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Understanding patterns of vegetation change at the Angkor World Heritage site by combining remote sensing results with local knowledge

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ABSTRACT
This research uses two disparate data types, quantitative bi-temporal Multivariate Alteration Detection (MAD) remote sensing with qualitative interview data, to examine the spatial and temporal relationships between patterns of vegetation change at the Angkor World Heritage site, Cambodia. The time period of the research data corresponds with periods where there were significant shifts in the regulations affecting management of the site. The findings suggest that components of change identified from MAD across different spatial and temporal scales can be translated to that observed in the field or ‘real world’. Although MAD results provide an indication of change at specific locations, the results from field investigations and interviews suggest, however, that the different forms of change identified are not always clearly understood. For example, in the case where MAD outputs and associated spectral plots suggest evidence of fire in the landscape, it is not clear whether this is the main contributor to vegetation loss at given sites. The research demonstrates that identifying patterns of vegetation change from satellite imagery is achievable using novel and largely under-utilized methods. However, understanding the forms of change and contributing factors are considerably more complex.

1. Background and context

To evaluate vegetation change in the Angkor World Heritage Site (‘Angkor’) this research combines two disparate types of data: qualitative social science data and quantitative remote sensing data, using a mixed methods approach (Cope and Elwood 2009; Creswell and Plano-Clark 2007; Fox et al. 2003; Jiang 2003). Qualitative approaches are uniquely positioned to attach meaning to place, while a purely quantitative approach based on remote sensing analysis alone cannot explain causal factors. By integrating or ‘mixing’...
quantitative remote sensing with qualitative interview data a more nuanced understanding of the processes and determinants of change can be had.

A major challenge to studies of land use and land cover (LULC) is the linking of data from social sciences with that from natural sciences. LULC studies using a hybrid approach incorporating data on social variables have been demonstrated to provide advantages to using remote sensing methods alone. Kong et al. (2019) used National Aeronautics and Space Administration (NASA) Land Remote-Sensing Satellite System (Landsat) time series data with information from local actors and stakeholders in understanding the drivers of deforestation and agricultural transformations in Cambodia’s north-west, and Cassidy et al. (2010) successfully used image classifications and spatial statistics with multi-scale household data in a LULC study. Fox and Vogler (2005) cross-border study of LULC change in Southeast Asia used unsupervised and supervised classification methods on Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images, complemented with interview data, in determining how socioeconomic factors influence changes identified from remote sensing. Lastly, Cassidy et al. (2013) successfully linked qualitative social data with remote sensing at varying temporal and spatial scales to better understand land cover change at locations in Cambodia and Thailand.

1.1. Remote sensing of vegetation

Medium and low resolution remotely sensed imagery obtained from Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellites have been used in a variety of geographic research relating to land cover (see Abdulaziz, Hurtado, and José 2009; Alaibakhsh et al. 2015; Cassidy et al. 2013; Rogan, Franklin, and Roberts 2002; Rogan and Chen 2004; Zhu 2017). Remote sensing imagery is well suited to change detection studies as it supports repeat coverage of the same area of land. Per-pixel thresholding (Lu, Li, and Moran 2014) which includes image differencing, vegetation index differencing, Principal Component Analysis (PCA) and regression analysis are commonly used, as are per-pixel classification-based change detection methods such as supervised and unsupervised classification.

A variety of methods for estimating change in vegetation cover from remotely sensed imagery have been demonstrated by multiple authors. Davies (2013) and Davies, Murphy, and Bruce (2016) used vegetation indices including the Enhanced Vegetation Index (EVI; Huete, Justice, and Leeuwen 1999) on images acquired from multiple satellite sensors to map the areal extent of change in vegetation near Angkor. Rogan, Franklin, and Roberts (2002) successfully used Normalized Difference Vegetation Index (NDVI; Rouse et al. 1973) differencing to stratify their study site into areas that approximately represent change versus no change using thresholds. Vegetation studies using remote sensing together with in-situ data at Angkor have been demonstrated by numerous authors (Davies, Murphy, and Bruce 2016; Singh et al. 2018, 2016, 2015).

