logged, one would not be able to tell the difference between it and primary forest" (ANON 1987). This view is contradictory to that held by most environmentalists. For example, in the following excerpt from his book *The Primary Source* Myers describes a forest after being selectively logged:

Whereas in a primary forest I would catch mere glimpses of sky through the canopy overhead, in the logged forest I would see much more sky than tree crowns. In a primary forest I walk around in the gloom of the forest floor, but in a logged forest I feel the direct glare of the sun most of the time, and in those extensive sectors where logging winches and bulldozing skidders have done their work, the ground sports no more vegetation than Times Square. Of wildlife I see virtually nothing. Instead of the chattering of monkeys in the tree tops, the constant rustle of small animals in the undergrowth, the steady songs of birds, and the buzz of insects all around, the forest is silent. Yet because the area has not become permanent farmland, or oil palm estate or a tea plantation, it cannot in some observers' eyes be designated as anything other than forest. In any case they also say that while it may look little like a forest right now, it will regenerate to a forest within a few years. But what sort of forest? (Myers 1984, p.171).

Wong's views are further refuted by the fact that it has been shown that on the Peninsula, in addition to the loss of forest cover, there has been a twenty-eight per cent decline in the biomass of the remaining forest as a result of

logging (Brown *et al.* 1991). This is a result of damage inflicted on the residual trees and an overall change in tree species composition (Kartawinata *et al.* 1981; Whitmore 1990).

2.4.2 Land Development Schemes

The other process that has historically accounted for large amounts of forest destruction in Peninsular Malaysia is land development schemes (Figure 2.1). Land development schemes linked to agricultural colonisation have been a hallmark of the Malaysian economy (DeKonnick 1981, 1986) and have played a central role in its programme of rural development and modernization. According to Aiken and Leigh (1992, p.65), "land development in thinly settled or frontier areas has been the single most important cause of deforestation in the Peninsula...". Much of the development has been for cash crops. Brookfield *et al.* (1990, p.506) have found that

the total area under agricultural land use comprised only 21% of the Peninsula in 1966, but 39% in 1982. By the time the conversion program reaches its planned limits in the mid-1990's, only 39% of the area will remain under forest... and around 45% will be under agriculture. Taking the whole period since the early 1950s, when about 73% of the area was estimated to be under forest..., almost one-half of the then-existing forests will have been cleared and converted....

One land development agency in particular has had a profound impact on the forest. The activities of the Federal

Figure 2.1
Regional development schemes in Peninsular Malaysia.

Source: Collins et al. 1991, p.41.

Land Development Authority (FELDA) have been responsible for approximately seven per cent of all forest conversions on the Peninsula (see also for example Table 2.1). Created in 1956, FELDA's mandate was to improve the socioeconomic status of the landless and unemployed.

FELDA has had a major impact on the forest because it was given authority to open up new areas for development. Furthermore, FELDA was responsible for bringing settlers to work in these new areas and supervising the transformation of land into large-scale agricultural schemes devoted to the production of mainly oil palm and rubber for export (Aiken and Leigh 1992). As a result of FELDA's activities, the annual area of forest cleared rose from about 80 km² in the early 1960s to over 350 km² in the late 1970s. However, as Aiken and Leigh (1992, p.68) point out:

Ironically, the amount of idle land in already established agricultural areas probably now exceeds the total amount of land that FELDA has brought into production. Surely it is the case... that the transfer of farmers to FELDA and other schemes contributes to the abandonment of land elsewhere (Aiken and Leigh 1992, p.68).

Since around 1970 the government has strongly encouraged the modernisation of rural life (Malaysia 1971). As a result, FELDA has sponsored many large-scale

Table 2.1
Development land by state 1971-80 (ha).

State	FELDA	FELCRA	RISDA	Regional authorities	State agencies	Private sector	Total
Selangor*	342	--	--	--	10189	8278	18810
Johor	81645	12782	2308	16307	18735	11038	142815
Melaka	2087	1621	--	--	--	3373	7081
N.Sembilan	62710	6735	2807	--	5567	12878	90697
Pahang	164869	8143	10434	18255	47033	13491	262225
Perak	17133	9332	7252	--	13530	7206	54453
P.Pinang	--	--	--	--	--	--	--
Kedah	6879	4377	1324	--	10942	184	23706
Kelantan	10693	1473	7338	5663	11048	379	36494
Perlis	3187	--	--	--	--	--	3187
Terengganu	22732	6247	--	15623	41492	4599	90693
TOTAL	372277	50710	31464	55848	158536	61327	730162

* Includes the Federal Territory

FELDA:Federal Land Development Authority FELCRA:Federal Land Consolidation and Rehabilitation Authority
RISDA:Rubber Industry Smallholders Development Authority

Taken from: Salleh 1988, p.131.

development projects. By 1990, at least 847,705 ha of land had been developed (Table 2.2). Most of this land (736,004 ha), was originally covered with forest (Bulletin FELDA 1993).

By 1990, "...the availability of new land was becoming scarce as ecological and environmental pressures favoured the preservation of the remaining forest land..." (Sutton and Buang 1995, p.127; see also Malaysia 1991) mainly because of FELDA initiatives. Therefore, as stated in the Sixth Malaysian Plan (1991-95) no new land was to be developed by FELDA except for the continuation of projects underway (Malaysia 1991). However, land conversion was not expected to stop entirely as the private sector was to become responsible for the majority of new land conversion working within the framework set out by the Regional Development Authorities (Malaysia 1991; Sutton and Buang 1995). As a result between 1991 and 1995 close to 265000 hectares of new land were developed (Malaysia 1996).

Even though FELDA has been responsible for large amounts of forest destruction, numerous researchers continue to cite FELDA as a success according to various production or social indicators (Oberai 1986; Hulme 1987; World Bank 1987). However, in addition to the damage FELDA has done to the forests, critics such as Kottack (1985) contend that

Table 2.2
Land development by FELDA, 1956-1990.

	Period	Area (ha)
First Malaya Plan	1956-60	6619
Second Malaya Plan	1961-5	48269
First Malaysia Plan	1966-70	72423
Second Malaysia Plan	1970-5	166847
Third Malaysia Plan	1976-80	216447
Fourth Malaysia Plan	1981-5	161600
Fifth Malaysia Plan	1986-90	175745
Sixth Malaysia Plan	1991-5	-
Total		847950

Source: Aiken and Leigh 1992, p.66.

FELDA fails to put people ahead of land settlement and 265000 economic objectives. According to Mehmet (1986, p.63) FELDA "...has tended to divert increasing surpluses to growth and diversification at the expense of its objectives of poverty amelioration". As a result, poverty is still widespread in Peninsular Malaysia. Those who have been relocated on large cash crop plantations often encounter appalling living conditions, sometimes worse than those they have left.

2.4.3 Other Causes

There are a number of other activities that are responsible for deforestation and forest degradation. One of the greatest threats to Malaysian forests during the 1990s is the construction and planning of hydro-electric dam projects (Ngau et al. 1987). These dams are intended to be the answer to Malaysia's future energy needs which are more important to those in charge of the country than conserving forests. For example, the Bakun Hydroelectric Dam project on Sarawak was postponed due to reasons which included environmental considerations, only to resurface two years later without any questions regarding environmental, economic, social and ecological impacts having been answered (ANON 1996). Even Taman Negara, the Peninsula's only national park, has been threatened with a possible hydro electric power project on

more than one occasion. Tho (1991) has estimated that as of 1990, at least 100,000 hectares of forest have already been inundated by dams.

Also contributing to deforestation and forest degradation is the growing effect of urbanization and highway construction (Brookfield et al. 1990). Many of these new roads are designed to promote tourism, economic development, expansion of agricultural areas and mineral prospecting, all of which will further increase the loss and deterioration of forest (ANON 1996). During the Sixth Malaysia Plan the total road network increased by 19.2 per cent from 53984 kilometres to 64328 kilometres. As a result, road density which measures road length over total area increased from 0.12 to 0.2 kilometre of road per square kilometre over the decade 1985-95 thereby increasing road coverage and accessible in any given area 67 per cent. Now even the most remote areas will become accessible.

2.5 Conservation in Peninsular Malaysia

2.5.1 Parks and Protected Areas

Although stimulating economic activity has always been the main goal of the Peninsula's administrators, it was realized at the turn of the century that the country's resources were fast disappearing. As Aiken (1994, p.49) states, "it was

characteristic of the many contradictions of colonialism... that some attention was also given to how these same natural assets, including wildlife, might be conserved or at least protected". One response was the establishment of protected areas.

The first protected area, Chior Game Reserve, was established in 1903. By the end of the colonial period in 1957, there were 20 protected areas. There are presently 25 such areas in Peninsular Malaysia. Figure 2.2 shows all of the protected areas over 50 square kilometres. Much of the current area that is protected is contained within Taman Negara. State forestry departments have also set aside pockets of virgin forest to serve as controls for comparing harvested and silviculturally treated forests and as undisturbed natural forests for general ecological and botanical studies. These small pockets are known as Virgin Jungle Reserves (VJR) and since the 1950s a total of 81 covering 910 square kilometres have been established throughout Peninsular Malaysia. Most of these areas, however, are much too small to provide any real protection for forest species. Nevertheless, Peninsular Malaysia has a total of 0.74 million ha of forest protected by legislation.

According to Aiken (1994), however, this figure does not accurately depict the current situation. Forest

Figure 2.2

**Map of Peninsular Malaysia showing protected areas
of at least 50 square kilometres in size.**

Source: Rhind and Iremonger 1996.

formations, such as lowland rain forest and mangrove forests, are under-represented in protected areas (Collins et al. 1991; Aiken, 1994). This is partly because since 1964 land-use planning has been guided by the Land Capability Classification. Protected areas are included in Class V which is land possessing little or no mineral, agricultural or productive forest development potential. Therefore, lowland rain forest for example, which is usually found on the most productive land, is not destined to be protected under these guidelines. Furthermore, Malaysia's protected areas have always suffered from insecure tenure. The former Director of the Malaysian Department of Wildlife and National Parks has even commented that "...most of Malaysia's protected areas only look good on paper having in most cases no secure land tenure" (Khan 1988, p.258).

Malaysia's protected areas are constantly under threat of rescission, excision and intrusions. The main reason for these threats according to Aiken (1994, p.52) was neatly summarized by Maxwell's comment that 'the interests of development and agricultural progress are paramount and must prevail'. Market-minded decision-makers have in many cases been able to lobby for the deletion or excision of parts of protected areas that have stood in the way of commercial development (Aiken, 1994). Illegal entry has occurred when

permission has not been granted.

Aside from Taman Negara, the Peninsula's only National Park, all parks can be easily degazetted for development if the state governments so choose. The reason for this is because the Malaysian constitution grants rights over land matters to the respective state governments. This means that state decision makers are in charge of land matters including the establishment and maintenance of parks and reserves. Even though a National Parks Act was created in 1980 (and amended in 1983) providing for the establishment of national parks, it has no legal force. Federal Ministers can only request states to put aside land. The states do not have to comply and are reluctant to lose control over land ownership. Consequently, the act has not been used. However, even though each state manages its own forests, it does so under a national forest policy which requests that each state should maintain 47 per cent of its land area as forest.

Currently, 4.68 million hectares are allocated to the Permanent Forest Estate (PFE) within Peninsular Malaysia (Figure 2.3). This land is meant to be under sustainable management. Forested lands outside the PFE, apart from those already established as conservation areas, are destined to be logged and may eventually be converted for agricultural

Figure 2.3

Map of Peninsular Malaysia showing the
Permanent Forest Estate (1995).

Source: Thang 1995, p.37.

use. Of the 0.72 million hectares of forest in protected areas, 0.53 million hectares are located outside the PFE. Only 0.19 hectares are within the Estate. This is unfortunate because, since they do not have the production forests of the PFE to act as a buffer, the majority of these already established areas will eventually become susceptible to edge effects as more land is cleared around them.

2.5.2 Conservation Initiatives

Legislation designed to supplement protected areas and conserve greater amounts of forest has recently been established in Malaysia. "The government is...formulating a National Conservation Strategy to provide a framework for comprehensive resource management and utilization" (Malaysia 1991 p.398). In support of this strategy nine states have begun to formulate their own conservation strategies with the assistance of the World Wildlife Fund for Nature. Furthermore, the National Forest Policy, established in 1978, was revised in 1992 in response to concerns about the loss of forests. Important aspects of forestry such as the conservation of biological diversity, sustainable utilisation of genetic resources, as well as the role of local communities in forest development will now be included. The National Forestry Act of 1984, was also amended in 1993 to deal with forest encroachment and illegal

logging. There is now a provision for the Police and Armed Forces to undertake surveillance activities.

The penalty for any forest offense has been increased from a maximum of RM 10,000 or imprisonment for a term not exceeding 3 years to a maximum of RM 500,000 and imprisonment not exceeding 20 years with a mandatory imprisonment of at least 1 year (Dato 1997, p.5).

A list of protected species of flora and fauna has also been created.

The Sixth Malaysian Plan (SMP), meant to guide the economy and development between 1991 and 1995, gave further attention to environmental issues and sustainable development. As stated by the Prime Minister of Malaysia The Sixth Malaysia Plan outlines "...programmes for the protection of the environment and ecology so as to maintain the long term sustainability of the country's resources and development" (Malaysia 1991, p.vi). In addition to addressing general environmental issues, the plan outlines certain objectives that are specifically designed to conserve forests. First, additional forested areas were to be designated in order to ensure ecological balance, minimize environmental degradation and preserve essential habitats and biodiversity. Second, large-scale reforestation programmes and research were to be carried out. Towards this end 101,300 hectares of logged-over areas will be

rehabilitated annually. Thirdly, tree cover was to be "...expanded to preserve the habitats, safeguard soil quality, reduce siltation and erosion, sustain climatic balances and also to absorb excessive carbon dioxide released into the atmosphere" (Malaysia 1991, p.399). The final objective is to carefully plan and monitor programmes and projects that are likely to adversely affect the environment. Interestingly, this last objective does not state that programmes or projects adversely affecting the environment will be stopped but rather simply monitored.