1.2. Multivariate alteration detection

Multivariate Alteration Detection (MAD; Alaibakhsh et al. 2015; Canty 2007; Canty and Nielsen 2008; Liao, Zhang, and Lin 2005; Nielsen, Conradsen, and Andersen 2002; Nielsen, Conradsen, and Simpson 1998; Nori, Elsiddig, and Niemeyer 2008) was the remote sensing
method chosen for this research, primarily because spatially coherent areas created from MAD are well suited to incorporating qualitative social, cultural and historic data. Components of MAD (variates) that show spatial coherence can be selected for inclusion in a bi-temporal change image, with areas of extreme bright and dark indicating change. In addition, MAD is a relatively simple technique to implement and replicate, and areas identified can be validated easily in the field. The ability to adopt a relatively simple field-based technique was considered important for this research given the opportunity for uptake of this method by the local management authority into its future management activities.

As a standalone method, MAD allows the analyst to output different types of change at multiple scales. While this is common with other remote sensing change detection methods such as supervised classification, MAD is particularly well suited to integrating qualitative data. To date research involving the MAD technique has been largely theoretically focused with limited work on relating categories of change to processes observed in the field. The current research extends existing studies using MAD to include qualitative data interpretation.

While it is not a new remote sensing change detection method MAD has seen limited application to date, despite evidence of its utility. Nielsen (2007) successfully applied the MAD method to Landsat TM and high resolution Système Probatoire d’Observation de la Terre (SPOT) imagery to identify areas of change and no change in an agricultural environment. Despite achieving good results using MAD to accurately detect land-cover change, Alaibakhsh et al. (2015) suggest the need for experts’ knowledge and ground truth data to accurately interpret MAD outputs. Liao, Zhang, and Lin (2005) demonstrated the possibilities for cross-sensor change using MAD, and Nori, Elsiddig, and Niemeyer (2008) found supervised classification and the MAD method to be useful in multi-temporal satellite imagery change detection studies.

Although the MAD method does not discriminate between cover types, whether it be vegetation or other types of land cover, the nature of the current research site, dominated by primary and secondary forest, shrubland and agriculture consisting largely of ricefields means that the change identified does relate predominantly to different types of vegetation.

1.3. Temporal and spatial extent of the study

The change periods used in this study (1990 to 2002 and 2002 to 2004) were chosen because they correspond with the periods where there were significant shifts in the regulations affecting management of Angkor. These periods factor in lag time from when regulations were introduced to change being observed on the ground. 1990 corresponds with the period just prior to World Heritage listing and the introduction of a Zoning and Environmental Management Plan (ZEMP) that followed in 1994. Five protected cultural zones were established with the formulation of the ZEMP. Zones 3 and 4 include drainage lines and one small area of archaeological interest (Royal Government of Cambodia 1994), while the most important temples are located in Zones 1 and 2, and Zone 5 encompasses the entire area of Siem Reap province. It was not within the scope of this research to include all zones; as such the focus is on Zones 1, 2 and 5, considered the most relevant (Figure 2). Accompanying World Heritage listing was
the establishment and implementation of controls on land use. In the year 2000 additional controls, specifically relating to forest clearing, were introduced by the management authority. Fieldwork was conducted over multiple field visits in 2008.

1.4. Management of Angkor

Management and conservation of Angkor occurs in various forms, and across various jurisdictions, the breadth of which could not be covered here. The long-standing interaction between people and the surrounding environment makes Angkor a cultural landscape, as recognized by the World Heritage Convention, and this contributed to the site’s 1992 listing as World Heritage. Management of the cultural landscapes of Angkor is overseen by the United Nations Educational, Scientific and Cultural Organization (UNESCO). The Authority for the Protection and Management of Angkor and the Region of Siem Reap (APSARA; Royal Government of Cambodia 1995) manages the site, while ongoing conservation projects, which aim to protect the important archaeological remains, are managed by the World Monuments Fund. Effective governance at Angkor has been challenged by the complexities of land titling, ownership and management (Gillespie 2009; Russell 1997).

2. Study site

Angkor is located on the northern floodplain of the Tonlé Sap (‘Great Lake’) in Siem Reap province, Cambodia (Figure 1). The approximate extent coordinates of the study area are 1,511,700 N, 372,000 W and 1,476,000 S, 420,000 E (Universal Transverse Mercator (UTM) Zone 48 North).

Together, the foothills and plateau to the north and north-east of Angkor, the Tonlé Sap to the south, and the Angkor plain in the centre create a diverse and topographically variable landscape. The central temple area of Angkor rises to a maximum elevation of 100 m above sea level. Some smaller hills and outcrops rise abruptly from the plains, and comprise a small portion of the total greater Angkor area.

Figure 1. Map of Cambodia showing Siem Reap province and the Angkor study site.
Like much of Southeast Asia, rainfall patterns throughout Cambodia are dominated by the monsoons. The wet season usually occurs between April and October and the dry season usually occurs between November and March (Rundell 1999). Considerable variation in temperature and rainfall occurs at the Angkor study site due to the sharp change in elevation between the floodplain and the plateau of Phnom Kulen. While Siem Reap (located on the floodplain) receives approximately 1500 mm of rainfall annually, Phnom Kulen receives closer to 2000 mm. In addition, a 3 to 4°C difference in the annual average temperature exists between these two locations (Ashwell and Fitzwilliams 1993).

The pattern of land use at Angkor was first established in the 8th century CE. Vast areas of land at Angkor were covered by forests during the Angkor period (9th to 16th century CE). However, over time a gradual change in land use has occurred with lowland forests becoming progressively more occupied. Since inscription of Angkor onto the World Heritage List in 1992 significant change in land cover and use has occurred. For example, surveys by the Technical Working Group on Forestry and Environment (2008) describe large areas of forest change due to clearing from 2002 to 2006 in Siem Reap province.

There are two primary reasons that Angkor was chosen for this research. Firstly, Angkor is the ideal setting for examining the complexities of World Heritage Site management which, as argued in this research, are best understood through effective integration of robust quantitative science with qualitative data. Secondly, this research was part of a larger multidisciplinary project at Angkor titled: ‘Living with Heritage: Integrating Time, Place and Culture for World Heritage Conservation’. While Angkor’s importance as an archaeological site is acknowledged (Evans 2016; Evans et al. 2013; Evans, Hanus, and Fletcher 2015; Penny et al. 2014), the focus of this research is on recent history at the site as it relates to changing patterns of vegetation cover.

3. Methods

This study uses Landsat-5 TM, Landsat-7 ETM+ and ASTER imagery. The ASTER images were acquired from the ASTER sensor (on-board the Terra satellite) while the Landsat images were acquired from the TM and ETM+ sensors, on-board the Landsat-5 and Landsat-7 satellites, respectively.

The need to match the date, spatial extent and spectral resolution of the selected imagery with the temporal periods and spatial scale identified for this research presented a significant constraint to the sourcing of suitable imagery. In addition, a requirement of bi-temporal MAD is the inclusion of images of the same type within each MAD change output. It was for these reasons that low and medium resolution Landsat and ASTER imagery were used.

Four images\(^2\) were obtained for this research (Table 1). Image pre-processing applied to all images included conversion to surface reflectance and orthorectification. The bandpass configuration of the two Landsat sensors is very similar, with the bands from the two sensors sharing a similar region of the spectrum. For both images the thermal band 6 was excluded due to incompatible spatial resolution with the other image bands. The panchromatic band 8 was excluded from the Landsat-7 image for the same reason, and because there was no corresponding band in the Landsat-5 image. Three bands of the ASTER imagery were used; these were band 1 (green), band 2 (red) and band 3 (near infrared).\(^3\) MAD processing was applied to two sets of image pairs: Landsat-5 (TM)
November 1990 to Landsat-7 (ETM+) 10 January 2002 and ASTER 3 January 2002 to ASTER 17 February 2004 (Figure 2).