To accomplish these objectives, the growth of agricultural sector was to be constrained by measures taken to control the exploitation of forest resources to a more sustainable level. As a result, its share of the economy declined from 18.7 per cent in 1990 to 13.6 per cent in 1995 (Malaysia 1996). The forestry sector was also not allowed to expand any further. As stated in section 1.82 of the SMP

...greater emphasis will be given to forest conservation to maintain environmental stability and ecological balance. The rate of logging will be reduced to ensure sustainable forest management in line with the National Forest Policy. At the same time continued efforts in rehabilitation and redevelopment of logged-over areas will enable the continued stable supply of timber to meet the needs of downstream processing into higher value-added timber products. In this way, production and protection will be harmonized so that the sound management and preservation of the forest will help advance economic

growth while ensuring protection for the lands climate, habitat and ecology of the country (Malaysia 1991, p.42).

However, it must be noted that during the Fifth Malaysian Plan, in spite of a policy to sustain yield levels, the annual felling rate of logs increased by 5.8 per cent annually. Nevertheless the production of sawlogs has declined by 4.3 per cent per annum during the plan period. In addition to curtailing the number of logs harvested the government has encouraged reforestation and indeed begun to reforest areas. However, the sizes of these areas are insignificant when compared to the amount being logged. Of greater significance, however, is the realization by the forestry department that the diversity of the flora and fauna is not disadvantageous to wood production policies and strategies and could in fact enable wood-based industries to take advantage of the changing demands of the timber market. As Dato (1997, p.4) states

A heterogeneous forest enhances prospects for the conservation of the total amount of biological diversity, protection of soil and water resources, maintenance of environmental stability and quality, as well as a fuller utilisation of the forest resources, particularly non-wood products, and that it minimizes the cost of regeneration (Dato 1997, p.4).

This has led to changes in the forest management systems employed by the logging industry and there has been a shift

from artificially stocking the residual forest with only a few commercially valuable species to letting forests regenerate naturally as much as possible.

Forest conversion for agriculture will slow down in the upcoming years as Malaysia moves toward greater industrialisation. Land and Regional Development was given a lower allocation of 2383 million RM, compared to 2946 RM in the Fifth Malaysian Plan. FELDA, instead of developing new areas as previously mentioned, began to concentrate on replanting programmes. However, as previously mentioned land development continues through private sector initiatives.

At the international level Malaysia became a signatory to the Convention Concerning World Cultural and Natural Heritage (World Heritage Convention) on December 7, 1988, although no sites have yet been nominated for inscription on the World Heritage List.

While it seems as though the Malaysian government has realized the importance of conserving its forest resources it will be interesting to see if these policy changes work and hold up especially during recessions. It is therefore extremely important that protected areas and the forests surrounding them be monitored. Consistent monitoring will ensure that new protected areas can be established within

the PFE if it can be established that those areas outside its boundaries are suffering too much from edge effects.

CHAPTER 3

DIGITAL CHANGE DETECTION

In the foreseeable future, the tropics will continue to be a biome experiencing rapid development pressure, population growth, and concomitant environmental change. The remote sensing community has the tools, data, and expertise available to assist in monitoring ecological processes and change in one of the Earth's least understood and most diverse biomes (Sader et al. 1990, p.1348).

3.1 Digital Change Detection

Prior to the 1970s, there was no efficient method available for quantifying land-cover changes over large areas (Nemani et al. 1996). In the past, monitoring and reporting changes were undertaken by individual countries, resulting in many controversial estimates that have been treated with a great deal of scepticism. However, with the advent of remote sensing and satellite imagery there is now the possibility for consistent repeatable, nonintrusive coverage at a relatively low cost.

Change detection "...is the process of identifying differences in the state of an object or phenomenon by observing it at different times" (Singh 1989, p.989). With

remotely sensed data, changes in land cover will result in changes to radiance values when all other variables are equal. Jha and Unni (1994, p.2544) have summarized the advantages of using satellites to monitor land-cover change as follows:

- 1) has a systematic period between overflights; 2) records imagery of the same geographic area at the same time of day to minimize diurnal sun angle effects; 3) maintains the same scale and look-angle geometry; 4) reduces relief displacement as much as possible; and 5) records reflected radiant flux in consistent and useful spectral regions.

Researchers also suggest that in light "...of rapid anthropogenic changes, only remote sensing can provide accurate and repeatable means of land cover analysis and monitoring" (Nemani et al. 1996, p.7157; see also Townshend et al. 1991 and Running et al. 1994).

Numerous methodologies have been developed to detect changes on digital images (Collins and Woodcock 1996; Jensen 1996). Table 3.1 provides a summary of the change detection techniques that form the basis of the methodology used in this research. These techniques were selected because they have all been used successfully in change detection studies of tropical environments. What follows are brief reviews of each of these techniques.

Table 3.1

Change detection studies used to formulate the methodology in this research.

Author	Date	Technique	Sensor	Location
Mantovani and Setzer	1997	Image Algebra	AVHRR (Band 3)	Amazonia
Riou and Seyler	1997	Texture Measures	SPOT	South Cameroon
Nemani and Running	1997	Surface Temperature-Vegetation Index Ratio	AVHRR	United States
Lambin and Ehrlich	1997	Surface Temperature and Vegetation Index Differencing	AVHRR	Sub-Saharan Africa
Lambin and Ehrlich	1996	Surface Temperature-Vegetation Index Ratio Differencing	AVHRR	Africa
Lambin and Ehrlich	1995	Surface Temperature-Vegetation Index Ratio Differencing	AVHRR (GAC)	Africa
Lambin and Strahler	1994	Spatial Structure, NDVI Differencing, PCA, Post Classification Analysis	AVHRR	Africa
Gong	1993	Image Algebra, PCA, Fuzzy Classification	Landsat TM	Kitchener-Waterloo Ontario
Malingreau and Tucker	1988	Image Algebra	AVHRR (Band 3)	Amazon Basin Brazil
Tucker et al.	1984	Image Algebra	AVHRR (Band 3)	Rondonia Brazil

3.2 Image Algebra

Change detection techniques can be grouped into one of two categories: those employing image algebra and those employing image transformations (Gong 1993). Image algebra contains those procedures that simply use some form of arithmetic on images obtained on different dates for the same spectral band (Figure 3.1). Gong (1993) defines the two images obtained for different dates of the same spectral band as band-pair images. These band-pair images can be subtracted from one another or ratioed. The resultant image from these procedures is referred to as a change component image. Thresholds or classifications can then be applied to the change component image in order to locate areas of change (Fung and LeDrew 1988; Pilon et al. 1988; Singh 1989; Gong 1993; Jensen 1996). In the case of subtracted images, any pixel not equal to, or approaching zero, may be considered as having undergone some form of change assuming all other factors are equal. "Band ratioing involves exactly the same logic except a ratio is computed and the...pixels that did not change have a ratio value of 1 in the change image" (Jensen 1996, p.266).

Due to their simplicity, these techniques were most commonly used in early change detection studies in various

Figure 3.1

Diagram of image algebra change detection.

Source: Jensen 1996, p.267

environments including the tropics (Wilson et al. 1976; Todd 1977; Weismiller et al. 1977; Howarth and Wickware 1981; Howarth and Boasson 1983; Nelson 1983). For example, Miller et al. (1978) used subtracted images to map changes in tropical forest cover in Northern Thailand. Singh (1989) has also superimposed multiple change component images to create a colour composite to monitor changes due to shifting cultivation in India. Research, however, has pointed out a number of problems associated with this technique (Weismiller et al. 1977; Riordan 1980). These include its sensitivity to misregistration, the existence of mixed pixels and failing to consider the starting and ending locations of a pixel in feature space (Riordan 1980).

A second group of change detection techniques have been developed employing image transformations (Gong 1993). These techniques include among others: post-classification analysis, vegetation index differencing, principal component analysis, fuzzy membership functions of change and the use of spatial information. Generally these techniques are more complex than image algebra and require greater computer processing capabilities.

3.3 Post-Classification Comparison

Post classification comparison is the most commonly used transformed image change detection procedure and the one most commonly used by countries in their national mapping surveys (Jensen et al. 1993). In this approach two classified maps are compared to detect changes (Figure 3.2). However, "the change map product exhibits an accuracy similar to the product of the accuracy of each individual map..." (Lambin and Ehrlich 1997, p.185). This means that two maps with accuracies of 80 per cent each, for example, will have an overall accuracy of approximately 64 per cent. Nevertheless, this technique has been used with some success. For example, Malingreau and Tucker (1988) used AVHRR thermal channel 3 (3.5-3.9 μm), which has the greatest spectral contrast between forest and non-forest, to map these two classes in Brazil between 1984-1986. They then compared the resultant classified maps in order to detect deforestation. After ground verification they found that their deforestation estimates were conservative and concluded that large-scale AVHRR-based deforestation studies are not significantly biased and are a good source of information.

Figure 3.2

**Diagram of multi-date post-classification comparison
change detection.**

Source: Jensen 1996, p.269

3.4 Vegetation Index Differencing

Research has shown that "...the use of the red and near-infrared channels of the sensors on board satellites are particularly well suited for the study of vegetation"

(Bannari et al. 1995, p.95) (see Figure 3.3). Various combinations of these channels are used to develop indices to assess the condition of vegetation. Empirical studies, at a variety of spatial scales and in different ecosystems, have successfully correlated vegetation indices with variables related to

(1) canopy quantities (green biomass, leaf area index, above-ground biomass per cent canopy cover, etc.) (2) state of the vegetation (stress, vigour, chlorophyll content, etc.), (3) solar radiation interaction with plant canopies (intercepted and absorbed photosynthetically active radiation, etc.), (4) vegetation moisture (leaf water content, water satisfaction index, plant canopy water stress etc.) (5) ecological variables (rainfall, potential and actual accumulated evapotranspiration, surface temperature) and (6) instantaneous rates associated with the activity of the vegetation (rates of photosynthesis and transportation, minimum canopy inverse resistance to transpiration loss, net carbon dioxide exchange rates) (Lambin and Strahler 1994, p.2101).

Vegetation indices are often more sensitive to biomass stress than individual spectral bands (Asrar et al. 1984).

Figure 3.3

Typical spectral reflectance characteristics for healthy green grass, dead or senescing grass, and bare dry soil.

Source: Jensen 1996, p.161

Thus, according to Baret (1986), vegetation indices of the same area taken at different times constitute an excellent method for the detection of vegetation changes when they are differenced.

Vegetation index differencing has become a commonly accepted technique to detect changes in forest cover (Malingreau et al. 1985; Malingreau 1986; Nelson and Holben 1986; Tucker et al. 1986; Malingreau et al. 1989; Singh 1989; Tucker et al. 1991). Nelson (1982, 1983) found that of the three methods he tested, image differencing, image ratioing and vegetation index differencing, the last was the most accurate. Conversely, Banner and Lynham (1981) found this approach to be less accurate than using post classification analysis to delineate forest clearcuts.

A promising technique combines the Normalized Difference Vegetation Index (NDVI) with surface temperature brightness (Ts) in order to detect changes. It has been found that the heat emitted by different objects can furnish significant information about the type and condition of an object (Lillesand and Kiefer 1994). For example, bare soil temperatures are normally higher than forest temperatures during the day and lower than forest temperatures during the night. This information can be used to distinguish between these two cover types. In this approach a surface

temperature brightness (Ts) image is created using the split window technique developed by Price (1984):

$$Ts = T4 + 3.33(T4 - T5) - 273$$

where T4 and T5 are true brightness temperatures in AVHRR channels 4 and 5. This image is then divided by an NDVI image which is simply the difference of the near-infrared (NIR- AVHRR channel 2) and the visible (VIS- AVHRR channel 1) reflectance values normalized over the sum of channels 1 and 2 to obtain a ratio. The Ts/NDVI ratio has been found to be especially sensitive to vegetation change due to its relationship with surface moisture availability and evapotranspiration (Lambin and Ehrlich 1997). Lambin and Ehrlich (1996, 1997) have analyzed the Ts/NDVI space to monitor changes in numerous studies and have obtained positive results at a variety of scales. In one case they used the ratio obtained to classify two maps and examine change in forest cover in Africa and achieved a high overall accuracy.

3.5 Principal Component Analysis

Another of the more frequently used techniques for change detection uses principal component analysis (PCA) (Gong

1993; Jensen 1996). PCA defines a rotation of an image based on image statistics so that the new axes are orthogonal to each other and point in the direction of decreasing order of variance (Guirguis et al. 1996) (Figure 3.4). It has been found that change is often a major component of the variance found between spectral bands (Gong 1993).

There are two types of areas of change visible in PCA images. First, there are those that extend over a substantial part of the scene. These changes are thought to be related to changes in atmospheric transmission or soil water status (Bryne et al. 1980; Singh 1989; Richardson and Milne 1983). The second type of change should be statistically minor and is usually associated with land-cover changes such as clearing of forest, construction of roads, etc. (Bryne et al. 1980). These are the areas of most interest in the majority of change detection studies (Richards 1984; Gong 1993) and are usually found in the minor components of a PCA image. Determining exactly which components represent land-cover change is, however, rather difficult and is conditional on the fact that these types of changes may only make up a small proportion of the entire image (Richards 1984; Fund and LeDrew 1987; Gong 1993).

To minimize problems associated with traditional PCA

Figure 3.4

Diagrammatic representation of the spatial relationship between the first two principal components.

(a) Scatterplot of data points collected from two remotely sensed bands labeled X_1 and X_2 with the means of the distribution labeled U_1 and U_2 . (b) A new coordinate system is created by shifting the axes to an X' system. The values for the new data points are found by the relationship $X'_1 = X_1 - U_1$ and $X'_2 = X_2 - U_2$. (c) The X' axis system is then rotated about its origin (U_1, U_2) so that PC_1 is projected through the semimajor axis of the distribution of points and the variance of PC_1 is a maximum. PC_2 must be perpendicular to PC_1 . The PC axes are the principal components of this two-dimensional data space.

change detection, Gong (1993) suggested using band-pair difference images instead of the original bands of a sensor as the input channels for the PCA transformation. This results in most of the change information being preserved in the first few components. However, because field reference information was not available, a detailed change detection study was not undertaken.

3.6 Fuzzy Membership Functions of Change

In his study Gong (1993) also used fuzzy memberships to locate areas of change. Fuzzy sets were first introduced in 1965 by Zadeh (1965). These membership functions produce classes without sharp boundaries. As a result of running a fuzzy classification each pixel in an image is assigned a membership grade which indicates the extent to which the pixel belongs to all the classes under consideration (Masselli et al. 1996). A graphical example of this can be seen in Figure 3.5. where the membership grade of a pixel (x) belonging to change ranges from 0 to 1. The further (x) is away from the mean, the higher is the chance that that pixel belongs to change. As (x) falls outside points a or d saturation occurs (Gong 1993). More sophisticated membership functions can be determined if statistical knowledge of change-classes is available.

Figure 3.5

An example fuzzy membership function of change.

Source: Gong 1993, p.24.

There are a number of advantages to using fuzzy membership functions in change detection studies of tropical environments. One advantage lies in the fact that they are better than traditional classifiers at evaluating pixels that may be mixed, which is often the case in such areas. The main advantage of these techniques compared to traditional classifiers, however, is the fact that each pixel is given a grade level and not just placed into a distinct class. Therefore, because classes are not discrete, pixels having undergone subtle changes will still be identified. For example, consider an image of a forest. Large changes in pixel radiance values will only occur when forest is completely removed, which can be the result of road construction or shifting cultivation, for example. A traditional classifier will classify pixels in these areas as belonging to the change class provided that the radiance change due to land-cover change is greater than a statistically set threshold. The fuzzy classifier will also, depending on the parameters used in the membership function, assign a high grade value to these pixels. In cases where minor changes have taken place, possibly the result of activities such as selective logging or where forest removal only makes up a small portion of each pixel, there will be

smaller changes in radiance values. If radiance values have not changed enough a traditional classifier will still classify these areas as completely unchanged. However, because the fuzzy classifier assigns a grade to each pixel and not a specific class type these pixels will still be shown to have undergone some amount of change. The pixels with lower grade values can then be further investigated to determine the cause of the lower radiance values. Once more information has been gathered, class intervals can be determined more precisely. This approach to change detection analysis is especially useful when using lower resolution imagery where change areas must be substantial in size to affect pixel radiance values.

3.7 Change Detection using Spatial Information

Most remote sensing studies have mainly used the spectral information contained in satellite imagery. However, a number of researchers have suggested using spatial information to aid in change detection studies. The spatial patterns of grey levels in an image are known as texture. Texture images can be created from spectral data where each pixel of the texture image has a value that represents some aspect of the spatial variation of a specified area surrounding the pixel (Jensen 1996). These images can

provide supplementary information to the spectral data.

Two of the most commonly used texture classification algorithms are based on first and second-order grey level statistics. First-order measures use simple statistics such as the variance, standard deviation, and grey level difference. For example, a measure of spectral variability over short distances, also known as local texture, is calculated from the deviation of brightness values within a window of specified size when moved over an entire image (Jensen 1996). Second-order measures are based on brightness value spatial dependency grey-level co-occurrence matrices. A co-occurrence matrix tabulates the frequency of occurrence of all possible grey levels for pairs of pixels sampled within the image. Sampling is usually of adjacent pixels in a specified direction or omnidirectionally. Texture measures provide information on the contents of the matrix and include measures such as the Angular Second Moment, Contrast and Correlation. For example, Contrast multiplies the frequency of occurrence of a pair of grey levels (the entry in 1 cell of the matrix) by the squared difference of the grey levels. This is repeated for all non-zero cells and summed. Off diagonal cells, where adjacent grey levels differ, thus have a squared contribution. Other measures provide different information on the matrix and image

texture.

The use of texture images for detecting changes in tropical environments is especially promising because it has been suggested that rain forest images are in fact better described by their textural rather than spectral properties (Riou and Seyler 1997). This is partly due to the fact that reflectance characteristics are often not distinct, because of the large amounts of vegetation diversity in tropical forests (Sader et al. 1990; Roy et al. 1991). Luckman et al. (1997) have successfully shown that at least three different stages of regrowth of tropical forests can be identified on texture images. Furthermore, according to Lambin and Strahler (1994a) spatial structure contains significant amounts of information because of the nature of many human land uses. For instance small scale logging or small holder farming schemes fragment the landscape while other uses such as large scale intensive agriculture and ranching increase landscape homogeneity.

Lambin and Strahler (1994a) compared the results of using NDVI, the spatial structure of NDVI and surface temperature for change detection. In their research they found that all three indicators showed a low degree of redundancy and were able to detect changes successfully. Furthermore, according to Lambin and Strahler (1994a,

p.2115) "among the three indicators... spatial structure will probably best reveal longer-term and longer-lasting changes in landscape ecology, such as those related to permanent clearing of natural vegetation by human activity".

3.8 An Alternative Approach that combines Change Images from Multiple Techniques

All of the methods discussed up to this point have proved effective in locating and mapping land-cover changes in some way or another. Some of the methods are better at finding subtle changes while others are more capable of finding larger ones. Most studies have only used one method to find change. Although comparisons between techniques have been made they have for the most part been treated individually. For example, although Lambin and Strahler (1994a) used three different techniques in their study, they treated each of these methods individually and did not evaluate what results would be obtained if the resultant change images were combined. It is hypothesized here that combining imagery derived from various change detection procedures in the same study would be more effective at detecting changes than individual methods, especially in cases where no training data are available. It is also hypothesized that the use of a fuzzy classifier that assigns pixels a membership grade instead of placing them into discrete change or non-change

classes would provide more information and could help to identify subtle changes, and changes that only make up a small portion of a pixel. The validity of this approach has yet to be demonstrated however.

Two of the objectives of this research are to test these hypotheses. To accomplish this, various binary change images will be combined. For each combination, any pixel locations having a value of zero on all change images were classified as having undergone no change. The change images derived from these combinations will be compared to a reference image created from World Conservation Monitoring Centre maps of forest cover in Peninsular Malaysia. The change images from the individual techniques will also be compared. The image with the highest amount of agreement with the reference image will then be reclassified using fuzzy membership functions. In order to evaluate the effectiveness of this approach, images of Peninsular Malaysia will be examined for changes to forest cover in and around protected areas.

CHAPTER 4

METHODOLOGY

The key to future progress lies in obtaining information from data : through rigorous experimental design, the testing of specific hypotheses, and the calibration and manipulation of large data sets (IGBP 1992, p.31).

4.1 Data

The source data used in this project are AVHRR Local Area Coverage (LAC) images acquired from onboard NOAA's (National Oceanic and Atmospheric Administration) Tiros satellites. These images have a pixel spacing of 1.1 kilometres at nadir. As a result of the relatively low resolution of these images changes of small spatial extent may be missed. Nevertheless, change information and information relevant to environmental monitoring at regional scales can be derived from the AVHRR sensor (Belward 1992; Townshend *et al.* 1994). In fact, according to Greegor (1986) the AVHRR sensor provides the most suitable data for mapping and monitoring the vegetation of large areas. Furthermore the AVHRR sensor offers the opportunity for a true early warning system

(Justice et al. 1985; Tucker et al. 1985). Advantages of the AVHRR sensor include daily global coverage, increasing the possibility of obtaining cloud-free images, coverage of large areas, reducing the need for mosaicing, and the low cost of data in comparison with other sensors (Sader et al. 1990; Belward 1992; Hastings and Emery 1992; Malingreau and Belward 1994; Jensen 1996; Mantovani and Setzer 1997). This has prompted the use of this sensor in a number of studies of tropical forest change (Tucker et al. 1984; Malingreau and Tucker 1988; Gastellu-Etcheberry et al. 1993).

The images used in this study are taken from a data set created by a collaborative effort on the part of various agencies which include the IGBP (International Geosphere Biosphere Project), the USGS (United States Geologic Society), NASA (National Aeronautic and Space Administration), ESA (European Space Agency), and NOAA. The data are free to users and made available for distribution by the USGS' Eros Data Centre through the world wide web at the following internet address:

<http://edcwww.cr.usgs.gov/landdaac/1KM/1kmhomepage.html>.

This data set is designed to provide high-level products for global research (Eidenshink and Faundeen 1994).

The data set is based on AVHRR (Local Area Coverage-LAC) 5-channel 10-bit signed raw data at 1.1 km pixel spacing at nadir for every daily afternoon pass over all land and coastal zones. The data have been collected continuously since April 1, 1992. Presently, a data set of over 20000 AVHRR images has been archived and composited in ten day intervals for the time period April 1, 1992 - May 30 1996 and is available for use.

Before the composites become available to users the raw data are first processed by the IGBP. This includes radiometrically calibrating, atmospherically correcting and geometrically registering the data using "widely accepted, well defined and documented processing standards" (Eidenshink and Faundeen 1996, p.5). The processing standards were established by the IGBP land cover working group and the AVHRR Pathfinder land science working group (James and Kalluri 1993).

The equations for radiometric calibration to radiance and reflectance for the visible and near-infrared channels are described by Teillet and Holben (1994). These equations also account for sensor degradation. The calibration coefficients for AVHRR thermal channels 3,4, and 5 are derived onboard the satellite using a view of a stable black body and deep space as references. The calibration process

thereby converts raw digital counts to radiance as described by Kidwell (1991). The radiance values for all channels are stored with 10-bit precision.

To minimize atmospheric effects on AVHRR channels 1 and 2, the data are corrected for ozone and Rayleigh scatter based on the work of Teillet (1991). Unfortunately, because of a lack of agreement on the part of researchers no correction for water vapour or aerosol has been applied. As a result of the atmospheric correction, the input radiance values from the calibrated visible and near-infrared channels are converted to surface reflectance in percentage values.

After the corrections have been completed, the Normalized Difference Vegetation Index (NDVI) is calculated in order to create the composite images. The resultant values range between -1.0 and 1.0, where increasing positive values indicate increasing amounts of vegetation and increasing negative values indicate non-vegetated surfaces. "The NDVI is examined pixel by pixel for each observation during the compositing period to determine the maximum value" (Eidenshink and Faundeen 1996, p.6). An assumption is then made that the highest value is the least contaminated by clouds and nearest to nadir (Holben 1986). This is the observation to be used when creating the composite image.

The compositing period employed is approximately ten days created by month. Thus for example, January has three composite images of 10, 10, and 11 days.

The next step is geometric registration and involves the transformation of the image from the sensor-based projection to an Earth surface-based projection. According to Eidenshink and Faundeen (1996, p.6) "this process includes calculating a satellite model, matching ground and image-based control points, and transformation and resampling the data to a map projection coordinate system". In this case the images are mapped using the sinusoidal projection which does not distort shapes or areas close to the equator.

The exact coverage of the imagery is from 0.881336° to 7.779136° North and from 99.211629° to 105.481417° East. Figure 4.1 shows the geographical extent of the coverage. These bounding coordinates result in images that are 768 by 768 pixels given a pixel size of 1.1 kilometres.

The earliest data set covers the time period from the tenth to twentieth of May in 1992. This time period was chosen after a visual analysis of NDVI images from all the composites available for the months of April, May, and June in 1992. These months were selected because they correspond to the dry season in Malaysia when vegetation is most

Figure 4.1
Geographical extent of NOAA AVHRR images
used in the study.

Adapted from: C.I.A. 1995.

stressed. This will increase the contrast between healthy and damaged vegetation, thereby increasing the chances of locating forest areas that have only been affected by activities that create subtle land-cover changes such as selective logging.

The anniversary date composite image in 1996 was then analyzed visually. Unfortunately, due to excessive cloud cover, this image could not be used. Therefore, the composite image for the last ten days of May in 1996 was chosen instead. Analysis of climatic data showed that there was no significant difference in weather conditions for these two time periods and therefore changes in radiance values would not be the result of climatic effects or seasonal change.

4.2 Methods

The methodology used to create the forest-cover change images can be separated into twelve steps:

- Download Images;
- Check Image-to-Image Registration;
- Create Transformed Images;
- Create Difference Images;
- Define Change Class Thresholds and Fuzzy Membership Parameters;

- Create Binary Change and Change Membership Images;
- Combine Different Images using Fuzzy Set Operations;
- Perform Unsupervised classifications and post-classification comparison;
- Apply principal component analysis to the difference images of the original channels and then combine the results;
- Use 1991 Map of Forest Cover to Mask out Areas Of Non-Forest;
- Agreement Assessment;
- Select Image with Highest Agreement to Analyze Forest Change within and Around Protected Areas In Peninsular Malaysia.