### 3.1. Multivariate alteration detection

There are two principal challenges associated with implementing remote sensing change detection methods which compare multispectral images. Firstly, images acquired from different satellite sensors which may have different image bands, or bands which combine different ranges of wavelength, constrain the ability to make robust quantitative comparisons between images. Secondly, the ability to statistically compare images acquired on different dates under different conditions is essential. Conditions may vary between images as a result of atmospheric differences and variation in illumination, thus requiring radiometric normalization. Given this, the MAD method is well suited to this research due to the lack of discrete un-vegetated areas of sufficient size at the study site required to use as calibration targets for image normalization. Normalization prior to implementation of the MAD procedure is not required as it is implicit within the procedure.

Patterns from MAD outputs are identified and interpreted using both qualitative and quantitative methods. MAD outputs show different aspects of vegetation change such as, in the case of this research, vegetation changing to soil or to rice paddy, vegetation growth, vegetation removal, or change in vegetation type. Although the opportunity for cross-sensor change using MAD has been demonstrated by Liao, Zhang, and Lin (2005), this was not considered in the current research given this earlier study is the only known

![Figure 2](image-url)
example to consider cross-sensor change using MAD. In addition, the efficacy of using ASTER imagery in cross-sensor MAD change was not known. Spectral plots aided the process of interpretation.

Although the MAD technique is somewhat specialized it is well suited to quantifying and monitoring vegetation cover change, and can add value to existing methods such as image classification or PCA. Interpretation of MAD can be enhanced with other quantitative techniques such as NDVI change, which was used in the broader research to generate maps of vegetation gain and loss and in examining forest cover change. While NDVI imagery provides a valuable mechanism for investigating patterns of vegetation gain and loss, and how these patterns may relate to processes occurring at certain times, it does not provide insight on the form of change. On the other hand, MAD change analysis allows partitioning of the landscape based on change characteristics, allowing the types of vegetation change to be more easily differentiated. MAD is well suited to on-the-ground verification as it has no bias in interpretation, which is important when integrating qualitative interview data.

4. **Generating MAD variates and MAD change components**

Based on canonical correlation analysis the MAD procedure uses multivariate data acquired at two points in time and covering the same geographical region (Nielsen 2007). Canonical correlation analysis finds pairs of linear combinations of data variables, with the first two combinations having the largest correlation and called the first canonical variates, the second two the largest correlation subject to the condition that they are orthogonal to the first canonical variates, with higher-order canonical correlations and canonical variates defined similarly (Nielsen, Conradsen, and Simpson 1998). The procedure requires each image pair used to generate MAD to be of the same type, in this case Landsat and ASTER. The iteration procedure used in the MAD algorithm (if it converges successfully) identifies no-change pixels which, if desired, can be used as invariant pixels for a subsequent radiometric normalization of the two images.

Un-vegetated invariant pixels were identified from each pair of input images using the MAD procedure. This procedure generated MAD variates and canonical variates. The canonical variates are components of new multispectral images generated by the MAD procedure, and are ordered by similarity (as measured by linear correlation) rather than, as in the original images, by wavelength (Canty and Nielsen 2008; Nielsen 2007). The uncorrelatedness (orthogonality) of the MAD variates makes them, in principle, useful for identifying different categories of change. When executing the MAD procedure it is desirable to use an optimal iteration of the canonical correlations, the convergence of the canonical correlations can be described as ‘zeroing in’ on the no-change observations (Canty and Nielsen 2008). This is demonstrated at Figure 3 which shows the number of iterations of the MAD transformation for the 1990 to 2002 Landsat MAD change image pair. The MAD transformation produces the MAD variates which contain uncorrelated information needed to quantify the temporal differences (Liao, Zhang, and Lin 2005). The method first calculates ordinary canonical and original MAD variates. The point on the y-axis where the regression curve flattens indicates the minimum desired number of iterations, which is equal to approximately 15 to 20 iterations in this case.
The next stage of the procedure involved selecting MAD variates for creating change images. Three band change composite images were created from the MAD variates for each image pair. The decision of which variates to choose involved identifying the three with the greatest amount of information (the least ‘noise’) to include in a colour composite change image. This is done by including variates which represent coherent spatial change. For example, Figure 4 shows variates which contain, and do not contain, coherent structural information. Areas of extreme bright and dark (contrast) indicate areas of change between the two dates. The ASTER imagery contains 3 bands; therefore there

Figure 3. MAD transformation on the 1990 to 2002 Landsat change image pair.