To begin, the composite images were downloaded from the internet as raw images. These images were then imported into the EASI/PACE image analysis software package (PCI Inc. 1996) and converted into a useable format (.pix). The IDRISI GIS software package was later used to conduct the fuzzy classification.

4.2.1 Image-to-Image Registration

Once the images were imported into EASI/PACE a check of the image-to-image registration of the two data sets, 1992 and 1996, was done. The importance of accurate image-to-image registration is essential for change detection studies. Townshend et al. (1992, p.1058) found that "results from simulations indicate the need to achieve high values of registration accuracy, otherwise substantial error terms

will be introduced when comparisons between images are made [on a pixel-by-pixel basis] for the purposes of detecting land-cover changes". For example, in their simulations Townshend et al. (1992) concluded that for vegetated areas registration accuracies of approximately 0.2 pixels or less are needed.

In order to check the registration accuracy of the data, twelve ground control points (GCPs) were selected and compared to each other on each of the NDVI images from 1992 and 1996. Table 4.1 lists the coordinates of the GCPs. Small islands usually comprising only a few pixels surrounding the peninsula were chosen as GCPs because they were easily recognizable on both images. This produced a root mean square (RMS) error of 0.02 and 0.03 for the x and y directions respectively. This is well within the suggested standards therefore further image-to-image registration was not required.

4.2.2 Creation of the Transformed Data

The next step was the creation of NDVI, Surface Brightness Temperature (Ts), Ts/NDVI ratio and texture images. As previously mentioned the NDVI is the difference of the NIR channel and the RED channel normalized over the sum of these two channels. The surface brightness temperature image was created using the split window technique developed by Price

Table 4.1

Location of ground control points and errors for the image-to-image registration.

ID #	error	residual		1992		1996	
GCP		X	Y	X	Y	X	Y
1	0.01	0.00	0.01	419.48	210.49	419.48	210.48
2	0.05	-0.02	0.04	228.45	624.39	228.45	624.45
3	0.01	0.01	0.01	81.49	173.51	81.49	173.51
4	0.04	-0.01	-0.04	631.46	576.48	631.48	576.46
5	0.03	-0.03	0.02	540.45	332.45	540.44	332.48
6	0.02	-0.02	-0.01	518.46	701.41	518.48	701.43
7	0.01	-0.01	-0.01	232.47	444.47	232.47	444.47
8	0.02	0.01	0.01	240.41	94.47	240.41	94.47
9	0.03	0.00	-0.03	168.48	299.52	168.48	299.48
10	0.06	0.04	-0.05	359.45	597.58	359.52	597.55
11	0.04	0.03	0.03	633.45	712.48	633.52	712.55
12	0.02	0.01	0.02	530.48	475.52	530.52	475.55

(1984) (see section 3.4). The Ts/NDVI image is the ratio of the surface temperature brightness image and the NDVI image. Two types of texture measures were used: Contrast, and Entropy. These are second-order measures and are computed from the grey level co-occurrence matrix in PCI (PCI Inc. 1996). These measures were chosen because it has been found that higher classification accuracies are obtained when using texture measures based on co-occurrence matrices than when using first-order measures (Jensen 1996). A 3 by 3 moving window and a direction of one pixel to the right were used to calculate all of the texture images. The texture measures were run on both the NDVI and AVHRR channel 3 images. These channels were chosen because it has been found that they produce the highest contrast between vegetated and non-vegetated areas (Singh 1989).

As a result of these transformations, seven new images were created for use in possible combinations in addition to the five original channels downloaded from the USGS for each of the two time periods under analysis. These images are described in Tables 4.2 and 4.3 and are displayed in Appendices A and B.

4.2.3 Change Mapping using Difference Images

Difference images for each band could then be created by subtracting the 1996 image from the 1992 image. Six

Table 4.2**NOAA AVHRR sensor system characteristics.**

Band	wavelength(um)	description	characteristic
1	0.580-0.680	Red	Daytime cloud, snow, and vegetation mapping
2	0.725- 1.10	Near-Infrared	Land-water interface delineation, snow, ice, and vegetation mapping
3	3.55- 3.93	Thermal	Monitoring hot targets, nighttime cloud mapping
4	10.30-11.30	Thermal	Day and night cloud and surface temperature mapping
5	11.50-12.50	Thermal	Cloud and surface temperatures, day and night cloud mapping

Source: Jensen 1996, p.45

Table 4.3

**Transformed images created from the five
original AVHRR bands.**

Band	Description
6	Normalized Difference Vegetation Index (NDVI)
7	Surface Brightness Temperature (Ts)
8	Ts/NDVI
9	Contrast texture measure run on NDVI
10	Entropy texture measure run on NDVI
11	Contrast texture measure run on Channel 3
12	Entropy texture measure run on Channel 3

different combinations of bands were then selected for further analysis. These combinations are described in Table 4.4 and were chosen because they cover the full range of data. Combination one is made up of the five difference images derived from the original channels of AVHRR imagery. Combination two uses only the texture difference images created. The third combination of channels combines the original bands and texture measures. The fourth combination is made up of images derived from individual change detection techniques. These are the difference images of Band 3, NDVI, Surface Temperature Brightness (Ts), Ts/NDVI, and two texture measures. The fourth combination was determined by a visual analysis of the difference images. The images that had the greatest contrast in brightness values and looked most like they could represent actual change were selected. The last combination makes use of all the channels available.

The histograms for all of the images were examined to obtain statistics that were used to threshold the images. These values were based on image statistics in order to determine which image or combination is most sensitive to change when not using training data. Furthermore, to allow for later comparisons, the same threshold range was used for each channel. The first standard deviation greater than the

Table 4.4

Various combinations of imagery analyzed.

Combo #1	Combo #2	Combo #3	Combo #4	Combo #5	Combo #6
Original Channels	Texture Measures	Original Band and Texture measure	Techniques	Visual Selection	All
Band 1	Contrast (NDVI)	Band 1	Band 3	Band 2	All the channels available
Band 2	Entropy (NDVI)	Band 2	NDVI	Band 4	
Band 3	Contrast (Band 3)	Band 3	Ts	Ts/NDVI	
Band 4	Entropy (Band 3)	Band 4	Ts/NDVI	Contrast (Band 3)	
Band 5		Band 5	Contrast (NDVI)		
		Contrast (NDVI)	Entropy (Band 3)		
		Entropy (NDVI)			
		Contrast (Band 3)			
		Entropy (Band 3)			

average pixel brightness value of the difference image was chosen, as this is a standard approach (Jensen 1996), and is based on the fact that in normal distributions 68.27 per cent of the observations lie within one standard deviation of the mean. The assumption is made that the majority of pixels are of unchanged areas and that on the difference images these pixels would be located close to the mean value regardless of cover type.

Water pixels, which made up approximately half the total number on each image, were masked out so that they would not influence the statistics relating to forest cover and forest cover change. A binary change image was then created for each technique being used. These images were then used in the various combinations. For each combination, any pixel locations having a value of zero on all change images were classified as having undergone no change.

4.2.4 Change Mapping using Post-Classification Comparison

Two unsupervised classifications were then performed. One was run on AVHRR channel 3 for each of the two time periods. The other was run on channels 1, 2, and 3, again for each of the two time periods. These channels were chosen because they have been used in past change detection studies in the tropics (Tucker et al. 1984; Malingreau and Tucker 1988; Singh 1989; Jensen 1996) . Three classes were mapped

corresponding to water, forest and non-forest. These images are displayed in Figures 4.2 and 4.3. Post-classification analysis was then applied to each set to create two change images that were also used in the agreement assessment.

4.2.5 Change Mapping using Principal Component Analysis of Difference Images

A principal component transformation was carried out on the difference images of the five original AVHRR channels. The resultant principal component difference images were thresholded and then combined in such a way that only the maximum pixel value at each pixel location was retained. The resultant image was also used in the agreement assessment.

4.2.6 Evaluation of Agreement of Change Mapping Techniques with Reference Data

The usefulness of combining images for change detection was then tested by comparing the images based on individual techniques and those of the combinations to a reference image through a cross-tabulation analysis. A map of forest cover from 1991 was used to mask out areas of non-forest (see Figure 4.4). The assumption could then be made that since the areas being evaluated were already covered with forest any significant changes to radiance values would be the result of forest cover loss. A KAPPA coefficient was then determined for each image compared to the reference image. The KAPPA coefficient is a statistical measure of

Figure 4.2

Unsupervised classifications of AVHRR channel 3.

1992

1996

Figure 4.3
Unsupervised classifications of AVHRR channels 1, 2, and 3.

similarity that ranges from 0 to 1.0, where a value of 0 means the two images being cross-tabulated have nothing in common and a value of 1.0 means the two images are exactly the same (Eastman 1998).

The reference image is based on data obtained from the World Conservation Monitoring Centre and includes digital files of Malaysian forests from 1991 (Rhind and Iremonger 1996) and 1996 (Iremonger *et al.* 1997) (Figure 4.4). Due to the restricted status of maps in Malaysia no official government maps could be obtained. As a result, the maps by the WCMC were the only ones available that correspond to the time period under analysis. Unfortunately, the accuracy of these maps is not known. They were based on government figures, recent unpublished maps and post-classification comparison of NOAA AVHRR imagery (Rhind and Iremonger 1996; Iremonger *et al.* 1997).

The change image with the most agreement with the reference image which will be discussed in the next chapter, was then used to demonstrate that increased amounts of change information are available when remotely sensed data are used in conjunction with fuzzy memberships. This image was also used to analyze changes occurring within and around Malaysia's protected areas. To accomplish this task, a map showing protected areas on Peninsular Malaysia (see Figure

Figure 4.4
Forest cover in Peninsular Malaysia.

Source: Rhind and Iremonger 1996.

Source: Iremonger et al. 1997.

2.1), also produced by the WCMC (Iremonger et al. 1997), was overlaid on the CCM image. Unfortunately, only protected areas of 50 square kilometres could be considered, because these were the only ones included on the digital files.

CHAPTER 5

IMAGE ANALYSIS AND DISCUSSION

5.1 Objectives

There were three main objectives in this research. The first was to conduct a review of deforestation and conservation measures in Peninsular Malaysia, the results of which were presented in CHAPTER 2. The second was to test the effectiveness of combining multiple forms of remotely sensed imagery for change detection studies. The final objective was to determine if more information is available when using fuzzy membership functions in change detection studies. The results of the second two objectives are presented in the upcoming sections.

5.2 Creation of the Binary Change and Change Membership Images

The difference images created by subtracting the 1996 images from the 1992 images are displayed in Appendix C. Table 5.1 shows how correlated these images are. An absolute correlation coefficient of 1 means that change information contained in two difference images is exactly the same and

Table 5.1
Correlation coefficients of difference images.

	DIF 1	DIF 2	DIF 3	DIF 4	DIF 5	DIF 6	DIF 7	DIF 8	DIF9	DIF10	DIF11
DIF 2	-0.23										
DIF 3	0.13	-0.07									
DIF 4	0.13	-0.04	0.02								
DIF 5	-0.07	0.04	-0.06	0.50							
DIF 6	0.36	-0.26	0.25	0.07	-0.09						
DIF 7	0.21	-0.08	0.08	0.61	-0.37	0.16					
DIF 8	0.03	0.00	-0.02	0.18	-0.06	-0.50	0.24				
DIF 9	0.02	-0.02	0.05	-0.01	-0.06	-0.04	0.04	0.20			
DIF10	0.04	-0.05	0.16	-0.07	-0.13	0.14	0.04	-0.03	0.31		
DIF11	-0.12	0.09	-0.17	-0.01	0.04	-0.28	-0.05	-0.06	-0.04	-0.16	
DIF12	-0.16	0.17	-0.14	-0.11	-0.05	-0.23	-0.07	-0.07	0.14	0.23	0.26

Diff 1= difference image of channel 1

Diff 2= difference image of channel 2

Diff 3= difference image of channel 3

Diff 4= difference image of channel 4

Diff 5= difference image of channel 5

Diff 6= difference image of NDVI

Diff 7= difference image of Ts

Diff 8= difference image of Ts/NDVI

Diff 9= difference image of NDVI-contrast

Diff 10= difference image of NDVI-entropy

Diff 11= difference image of Band 3-contrast

Diff 12= difference image of Band 3-entropy

Note: sample size of 589824 pixels.

therefore, one image is redundant. A value of 0 means there is no change information duplicated in the two bands. Values approaching these two extremes indicate the relative amount of redundancy.

All of the difference images have a low degree of data redundancy, meaning there is unique information in almost every channel. Only two channels are correlated to a relatively high degree ($>.50$). These are AVHRR channel 4 (thermal) and the NDVI image. This finding suggests that all the channels will contribute some unique information and that all of these channels are necessary in order to detect all of the changes in the study area.

The image statistics used as the input parameters for class thresholding and the fuzzy membership of change classifier are contained in Table 5.2. As stated in the methodology, the class thresholds were based on the first standard deviation of forest pixels in each image. A decision was made to use statistics derived only from pixels that were classified as forest on the 1991 reference image. This was done to ensure that the class thresholds would relate to changes occurring to forest and not to other cover types such as water which made up large portions of the images. Analysis of image statistics confirmed the fact

Table 5.2**Image statistics used for class thresholding.**

Band	Mean	1 standard deviation
1 (RED)	132.038607	± 48.071663
2 (NIR)	121.513290	± 37.033016
3 (THERMAL)	137.411439	± 19.530880
NDVI	82.017518	± 27.336239
Ts	129.702877	± 25.923649
Ts/NDVI	221.619223	± 16.510498
Contrast (NDVI)	156.090456	± 7.832747
Entropy (NDVI)	123.432261	± 46.732922
Contrast (BAND 3)	122.030541	± 11.231778
Entropy (BAND 3)	111.948321	± 42.490257
PCD 1	103.413042	± 49.700104
PCD 2	203.013825	± 38.038773
PCD 3	121.804607	± 34.774670

that including water pixels would have strongly influenced the standard deviations resulting in smaller ranges. Using these statistics would have produced an overestimation of forest cover change.

5.3 Agreement Assessment of Binary Change Images

Appendix D shows all of the binary change/no-change images created. Although many of them look the same they are in fact quite different. Figure 5.1 compares the total number of change pixels. When using plus or minus 1 standard deviation to threshold the difference images, all of the individual bands and the texture measures severely underestimated the amount of change when compared to the reference image. The two post-classification comparison images resulting from the unsupervised classification of band 3 and bands 1,2, and 3 also undersampled the amount of change. Only the combined imagery and the PCA change image had similar numbers of change pixels compared to the reference image. This implies that the use of 1 standard deviation as the thresholding value was too large for the individual bands. A smaller range may be needed. However, this means that more than 32 per cent of the total number of forest pixels have undergone changes. This seems highly

Figure 5.1
Number of Pixels classified as change.

unlikely when compared to previous change studies of Malaysia.

A cross-tabulation between the binary change images and the reference image, was conducted to determine the amount of image similarity. A KAPPA coefficient was calculated for each image. As stated in CHAPTER 4 the KAPPA coefficient ranges from 0 - 1.0. where 0 indicates no agreement and 1.0 indicates perfect agreement with the reference image meaning that the two images are showing exactly the same information. Once again, water pixels were excluded from the analysis.

The results of the agreement assessments are presented in Figure 5.2. The results range from a low of 0.1120 for the surface temperature brightness image (Ts) to a high of 0.6558 for combination 6 which was made up of all the images available. In fact only the combined change images and the image based on PCA difference images had KAPPA coefficients above 0.50. The highest change image based on an individual band was only 0.40 and was from the entropy texture measure applied to channel 3. These results clearly indicate that combined imagery is more effective at locating change, and is therefore more effective than simply using one band or technique.

The agreement assessment produced some other

Figure 5.2
Comparison of similarity between various change
detection procedures and a reference map.

interesting findings that are worth mentioning. First, although both of the post-classification comparisons had similar numbers of change pixels they were not correlated with each other to a high degree having only a KAPPA coefficient of 0.3024 when cross-tabulated with each other. This is surprising since they were created using the same technique and had one channel in common. Second, almost identical results were obtained for combination one and the PCA change image. In both of these cases only the original channels were used in the construction of the respective change images. When cross-tabulated with each other, a KAPPA coefficient of 0.9462 was obtained. This suggests that almost exactly the same information is being shown. This is not surprising since the PCA transformation simply replicates the original data in a different form. Therefore, due to the increased amounts of processing time required to run the PCA transformation, and the fact that no new information is produced, it can be concluded that this approach is not worth using in future change studies using this type of data.

5.4 Test Site Analysis

A further assessment using test sites was undertaken to determine where the change images differed from the

reference image. This was done in an attempt to ascertain if any test sites wrongly classified had common characteristics. A total of 30 test sites covering various forest classes were selected for analysis from the reference image. Fifteen sites were known change areas and the other fifteen were unchanged areas (Figure 5.3). The test sites were compared to the same position on the change images. The 5 images with the highest KAPPA coefficients were selected for analysis. These were the change images based on combinations 1,2,3,4,and 6. The average of a 5 by 5 window at the test site were calculated and used for the assessment. This was done in order to eliminate errors that might be a result of the minimum mapping unit employed on the reference maps. The selection of a 5 by 5 window was based on the smallest size of polygon found on the reference maps.

Once again only average agreements were obtained. All of the images overestimated change, classifying many unchanged areas incorrectly. Further analysis, however, showed that out of the 30 test sites, 6 were incorrectly classified on all of the images tested. These were test sites 2, 18, 19, 23, 27, and 29. All of these sites represented unchanged areas on the reference image. If these test sites are not included, the level of agreement of each

Figure 5.3

Test sites used in the second accuracy assessment.

change image increases considerably. In 4 of the 6 cases the test sites were located in either montane (18,2) or inland swamp forest (27,23) areas. The remaining 2 test sites were located close to forest class boundaries and may therefore be mixed pixels. There are three possible explanations for the low level of agreement.

First there is the possibility that the reference maps used in the agreement assessment may not be entirely accurate. The maps used had a scale of 1:1000000 and due to their small scale may be too generalized to precisely depict all of the changes that have occurred. This could explain why many of the test sites on the change images were incorrectly found to have undergone changes. Unfortunately, due to the restricted status of maps in Malaysia these were the only reference maps available covering the time period under analysis. The use of a 5 by 5 window to analyze the test sites, however, should have accounted for any problems arising from generalizations on the reference map by essentially degrading the resolution of the imagery to correspond more closely to that of the reference map.

Second, the decision to treat the forest as one general class was a source of error. The choice of threshold parameters for the change classification did not work well for all forest classes. This is because forest classes that

only make up a small proportion of pixels did not contribute significantly to the image statistics used. As a result the image statistics did not accurately reflect the amount of change occurring to classes of small spatial extent. For instance, the lowland rain forest class which is the most extensive forest formation, undoubtedly contributed the most to the image statistics used here. The change images in turn reflected changes to this class more accurately than any others. This explains why there was more agreement with the reference image for this class than for inland swamp and montane forest which are for the most part incorrectly classified.

The class thresholds need to be different for these two classes. To illustrate this, image statistics from the difference image of channel 2 of known change and unchange areas were obtained. As can be seen in Table 5.3 and Figure 5.4, statistics for three class types (montane, inland swamp and lowland rain forest) showed that grey level values were in fact quite different, and therefore different change thresholds are needed for each class. In this case, for example, the selection of the thresholds used to classify change on the difference image of channel 2 resulted in only the lowland rain forest class being correctly classified to a large extent. Change was overestimated in the two other

Table 5.3

Grey level brightness values for different forest type on the channel 2 difference image.

Forest Type	Unchanged Pixel Value (0-255)	Change
Lowland Rain Forest	approx. 130	± 30
Inland Swamp Forest	approx. 75	± 20
Montane Forest	approx. 80	± 25

Figure 5.4

Grey-level brightness values for different forest classes.

classes because their mean values for unchanged areas fell outside the range of values that could be considered as belonging to the unchanged class. As a result, these two forest types were always classified as having undergone change. Altering the input parameters in order to reflect changes to the other forest types, however, would have resulted in overestimating change in the lowland rain forest areas. Therefore, it is recommended that the different forest types be treated separately in future research. This can be done by masking out the different forest classes. However, an accurate thematic map is required to do this. Treating the forest class separately could also be accomplished without the use of a thematic map if spectral ranges for each class could be determined. Different bands could then be selected that will locate changes in only one class. The resultant change images could then be combined using a similar approach to the one outlined in this research where only the maximum value at each pixel location is retained.

The third reason why poor accuracies may have been achieved is because of the data used. As previously stated, AVHRR images have a relatively low resolution and broad spectral ranges. Furthermore in retrospect, the use of composited images may have also been a source of error and

been responsible for creating larger brightness value ranges for each unchanged class. However, more research into the effect that compositing has on class statistics is necessary before any conclusions can be made.

The results of this first analysis do show that, in general, combining more than one change image derived from different change detection techniques in the same study is much more effective at locating change than any one technique in its own. This approach also produced change images that were more like that of the reference image than when using individual change images.

5.5 Fuzzy Membership Image

Fuzzy classifications were run on all the images that were part of combination 6 since it had the most agreement with the reference image. The resultant change membership images were then combined to produce a new change membership image showing the maximum grade value at each pixel location. Figure 5.5 shows the number of pixels at five different membership grade levels. Although there is not a large increase in the number of pixels that may belong to the change class over the binary change image produced earlier, this new image clearly has more information that could be used by analysts when assessing areas of change.

Figure 5.5
Number of pixels at each change membership grade on the
combination 6 image.

Furthermore, there is a distinct spatial pattern associated with the different membership grades. Most of the pixels with lower membership grades seem to be either around the edges or in the centre of larger contiguous groups of pixels with high membership grades. The pixels with lower membership grades may represent the initial stages of change occurring to forest cover at these locations and could be associated with road construction, flooding of forest by dams, and edge effects. These areas are of most interest in land-cover change studies because they represent areas that are just beginning to undergo change. This means that actions could still be taken to reduce or control the amount of change that will take place in the future.

Even more information is available from the change membership image when it is combined with a factor map such as in Figure 5.6. This map shows how many images used in a combination found change occurring at the same pixel location. The resultant bivariate change membership image could have a legend similar to the one in Figure 5.7, where hue represents the number of bands identifying change at a pixel location and value represents the membership grade level. Such a map would allow for more certainty in change studies. However, a bivariate map such as the one just described will only work if change to each forest class can

Figure 5.6
Factor map that shows the number of bands classifying pixels
as having undergone change.

Figure 5.7

A possible design for a bivariate change map legend.

be correctly classified to a large extent. Due to the problems associated with classifications to swamp forest and montane forest in this study, this type of map could not be used in the following discussion of changes occurring in Malaysia.

5.6 Changes Occurring in and around Protected Areas in Peninsular Malaysia

The change membership image of combination 6 was selected to test the effectiveness of using a fuzzy classifier in conjunction with remotely sensed data to monitor changes occurring to forest cover in and around protected areas.

As illustrated on Figure 5.8 most of the changes since 1992 have taken place on the West side of the Peninsula. It should be noted, however, that changes occurring to montane forest and inland swamp areas were not considered due to the low agreement with the reference image achieved for these two forest types and their small areal extent.

Interestingly, if these images are compared to Figure 2.1 many changes are located in close proximity to past regional development schemes. Furthermore, the changes also seem to follow the road network. If a comparison is also made with Figure 2.3 which shows the permanent forest estate most of the changes are taking place within its boundaries. This was

Figure 5.8
Change membership images showing changes to Peninsular Malaysia's forest cover.
 changes occurring outside protected areas changes occurring within protected areas

expected; however, the high membership grade of the majority of these changes was somewhat surprising. It was assumed that the majority of pixels would be in the lower membership grades. If the information on these images is taken to be correct it implies that the species composition of the forest in the PFE has been severely altered. This is the only possible explanation because the PFE is supposed to maintain a continuous cover of forest. Undoubtedly, selective logging operations, even though they are not removing forest entirely, are having a large effect on the forest.

Figure 5.8 also shows changes occurring within protected areas. Most of the protected areas are providing some amount of protection to the forest cover in their interior. For example, only 2967 pixels out of a total of 8437 pixels located in protected areas were classified as having undergone change. However, there are significant amounts of change taking place especially within Taman Negara, the Peninsula's largest park (1678 pixels out of 3879). There also seems to be a spatial pattern to these changes which seem to follow paths that are most likely related to access roads. Many of the changes in the smaller parks are occurring along their boundaries and are likely the result of edge effects. This is especially noticeable

around parks not in the PFE that do not have a protective buffer of forest around them.

The change membership image clearly shows that changes are taking place in and around protected areas in Peninsular Malaysia. Clearly the monitoring of protected areas with remote sensing could be used to alert resource managers to problems and thereby ensuring their continued integrity. This technology represents a valuable tool for resource managers if used correctly.

CHAPTER 6

CONCLUSION

"Uncertainty is fruitful... so long as it is accompanied by the wish to understand"

Antonio Machado (1887-1939)

6.1 Summary and Conclusions

Tropical deforestation and forest degradation are causing the loss of numerous species around the world. These ecosystems are home to the majority of the Earth's living creatures; however, human actions are threatening the survival of these important ecosystems. It is expected that if forest cover and population predictions are correct, by the year 2025 the ratio of forest cover to people will have been reduced from 0.7 hectares to only .46 hectares, most of which will be contained in protected areas (Iremonger et al. 1997). If protected areas are to safeguard species effectively there must be a continuing assessment of their integrity. Remote sensing offers researchers the opportunity to monitor protected areas and the forests surrounding them without having to undertake a detailed study in the field.

There were three main objectives to this research. The first was conduct a historical review of deforestation and conservation in Peninsular Malaysia. The second was to evaluate an alternative approach to change detection studies that combines different forms of remotely sensed imagery. It was hypothesized that such an approach would be more capable of detecting subtle forest cover changes than a single band or technique, especially when no training data are used. The final objective was to show that increased amounts of change information is available when using fuzzy membership classifications on change images derived from remotely sensed data and can be an effective tool for monitoring protected areas.

The results obtained clearly showed that using combinations of imagery from different change detection techniques were more capable of detecting changes. Such an approach is especially useful when the majority of data are uncorrelated and when no training data are available and image statistics must be used to construct change class thresholds. The change images produced by combining imagery were also more similar to the reference image used in this study than the images resulting from the individual techniques.

This study has also shown that even more change

information was obtained when using fuzzy membership grades in conjunction with combined imagery. This extra information would otherwise be excluded in traditional binary change images. As a result, pixels with low membership grades were able to be identified. This change membership image was examined allowing for a few general observations to be made about changes occurring in and around protected areas in Peninsular Malaysia.