Figure 4. MAD variates of the same spatial extent; (a) with and (b) without structural information.
was no requirement to select MAD variates at the exclusion of others to create the ASTER change images.

In summary, the MAD procedure makes image pairs as similar as possible before comparing them. Where A = first n-band image and B = second n-band image, canonical correlation, C, of images A and B generates (Equation 1):

\[ CA_1, CA_2, \ldots, CA_n = \text{canonical variates of image } A \text{ and } \]

\[ CB_1, CB_2, \ldots, CB_n = \text{canonical variates of image } B \]

CA\(_1\) and CB\(_1\) are maximally correlated
CA\(_2\) and CB\(_2\) are maximally correlated (subject to being uncorrelated with CA\(_1\) and CB\(_1\))
CA\(_n\) and CB\(_n\) are maximally correlated (subject to being uncorrelated with all other canonical variates)

The steps described result in the image bands being ordered based on similarity (correlation), rather than spectral wavelength (as in the original images), thus, can be compared for changes. Additionally, the uncorrelated MAD variates, used for identifying categories of change, are defined as (Equation 2):

\[ \text{MAD}_1 = CA_1 - CB_1 \text{ and } \]

\[ \text{MAD}_2 = CA_2 - CB_2 \text{ (is uncorrelated with MAD}_1) \text{ } \]

\[ \text{MAD}_n = (CA_n) - (CB_n) \text{ (is uncorrelated with MAD}_1, \text{ MAD}_2, \ldots, \text{ MAD}_(n-1)) \text{ } \]

All MAD processing was performed using ENVI™ software and MAD ENVI™/IDL extensions developed by Canty (2007).

Interviews

Semi-structured interviews based on the mixed methods approach (Creswell and Plano-Clark 2007; Rindfuss et al. 2003; Tashakkori and Teddlie 2003), and carried out between February and April 2008 were used to generate information on vegetation cover, and land and resource access issues faced by local communities. Thirty-seven interviews in ten villages assisted in understanding local perceptions of change in vegetation cover and natural resource access.

A summary of the interview questions are shown here:

- Do people from your village use forest vegetation resources, and if so what for?
- Has the way you use forests changed, and is this due to reasons relating to controls on access?
- Has vegetation cover in your immediate area declined? If so, why and when did this begin to occur?
- How has use and access to forests changed, for example do you travel further today than in the past?
- Have you experienced a decline or shortage in the availability of forest resources?

Interview responses and observations at locations identified from MAD are summarized in Table 3 in the Findings and Discussion.

Spatial data identifying different types of vegetation change\(^5\) were created from locations identified from the MAD outputs. These locations informed the location of interviews and landscape interpretation. Spectral plots at each location identified from time 1 and 2 of the change input images supplemented this process.
Table 2. Description of categories of change derived from Landsat 1990 to 2002 MAD change and ASTER 2002 to 2004 MAD change from field observations.