The change membership images suggest that the changes occurring to lowland rain forest within Malaysia's Permanent Forest Estate maybe more significant than generally reported and raise a number of questions regarding the effectiveness of Malaysia's conservation strategies. For example, even though the Malaysian government has pledged to maintain at least 50 per cent of its land area covered with forest the question remains as to what kind of forest this will be. Results from this research suggest that significant changes in forest composition may be taking place and while forest cover may still be present it is becoming a very different forest from what was originally there.

The change membership images also show that changes occurring within protected areas seem to have a distinct spatial pattern. These changes seem to be for the most part along what appear to be corridors that may be associated

with roads or along boundary edges. Over time the cumulative impact of changes linked to the resultant edge effects could become significant if no action is taken. Buffer zones around the protected areas may need to be established to ensure their continued integrity.

The usefulness of remote sensing technology has not been lost on the Malaysian Government. As stated in the Seventh Malaysian Plan:

The Malaysian Centre for Remote Sensing (MACRES) will provide real time monitoring of the environment and natural resources through the use of satellite and other remote sensing sources. Efforts will be initiated to prepare indicators of sustainable development that will provide a yardstick for monitoring and evaluating progress (Malaysia 1996, p.616).

To this end the cabinet has directed MACRES to begin to monitor all environmentally sensitive and protected areas (Nor 1999). Already satellite images taken in March 1998 have been used to show that land clearing was taking place along the borders of Taman Negara which was also evident in this study. Other images have identified major threats from encroachments to the Air Hitam, South Kuala Langat and North Kuala Langat forest reserves.

As outlined in this thesis, significant progress has been made in conserving forests in Peninsular Malaysia. Recently the government has even decided to classify forest reserves at altitudes of 1000m and above as protected forest

(ANON 1999) which has been welcomed by environmental groups such as the World Wildlife Fund for Nature (WWF) and Sahabat Alam Malaysia (SAM). Furthermore, Malaysia is currently the only country to have met the International Tropical Timber Organisation's (ITTO) guidelines for sustainable forest management (Ghazali 1999). However, it should be noted that the ITTO's guidelines and criteria on the matter are different from many environmental organizations which have different ideas about what constitutes sustainability. Nevertheless, it seems as though Malaysia is attempting to protect its valuable natural resources and the Seventh Malaysia Plan (1995-2001) will once again try to integrate environmental aspects with development planning. Hopefully, conservation initiatives will not take a back seat to development plans in light of the recent economic downturn of the Asian economy.

6.2 Limitations

A major limitation in this study was the lack of accurate reference data. The accuracy of the reference image used was not known, therefore no conclusive statements regarding the accuracy of combining images derived from different change detection techniques. When compared to previous studies of Malaysia, the level of change found using this technique are

much higher. This may, however, just be a result of the incorrect classification of certain forest types.

Furthermore, larger amounts of change were expected as a result of using fuzzy membership functions.

Another limitation was the lack of remotely sensed data that could be obtained. Data from the AVHRR sensor have low spatial resolution which has an effect on the results. The individual techniques may be just as good at locating change as the combined approach when using higher resolution imagery because there would be fewer mixed pixels. Unfortunately, no other data were available to test this hypothesis.

6.3 Future Research

There are many variables involved in the design of a change detection study. These range from the choice of data to be used to the selection of class intervals used to display changes. This research has only considered a few. Many more require testing. The viability of the approach discussed in this study should be reexamined when using training data based on individual forest types and their associated spectral ranges to define precise class thresholds and the input parameters for the fuzzy classifier. The choice of input parameters had a profound impact on the results

obtained. Other variables that need to be considered in future research include: testing this procedure on different forms of imagery that have either a higher resolution or more precise and narrow spectral ranges; the effects of compositing on spectral ranges; analysis of minor principal components; and the use of different texture measures, vegetation indices and non-linear functions with the fuzzy classifier. Finally to effectively test all these variables, more accurate reference data are needed which may include field observations. The importance of using accurate training data cannot be understated. Only when all of these variables have been examined and tested can a truly accurate change detection procedure be established and employed.

REFERENCES

- Aiken, S.R., and Leigh, C.H. (1992). *Vanishing Rain Forests: The Ecological Transition in Malaysia*. Clarendon Press : Oxford.
- Aiken, S.R. (1993). Struggling to Save Malaysia's Endau-Rompin Rain Forest 1972-92. *Environmental Conservation*, 20, 157-162.
- Aiken, S.R. (1994). Peninsular Malaysia's protected areas' coverage, 1903-92: creation, rescission, excision, and intrusion. *Environmental Conservation*, 21, 49-56.
- Allen, J.C. and Barnes, D.F. (1985). The causes of deforestation in developing countries. *Annals of the Association of American Geographers*, 75, 163-84.
- ANON (1987). Conflict Of Interest. *The Star*, September 5th.
- ANON (1996). The proposed Highland Highway. *Malayan Naturalist*, 50, 14-21.
- ANON (1999). Move to preserve forests lauded. *The Star*, January 30.
- Arnold, J.E.M. and Minzava, E.M. (1985). Forest for People-The Developing Country Case. *Commonwealth Forestry Review*, 64, 209-210
- Asrar, G., Fuchs, M., Kanemasu, E. and Hatfield, J. (1984). Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. *Agron. Journal*, 76, 300-6.
- Badshah, M.A. (1962). Parks: Their principles and purposes. In: A. Adams ed., *First World Conference on National Parks*. Washington, D.C.: U.S. Department of the Interior, National Park Service. pp. 24-33.
- Bannari, A., Morin, D., Bonn, F. and Huete, A.R. (1995). A review of vegetation indices. *Remote Sensing Reviews*, 13, 95-120.

- Banner, A.V., and Lynham, T. (1981). Multitemporal analysis of Landsat data for forest cut over mapping-a trial of two procedures. *Proceedings of the 7th Canadian Symposium on Remote Sensing held in Winnipeg in 1981*, Canadian Remote Sensing Society : Winnipeg, pp.233-240.
- Baret, F. (1986). *Contribution au suivi radiometrique de cultures de cereals*. Thèse de Doctorat, Universite Paris-Sud Orsay, France.
- Barlow, C. (1978). *The Natural Rubber Industry: Its Development Technology and Economy in Malaysia*. Oxford University Press : Kuala Lumpur.
- Belward, A.S. (1992). Spatial Attributes of AVHRR Imagery for Environmental Monitoring. *International Journal of Remote Sensing*, 13, 193-208.
- Bernard, S. And Dekoninck, R. (1997). The Fate of Peninsular Malaysia's Forest : The Case of Pahang (1972-1992). *Malaysia Journal of Tropical Geography*, 28, 1-8.
- Bonan, G., Pollard, D., and Thompson, S. (1992). Effects of boreal forest vegetation on climate. *Nature*, 359, 716-718.
- Brandon, K.E. and Wells, M. (1992). Planning for people and parks: design dilemmas. *World-Development*, 20, 557-570.
- Brookfield, H. and Byron, Y. (1990). Deforestation and timber extraction in Borneo and the Malay Peninsula: the record since 1965. *Global Environmental Change*, 1, 42-56.
- Brookfield, H., Lian, F.J., Low-Kwai-Sim, and Potter, L. (1990). Borneo and the Malay Peninsula. In: *The Earth as transformed by human action*, ed. Turner, B., Cambridge University Press, pp. 495-512.
- Brookfield, H.C. (1988). The new great age of clearance and beyond: what sustainable development is possible? In: *People of the Tropical Rainforest*, ed. J.Denslow and C. Padoch. University of California Press : Berkeley and Los Angeles.

- Brown, S., Gillespie, A.J.R. and Lugo, A.E. (1991). Biomass of tropical forests of South and Southeast Asia. *Canadian Journal of Forest Research*, 21, 111-117.
- Bulletin FELDA (1993). No. 07/93, July 1993, Kuala Lumpur : FELDA Headquarters.
- Byrne G.F., Crapper, P.F. and Mayo K.K. (1980). Monitoring Land-Cover Change by principal component analysis of multitemporal Landsat Data. *Remote Sensing of Environment*, 10, 175-184.
- Central Intelligence Agency (1995). *Map of South East Asia*.
- Chin, S.C. (1990). The System Must Change: The Promotion of Sustainable Forest Management in Sarawak. *Wallaceana*, 61, 1-8.
- Christenson, E., Jenson, J., Ramsey, E., and Mackey, H., Jr. (1988). Aircraft MSS data registration and vegetation classification of wetland change detection. *International Journal of Remote Sensing*, 9, 23-38.
- Cleary, M. and Shaw, B. (1994). Ethnicity, development and the New Economic Policy: the experience of Malaysia, 1971-1990. *Pacific-Viewpoint*, 35, 83-107.
- Collins, J.B. and Woodcock, C.E. (1996) An Assessment of Several Linear Change Detection Techniques for Mapping Forest Mortality Using Multitemporal Landsat TM Data. *Remote Sensing of the Environment*, 56, 66-77.
- Collins, N.M., Sayer, J.A., and Whitmore, T.C. (1991). *The Conservation Atlas of Tropical Forests: Asia and the Pacific*. Simon and Schuster : Toronto.
- Cranbrook, Earl of (Ed.) (1988). *Malaysia*. Permagon Press : Oxford.
- Dato, H.S. (1997). *Sustainable Forest Management - The Malaysia Experience*. Voluntary Paper for the XI World Forestry Congress, 13-23, October 1997, Antalya, Turkey.

- Department of Environment (1991). *Environmental Quality Report 1989*. Kuala Lumpur.
- DeKoninck, R. (1981). Enjeux et strategies spatiales de l'Etat en Malaysia. *Herodote*, 21, 84-115.
- DeKoninck, R. (1986). Les politiques du developpement agricole en Malaysia ou l'impatience de l'Etat tutelaire. *Archipel*, 31, 131-153.
- Dinerstein, E. and Wikramanayake, E.D. (1993). Beyond 'hotspots': how to prioritize investments to conserve biodiversity in the Indo-Pacific region. *Conservation Biology*, 7, 53-65.
- Dixon, J.A. and Sherman, P.B. (1991). Economics of protected areas. *Ambio*, 20, 68-74.
- Eastman, J.R. and Fulk, M. (1993). Long sequence time series evaluation using standardized principal components. *Photogrammetric Engineering and Remote Sensing*, 59, 991-996.
- Eastman, J.R. (1998). Help File, IDRISI for Windows, version 2.
- Ehrlich, P.R. (1980). The strategy of conservation, 1980-2000. In: Soulé, M.E. and Wilcox, B.A. (eds), *Conservation biology: an evolutionary-ecological perspective*. Sinauer Associates : Massachusetts, pp.329-44.
- Ehrlich, P.R. and A.H. Ehrlich (1981). *Extinction: The Causes and Consequences of the Disappearance of Species*. Random House : New York.
- Eidenshink, J.C., and J.L. Faundeen. (1994). The 1 km AVHRR global land data set: first stages of implementation. *International Journal of Remote Sensing*, 15, 3443-3462.
- Eidenshink, J. And Faundeen J.L. (1996). The 1-km AVHRR Global Land Data Set: An Update. *Global Change Newsletter*, 27, 5-6.
- Estes, J.E. (1992). Technology and Policy Issues Impact Global Monitoring. *GIS World*, 5, 52-55.

- FAO/UNEP (1993). *Tropical Resource Assessment*. FAO : Rome.
- FAO (1987). *Assessment of Forest Resources in Six Countries*. FAO : Bangkok.
- Fung, T. And LeDrew, E. (1997). Application of Principal Component Analysis to Change Detection. *Photogrammetric Engineering and Remote Sensing*, 53, 1649-1658.
- Gastellu-Etchegorry, Estreguil, C., Mougin, E. and Laumonier, Y. (1993). A GIS based methodology for small scale monitoring of tropical forests- a case study in Sumatra. *International Journal of Remote Sensing*, 14, 2349-2368.
- General Electric Co. and Department of Natural Resources (1977). *Forest Inventory of the Philippine Islands using LANDSAT Multispectral Scanner Digital Data*. General Electric Co : Maryland.
- Ghaffar, F.A. (1994). Structural change and regional growth in Malaysia 1970-90. *Malaysian Journal of Tropical Geography*, 25, 79-89.
- Ghazali, F. (1999). King of tropical timber hill come year 2000?. *Buissness Times*, January 15.
- Gong, P. (1993). Change detection using principal Component analysis and fuzzy set theory. *Canadian Journal of Remote Sensing*, 19, 22-29.
- Grainger, A. (1983). Improving the monitoring of deforestation in the humid tropics. In: Sutton, S.L., Whitmore, T.C., and Chadwick, A.C. (eds), *Tropical Rain Forest - Ecology and Management*. Blackwell Scientific Publications : Oxford, pp.387-95.
- Grainger, A. (1993a). Rates of deforestation in the humid tropics: estimates and measurements. *The Geographical Journal*, 159, 33-44.
- Grainger. (1993b). *Controlling tropical deforestation*. Earthscan : London.
- Grainger, A. (1996). An evaluation of the FAO tropical forest resource assessment, 1990. *The Geographical Journal*, 162, 73-79.

- Greegor Jr., D.H. (1986). Ecology from space. *BioScience*, 36, 29-432.
- Guirguis, H.M., Hassan, H.M. El-Raey, M. and Hussain M.M.A. (1996). Multi-temporal Change of Lake Brullus, Egypt, from 1983 to 1991. *International Journal of Remote Sensing*, 17, 2915-2921.
- Hall, J.B., Botkin, D.B., Strebel, D.E., Woods, K.D. and Goetz, S.L. (1991). Large-scale patterns of forest succession as determined by remote sensing. *Ecology*, 72, 628-40.
- Ham, S.H., Sutherland, D.S. and Meganck, R.A. (1993). Applying environmental interpretation in protected areas of developing countries: problems in exporting a US model. *Environmental Conservation*, 20, 232-242.
- Hanbury-Tenison, R. (1990). No Surrender in Sarawak. *New Scientist*, 128, 28-29.
- Harris, L.D. (1984). *The fragmented forest: Island biogeography theory and the preservation of biotic diversity*. University of Chicago Press : Chicago, Illinois.
- Hastings, D.A. and Emery, W.J. (1992). The Advanced Very High Resolution Radiometer (AVHRR): A brief reference guide. *Photogrammetric Engineering and Remote Sensing*, 58, 1183-1188.
- Holben, B.N. (1986). Characteristics of maximum-value composite images from temporal AVHRR data. *The International Journal of Remote Sensing*, 7, 1417-1434.
- Houghton, R.A. (1990). Deforestation and Climate Change. *Environmental Science Technology*, 24, 414-20.
- Howarth, J.P., and Boasson, E. (1983). Landsat digital enhancements for change detection in urban environment. *Remote Sensing of Environment*, 13, 149-160.
- Howarth, J.P. and Wickware, G.M. (1981). Procedure for change detection using Landsat digital data. *International Journal of Remote Sensing*, 2, 277-291.

- Hulme, D. (1987). State-sponsored land settlement policies: theory and practice. *Dev. Change*, 18, 413-436.
- Hurst, P. (1987). Forest Destruction in South East Asia. *The Ecologist*, 17, 170-174
- IGBP (1992). *Global Change : Reducing Uncertainties*. IGBP : Stockholm, Sweden
- Iremonger, S. Ravillious, C. And Quinton, T. (eds) (1997). *A global overview of forest conservation*. CD-ROM. WCMC and CIFOR : Cambridge, U.K.
- James, M.E., and Kalluri, S. (1993). The Pathfinder AVHRR land data set: An improved coarse resolution data set for terrestrial monitoring. *The International Journal of Remote Sensing*, 15, 3347-3364.
- Jensen, J.R. (1996). *Introductory digital image processing: A remote sensing perspective*, Second Edition, Prentice-Hall : Englewood Cliffs N.J..
- Jensen, J.R., Cowen, D.J., Narumalani, S., Althausen, J.D., and Weatherbee, O. (1993). An Evaluation of CoastWatch Change Detection Protocol in South Carolina. *Photogrammetric Engineering and Remote Sensing*, 59, 1039-1046.
- Jensen, J.R. and Narumalani, S. (1992). Improved Remote Sensing and GIS Reliability Diagrams, Image Genealogy Diagrams, and Thematic Map Legends to Enhance Communication. *International Archives of Photogrammetry and Remote Sensing*, 6, 125-132.
- Jha, C.S. And Unni, N.V.M. (1994). Digital Change Detection of Forest Conservation of a Dry Tropical Indian Forest Region. *International Journal of Remote Sensing*, 15, 2543-2552.
- Johns, A.D. (1985). Selective Logging and Wildlife Conservation in Tropical Rain-Forest: Problems and Recommendations, *Biological Conservation*, 31, 55-75.

- Jusoff, K. And D'Souza G. (1996). Quantifying Disturbed Hill Dipterocarp Forest Lands in Ulu Tembeling, Malaysia with HRV/SPOT Images. *Journal of Photogrammetry and Remote Sensing*, 51, 39-48.
- Justice, C.O., Townshend, J.R.G., Holben, B.N. and Tucker, C.J. (1985). Analysis of the phenology of global vegetation using meteorological satellite data. *International Journal of Remote Sensing*, 6, 1271-1318.
- Kartawinata, K., Adisoemarto, S., Riswan, S. and Vayda, A.P. (1981). The impact of man on a tropical forest in Indonesia. *Ambio*, 10, 115-9.
- Kates, R.W., Turner, B.L., II and Clark, W.C. (1990). The great transformation. In: *The Earth as Transformed by Human Action*. Turner, B.L.II, Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T. and Meyer, W.B. (eds). Cambridge university Press : Cambridge, pp. 1-17.
- Khan, Mohd Khan Bin Momin (1988). Animal conservation strategies. In: Cranbrook, Earl of (ed). *Malaysia*. Oxford : Permagon Press,. pp. 251-72.
- Kidwell, K.B. (1991). *NOAA Polar Orbiter Data User's Guide*. NOAA NESDIS, National Climate Data Center : Washington, D.C..
- Kiew, R. (1983). Conservation of Malaysian plant species. *Malayan Naturalist*, 37, 2-5.
- Kottak, C.P. (1985). When people don't come first: some sociological lessons from completed projects, In: *Putting people first, Sociological Variables in Rural Development*, M.M. Cernea (Ed.). Oxford University Press : Oxford. pp.325-356.
- Krement, C., Merenlender, A.M. and Murphy, D.D. (1994). Ecological Monitoring: A Vital Need for Integrated Conservation and Development Programs in the Tropics. *Conservation Biology*, 8, 388-397.
- Kummer, D.M. (1992). Remote sensing and tropical deforestation: A cautionary note from the Philippines. *Photogrammetric Engineering and Remote Sensing*, 58, 1469-71.

- Lambin, E.F., and Strahler, A.H. (1994a). Indicators of land-cover change for change-vector analysis in multitemporal space at coarse spatial scales. *International Journal of Remote Sensing*, 15, 2099-2119.
- Lambin, E.F., and Strahler, A.H. (1994b). Change-vector analysis: a tool to detect and categorize land-cover change processes using high temporal-resolution satellite data. *Remote Sensing of the Environment*, 48, 231-244.
- Lambin, E.F., and Ehrlich, D. (1995). Combining vegetation indices and surface temperature for land-cover mapping at broad spatial scales. *International Journal of Remote Sensing*, 16, 573-579.
- Lambin, E.F., and Ehrlich, D. (1996). The surface temperature-vegetation index space for land cover and land-cover change analysis. *International Journal of Remote Sensing*, 17, 463-487.
- Lambin, E.F. and Ehrlich, D. (1997). Land-Cover Changes in Sub-Saharan Africa (1982-1991): Application of a Change Index Based on Remotely Sensed Surface Temperature and Vegetation Indices at a Continental Scale. *Remote Sensing of the Environment*, 61, 181-200.
- Lanly, J.P. (ed) (1981). *Tropical Forest Resource Assessment Project*. FAO : Rome.
- Ledec. G. and Goodland R. (1988). *Wildlands: Their Protection and Management in Economic Development*. World Bank : Washington, D.C..
- Leong, C.P., Lim, S.F., Lim, J.T. (1988). *Report on Rain Acidity Analysis Based on Data from the National Acid Rain Monitoring Network*. Malaysian Meteorological Service : Petaling, Jaya.
- Lillesand, T.M. and Kiefer, R.W. (1994). *Remote Sensing And Image Interpretation*, Third Edition. John Wiley and Sons Inc. : New York.
- Lovejoy, T.E. (1989). Deforestation and species extinction. In: Botkin, D.B. (ed). *Changing the Global Environment*. Academic Press : Washington.

- Luckman, A., Frery, A.C., Yanasse, C.C.F. and Groom, G.B. (1997). Texture in airborne SAR imagery of tropical forests and its relationship to forest regeneration stage. *International Journal of Remote Sensing*, 18, 1333-1349.
- Malaysia, Government of Malaysia (1991). Sixth Malaysian Plan 1991-1995. National Printing Department : Kuala Lumpur.
- Malaysia, Government of Malaysia (1996). Seventh Malaysian Plan. 1996-2000. National Printing Department : Kuala Lumpur.
- Malingreau, J.P., Tucker, C.J., and Laporte, N. (1989). AVHRR for monitoring global tropical deforestation. *International Journal of Remote Sensing*, 10, 855-867.
- Malingreau, J.P., Verstraete, M.M. and Achard, F. (1992). Monitoring global tropical deforestation: a challenge for remote sensing. In: *Terra-1: understanding the terrestrial environment*. Taylor and Francis. pp. 121-31.
- Malingreau, J.P., Stephens, G., and Fellows, L. (1985). Remote Sensing of Forest Fires: Kalimantan and North Borneo in 1982-83. *Ambio*, 14, 314-321.
- Malingreau, J.P. and Tucker, C.J. (1988). Large-scale deforestation in the southeastern Amazon Basin of Brazil. *Ambio*, 17, 49-55.
- Malingreau, J.P. (1986). Global vegetation dynamics: satellite observation over Asia. *International Journal of Remote Sensing*, 7, 1121-1146.
- Mantovani, A.C. and Setzer, A.W. (1997). Deforestation Detection in the Amazon with an AVHRR-Based System, *International Journal of Remote Sensing*, 18, 273-286.
- Masselli, F. Rodolfi, A., and Conese, C. (1996). Fuzzy classifications of spatially degraded Thematic Mapper data for the estimation of sub-pixel components. *International Journal of Remote Sensing*, 17, 537-551.
- Mehmet, O. (1986). *Development in Malaysia: poverty, wealth and trusteeship*. Croom Helm : London.

- Melillo, J.M., Palm, C.A., Houghton, R.A., Woodwell, G.M. and Myers, N. (1985). A comparison of two recent estimates of disturbance in tropical forests. *Environmental Conservation*, 12, 37-40.
- Miller, L.D., Nualchawee, K., and Tom, C. (1978). *Analysis of the dynamics of shifting cultivation in the tropical forests of northern Thailand using landscape modelling and classification of Landsat imagery*. NASA technical memorandum 79545, Goddard Space Flight Centre : Greenbelt, Maryland, USA.
- Munasinghe, M. (1992). Biodiversity protection policy: environmental valuation and distribution issues. *Ambio*, 21, 227-236.
- Myers, N. (1980). *Conversion of tropical moist forests*. Washington DC : US National Research Council.
- Myers, N. (1983). The Tropical Forest Issue. In: O'Riordan, T. and Turner, K. (eds). *Progress in Resource Management*, 4. John Wiley and Sons : Toronto. pp. 1-28.
- Myers, N. (1984). *The Primary Source*. Norton : London.
- Myers, N. (1988). Tropical Deforestation and Remote Sensing. *Forest Ecology and Management*, 23, 215-25.
- Myers, N. (1989a). *Deforestation rates in tropical forests and their climatic implications*. Friends of the Earth (UK) : London.
- Myers, N. (1989b). A major extinction Spasm: predictable and inevitable?. In: Weston, D. and Pearl (eds). *Conservation for the twenty-first century*. Oxford University Press : New York. pp. 42-49.
- Myers, N. (1993). Tropical forests: the main deforestation fronts. *Environmental Conservation*, 20, 9-16.
- Nelson, R., and Holben, B. (1986). Identifying deforestation in Brazil using multiresolution satellite data. *International Journal of Remote Sensing*, 7, 429-448.
- Nelson, R.F. (1982). *Detecting forest canopy change using Landsat*. NASA technical memorandum 83918. Goddard Space Flight Centre, Greenbelt, Maryland, USA.

- Nelson, R.F. (1983). Detecting forest canopy change due to insect activity using Landsat MSS. *Photogrammetric Engineering and Remote Sensing*, 49, 1303-1314.
- Nemani, R.R., Running, S.W., Pielke, R.A. and Chase T.W. (1996). Global vegetation cover changes from coarse resolution satellite data. *Journal of Geophysical Research*, 101, 7157-7162.
- Nemani, R. and Running, S. (1997). Land Cover Characterization Using Multitemporal Red, Near-ir and Thermal-ir Data from NOAA/AVHRR. *Ecological Applications*, 7, 79-90.
- Ng, F.S.P. and Low, C.M. (1982). Check list of endemic trees of the Malay Peninsula. *Forest Research Institute Research Pamphlet*, 88.
- Ngau, H., Apoi, T.J. and Ling, C.Y. (1987). Malaysia Timber: Exploitation for Whom? *The Ecologist*, 17, 175-179.
- Nor, S.M. (1999). Satellite images effective tool to check on land use. *New Straights Times*, February 8.
- Oberai, A.S. (1986). Land settlement policies and population redistribution, *International Labour Review*, 125, 141-161.
- PCI Inc. (1996). *EASI/PACE User's Manual* (version 5.0), PCI Inc., Richmond Hill, Ontario.
- Pearce, F. (1990). Hit and Run in Sarawak. *New Scientist*, 126, 24-27.
- Pilon, P.G., Howarth, P.J., Bullock, R.A., and Adeniyi, P.O. (1988). An Enhanced Classification Approach to Change Detection in the Semi-Arid Environments. *Photogrammetric Engineering and Remote Sensing*, 54, 1709-1716.
- Pimentel, D., Sstachow, U., Takacs, D. Brubaker, H., Dumas, A., Meaney, J., O'Neil, J., Onsi, D. and Corzilius, D., (1992). Conserving Biological Diversity in Agricultural/Forestry Systems. *BioScience*, 42, 354-362.

- Price, J.C. (1984). Land surface temperature measurements from the split-window channels of the NOAA 7 advanced very high resolution radiometer. *Journal of Geophysical Research*, 85, 7231-7237.
- Price, J.C., (1987). Calibration of satellite radiometers and comparison of vegetation indices. *Remote Sensing of Environment*, 21, 15-27.
- Prins, H.H.T. and Wind, J. (1993). Research for nature conservation in South East Asia. *Biological Conservation*, 63, 43-46.
- Rachagan, S.S. and Bahrin, Tunku Shamsul (1983). Development without destruction: the need for a pragmatic forest policy in Malaysia. *Planter*, 58, 491-506.
- Reid, W.V. and Miller, K.R. (1989). *Keeping Options Alive: the scientific basis for conserving biodiversity*. World Resources Institute : Washington D.C..
- Rhind, J. And Iremonger, S. (eds)(1996). *Tropical Moist Forests and Protected Areas: the digital files*, version 1, WCMC and CIFOR : Cambridge, U.K.
- Richards, J.A. (1984). Thematic Mapping from Multitemporal Image Data Using the Principal Components Transformation. *Remote Sensing of Environment*, 16, 35-46.
- Richardson, A.J., and Milne, A.K. (1983). Mapping fire burns and vegetation regeneration using principal components analysis. *Proceedings of IGARSS'83 held in San Francisco in 1983*, I.E.E.E. : New York, pp.51-56.
- Riordon, C.J. (1980). *Non-urban to urban land cover change detection using Landsat data*. Summary Report of the Colorado Agricultural Research Experiment Station. Fort Collins, Colorado U.S.A..
- Riou, R. And Seyler, F. (1997). Texture Analysis of Tropical Rain Forests Infrared Satellite Images. *Photogrammetric Engineering and Remote Sensing*, 63, 515-521.
- Rogers, P. (1990). Hydrology and water quality. In: *Global Land-use and Land-cover change*, W.B. Meyer and B.L. Turner II (eds). Cambridge University Press : Cambridge.

- Roy, R.S., Ranganath, B.K., Diwakar, P.G., Vohra, T.P.S., Bhan, S.K., Singh, J.J., and Pandian, V.C. (1991). Tropical forest type mapping and monitoring using remote sensing. *International Journal of Remote Sensing*, 12, 2205-2225.
- Rubeli, K. (1989). Pride and Protest in Malaysia. *New Scientist*, 124, 49-52.
- Running, S.W., Loveland, T., and Pierce, L.L. (1994). A vegetation classification logic based on remote sensing for use in global biogeochemical models. *Ambio*, 23, 77-81.
- Sader, J.A., Stone, T.A. and Joyce, A.T. (1990). Remote sensing of tropical forests: An overview of research and applications using non-photographic sensors. *Photogrammetric Engineering and Remote Sensing*, 56, 1343-51.
- Salleh Mohd. Nor (1988). Forest management. In: Malaysia (ed) Earl of Cranbrook. Pergamon Press : Oxford. pp.126-137.
- Sawada, H., Nakakita, O., Awaya, Y., Hamzah, K.A. and Hassan, A. (1991). Development of monitoring system for tropical rain forest management in the peninsula Malaysia: The joint Malaysia-Japan research project on remote sensing. *IGARSS'91*, 1153-1156.
- Sham, S. Cheang, B.K., Leong, C.P. and Lim, S.E. (1991). The August 1990 Haze in Malaysia With Special Reference to the Klang Valley Region. *Malaysian Meteorological Service Technical Note No. 49*, Petaling Jaya.
- Sham-Sani (1993). Economic development and environmental management in Malaysia. *New Zealand Geographer*, 49, 64-68.
- Shukla, J., C. Nobre, and P. Sellers. (1990). Amazon deforestation and climate change. *Science*, 247, 1322-1325.
- Simberloff, D. (1986). In: Elliot, K.K (ed), *Dynamics of Extinction*. Wiley : New York.

- Singh, A. (1989). Digital Change Detection Techniques Using Remotely-Sensed Data. *International Journal of Remote Sensing*, 10, 989-1003.
- Sommer, A. (1976). Attempt at an assessment of the world's tropical forests. *Unasylva*, 28, 5-25.
- Soulé, M.E. (1991). Conservation: tactics for a constant crisis. *Science*, 253, 744-750.
- Steenis, C.G.G.J. van (1950). The delimitation of Malaysia and its main plant geographical divisions. *Flora Melesiana, Series 1, 1*, lxx-lxxv.
- Steenis, C.G.G.J. van, (1971). Plant conservation in Malaysia. *Bulletin du Jardin Botanique National de Belgique*, 41, 189-202.
- Steenis, C.G.G.J. van (1979). Plant-geography of east malesia. *Botanical Journal of the Linnean Society of London*, 79, 97-178.
- Stevens, W.E. (1968). *The Conservation of Wildlife in West Malaysia*. Office of the Chief Game Warden, Federal Game Department, Ministry of Lands and Mines, Malaysia.
- Sutton, K. and Buang, A. (1995). A new role for Malaysia's FELDA: from land settlement agency to plantation company. *Geography*, 80, 125-137.
- Teillet, P.M. (1991). Radiometric and atmospheric correction procedures for AVHRR preprocessing in the solar reflective channels. *Proceedings of the Fifth International Colloquium on Spectral Signatures of Objects in Remote Sensing*. Courchevel, France, 1991, pp.511-516.
- Teillet, P.M. and Holben, B.N. (1994). Towards operational radiometric calibration of NOAA AVHRR imagery in the visible and infrared channels. *Canadian Journal of Remote Sensing*, 20, 1-10.
- Thang,, H.C. (1993). *Monitoring Forest Cover with the Use of Satellite Data in Malaysia*. Paper presented at the Regional Workshop on Tropical Forest Ecosystem Research, Conservation and Repatriation, Hanoi, Vietnam, 28 June-1 July, 1993.

- Thang, H.C. (1995). *Forest Resource Monitoring Systems in Malaysia*. Paper Presented at the Expert Consultation on Forest Resources Monitoring Systems, Bangkok, Thailand, February 27 - March 3
- Thapa, G.B. and Weber, K.E. (1990). Actors and Factors of Deforestation in Tropical Asia. *Environmental Conservation*, 17, 19-27.
- Tho, Y.P. (1991) Conservation of biodiversity-international and national perspectives. *Proceedings of the National Seminar on Environment and Development*, Kuala Lumpur, July 9-11 1990, 266-313.
- Thomas, W.L., Jr., (ed) (1956). *Man's Role in Changing the Face of the Earth*. University of Chicago Press : Chicago.
- Thorsell, J.W. (1990). Research in tropical protected areas: some guidelines for managers. *Environmental Conservation*, 17, 4-18.
- Tucker, C.J., Townshend, J.R.G. and Goff, T.E. (1984). Intensive forest clearing in Rondonia Brazil as detected by satellite remote sensing. *Remote Sensing of Environment*, 15, 255-61.
- Todd, W.J. (1977). Urban and regional land use change detected by using Landsat data. *Journal of Research by the US Geological Survey*, 527-534.
- Townshend, J.R.G., Justice, C.O., Skole, D., Mallingreau, J.P., Cihlar, J., Teillet, P.M., Sadowski, F., and Rittenberg, S. (1994). The 1-km AVHRR global data set: needs of the International Geosphere Biosphere Program. *International Journal of Remote Sensing*, 15, 3319-3332.
- Townshend, J.R.G., Justice, C.O., Li, W., Gurney, C., and McManus, J. (1991). Global Land cover classification by remote sensing: Present capabilities and future possibilities. *Remote Sensing of the Environment*, 35, 243-255.

- Townshend, J.R.G., Justice, C.O., Gurney, C. and McManus, J. (1992). the impact of misregistration on change detection. *IEEE Transactions on Geoscience and Remote Sensing*, 30, 1054-1060.
- Tucker, C.J., Townshend, J.R.G, and Goff, T.E. (1985). African land-cover classification using satellite data. *Science*, 227, 369-375.
- Tucker, C.J., Justice, C.O., and Prince, S.D. (1986) Monitoring the grasslands of the Sahel 1984-1985. *International Journal of Remote Sensing*, 7, 1571-1581.
- Turner II, B.L., Meyer, W.B. and Skole, D.L. (1994). Global Land-Use/Land-Cover Change: Towards and Integrated Program of Study. *Ambio*, 23, 91-95.
- Turner, B.L., Skole, D., Sanderson, S., Fishcher, G., Fresco, L. And Leemans, R. (1995). Land-Use and Land-Cover Change. *IGBP Report No. 35*, IGBP : Stockholm
- U.S. Interagency Task Force on Tropical Forests (1980). *The worlds tropical forests: A policy, strategy and program for the United States*. Report to the President. Government Printing Office : Washington D.C..
- Voon Phin Keong. (1994). Malaysia and Pacific Asia: emerging economic patterns and relations. *Malaysian Journal of Tropical Geography*, 25, 143-159.
- Waring, R.H., Aber, J.D., Melillo, J.M. and Moore III, B. (1986). Precursors of change in terrestrial ecosystems. *BioScience*, 36, 433-438.
- WCED, (World Commission on Environment and Development) (1987). *Our Common Future*. Oxford : Oxford University Press.
- Weismiller, R.A., Kristof, S.J. Scholz, D.K., Anuta, P.E., and Momen, S.A. (1977). Change detection in coastal zone environments. *Photogrammetric Engineering and Remote Sensing*, 43, 1533-1539.
- Wells, D.R. (1988). Birds. In Malaysia (ed) Earl of Cranbrook. Pergamon Press : Oxford. pp.167-95.

- Weston, D. and Pearl (eds) (1989). *Conservation for the twenty-first century*. Oxford University Press : New York.
- Whitmore, T.C. (1984a). *Tropical Rain Forests of the Far East*, 2ed. Clarendon Press : Oxford.
- Whitmore, T.C. (1984b). A vegetation map of Malesia at scale 1 : 5 million. *Journal of Biogeography*, 11, 461-71.
- Whitmore, T.C. (1988). Forest types and forest zonation. In: Cranbrook, Earl of (Ed). *Malaysia*. Oxford : Permagon Press.
- Whitmore, T.C. (1990). *An introduction to tropical rain forests*. Clarendon Press : Oxford.
- Wilson, E.O. (1985). *Issues in Science and Technology*, 2 20-29.
- Wilson, E.O., (1988). *Biodiversity*. Washington DC : National Academy Press.
- Wilson, J.R., Blackman, C., and Spann, G.W. (1976). *Land use change detection using Landsat data*. Proceedings of the 5th Annual Remote Sensing of Earth Resources Conference held in Tullahoma, Tennessee, in 1976, University of Tennessee : Tennessee.
- Wilson, E.O. (1992). The Effect of Complex Social Life of Evolution and Biodiversity. *Oikos*, 63, 13-18.
- Wolman, M.G. and Fournier, F.G.A (eds) (1987). *Land Transformation in Agriculture*. Wiley : Chichester.
- Woodley, S. (1990). A Scheme for Ecological Monitoring National Parks and Protected Areas. *Environments*, 23, 50-73.
- Woodwell, G.M., Houghton, R.A., Stone, T.A., Nelson, R.F. and Kovalick, W. (1987). Deforestation in the tropics: New measurements in the Amazon Basin using Landsat and NOAA Advanced Very High Resolution Radiometer Imagery. *Journal of Geographical Research*, 92, 2157-2163.

World Bank (1987). A World Bank Evaluations Study. *The Jengka Triangle Projects in Malaysia, Impact Evaluation Report*. Operations Evaluation Department World Bank : Washington, D.C.

Zadeh, L.A. (1965). Fuzzy Sets. *Information and Control*, 8, 338-353.

Appendix A
AVHRR Images

Grey Level Brightness Values

Figure A-1

NOAA AVHRR channel 1.

1992

1996

Figure A-2

NOAA AVHRR channel 2.

1992

1996

Figure A-3

NOAA AVHRR channel 3.

1992

1996

Figure A-4

NOAA AVHRR channel 4.

1992

1996

Figure A-5
NOAA AVHRR channel 5.

1992

1996

Appendix B
Transformed Images

Grey Level Brightness Values

Figure B-1

NDVI image.

1992

1996

Figure B-2

Surface temperature brightness (Ts) image.

1992

1996

Figure B-3

Ts/NDVI image.

1992

1996

Figure B-4

Contrast texture measure applied to NDVI image.

1992

1996

Figure B-5

Entropy texture measure applied to NDVI image.

1992

1996

Figure B-6

Contrast texture measure applied to band 3 image.

1992

1996

Figure B-7

Entropy texture measure applied to band 3 image.

1992

1996

Appendix C

**Difference Images Created by Subtracting 1996
Image from 1992 Image**

Figure C-1
Channel 1 difference image.

Figure C-2
Channel 2 difference image.

Figure C-3
Channel 3 difference image.

Figure C-4
Channel 4 difference image.

Figure C-5
Channel 5 difference image.

Figure C-6
NDVI difference image.

Figure C-7
Surface temperature brightness (Ts) difference image.

Figure C-8
Ts/NDVI difference image.

Figure C-9
Contrast texture measure (NDVI) difference image.

Figure C-10
Entropy texture measure (NDVI) difference image.

Figure C-11
Contrast texture measure (band 3) difference image.

Figure C-12
Entropy texture measure (band 3) difference image.

Appendix D

Binary Change/No-Change Images

D-1
Channel 3 post-classification
change image.

D-2
Multi-spectral post-classification
change image.

D-3
Channel 1 (RED) change image.

D-4
Channel 2 (NIR) change image.

D-5
Channel 3 change image.

D-6
NDVI differencing change image.

D-7

Surface temperature brightness (Ts) change image.

D-8

Ts/NDVI change image.

D-9

Contrast texture measure (NDVI) change image.

D-10

Entropy texture measure (NDVI) change image.

D-11

Contrast texture measure (band 3) change image.

D-12

Entropy texture measure (band 3) change image.

D-13

Principal component difference change image.

D-14

Combination 1 change image.

D-15
Combination 2 change image.

D-16
Combination 3 change image.

D-17
Combination 4 change image.

D-18
Combination 5 change image.

D-19
Combination 4 change image.