<table>
<thead>
<tr>
<th>Image tone</th>
<th>Category description</th>
<th>Category number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Areas of stable forest cover, including both primary and secondary forest. Includes locations that have experienced only small amounts of disturbance between 1990 and 2002. Includes forests managed by local people for non-timber forest products (NTFPs) and timber</td>
<td>Landsat 1</td>
</tr>
<tr>
<td></td>
<td>Patchwork clearing at variable spatial scales resulting in bare ground and conversion of some areas to roads, quarry's and possibly structures. Significant disturbance of vegetation including post-clearing burning</td>
<td>Landsat 2</td>
</tr>
<tr>
<td></td>
<td>Patchwork clearing of primary forest commonly 100 m in diameter in scattered locations on the plateau of Phnom Kulen. Also occurs at larger spatial scales in selected locations on the plains. Indicates complete removal of vegetation and exposure of surface soil</td>
<td>Landsat 3</td>
</tr>
<tr>
<td></td>
<td>Conversion from forest to non-vegetation. May be associated with large scale agriculture, land-grabbing, chamkar, or village expansion and associated boundary demarcation. Some scattered remnant forest trees. Common on the slopes, foothills and plains in the north of the study site</td>
<td>Landsat 4</td>
</tr>
<tr>
<td></td>
<td>Areas of stable forest cover, including both primary and secondary forest. Corresponds with locations that have experienced minimal disturbance between 2002 and 2004. Includes forests managed by local people for NTFPs and timber</td>
<td>ASTER 1</td>
</tr>
<tr>
<td></td>
<td>Patchwork clearing of primary forest commonly 100 m to 200 m in diameter at various locations on the plateau of Phnom Kulen. Associated with post-clearing burning and conversion to permanent and non-permanent chamkar agriculture</td>
<td>ASTER 2</td>
</tr>
<tr>
<td></td>
<td>Forest clearing common on the foothills of Phnom Kulen. Some areas may be associated with conversion to smaller plantations such as banana</td>
<td>ASTER 3</td>
</tr>
<tr>
<td></td>
<td>May represent conversion of forest to shrubland or grassland, or conversion to large scale agricultural plantations after 2004. According to interviews with local people this category may in some instances be linked to land grabbing and village encroachment into neighbouring forests</td>
<td>ASTER 4</td>
</tr>
</tbody>
</table>

5. Results

Homogenous areas (categories of change) identified from the ASTER 2002 to 2004 and Landsat 1990 to 2002 MAD change composite images are examined here (Table 2). A description of each category of change, quantified from field observations and interview data, assisted in interpreting change. The categories refer to generic and specific locations, in order to demonstrate the efficacy of MAD interpretation. Distinct areas of homogenous spectra (image tones) observed in the MAD change composite images show unique patterns of change in land cover, specifically relating to vegetation in this research. The image tones for each location can be seen in the corresponding change images (Figure 8). The range of colours represented as image tones for each change image, although not exhaustive, was selected to represent the range of homogenous tones contained in each image.

5.1. Spectral plots

Spectral plots aided in understanding the spectral change characteristics present at distinct locations identified in each pair of change images. Existing research describing the spectral patterns of known substrates assisted in clarifying the change identified from the spectral plots (see, for example, Curran 1985; Lillesand, Kiefer, and Chipman 2004). Because MAD mixes the spectral bands of the images involved, physical interpretation of observed changes is made more difficult (Canty 2007). While Canty’s (2007) original
Table 3. Summary of responses from semi-structured interviews by village.

<table>
<thead>
<tr>
<th>Village name</th>
<th>Key responses and observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kla Knum</td>
<td>Conversion of areas of primary forest to swidden agriculture throughout the mid to late 1990s. Decline in tree cover associated with de-mining in 1993–1994 which increased access to forested areas by villagers and outsiders. Reduction in commonly available forest species in the five years prior to interview in 2008, associated with restrictions on access.</td>
</tr>
<tr>
<td>Thmei</td>
<td>Primary forest existed near the village up until the mid-2000s. Restrictions put in place immediately after the Khmer Rouge period (circa 1980) resulted in reduced access to forests for resource use by local villagers. Forest by neighbouring villagers and outsiders from as far away as Phnom Penh, with a consequent decline in good quality timber which has forced locals to rely on poorer quality timber for their own needs. The late 1990s, the period when the last of the Khmer Rouge soldiers joined forces with the government, saw losses of some larger forest species, particularly at the foot of the mountains. At the time of interview in 2008 only few areas near the village still contained remnant stands of forest containing valuable timber species.</td>
</tr>
<tr>
<td>Anglong Thom</td>
<td>Conversion of some areas of primary forest to swidden agriculture throughout the mid to late 1990s into the 2000s. The mid-1990s saw controls established by the management authority which resulted in restrictions on local people accessing forests. Further regulations by the management authority in the early 2000s designed to place restrictions on local people’s access to forests. Secondary forests continued to be used for extraction of NTFPs. Removal of landmines by the HALO Trust has resulted in increased forest resource extraction activities in this area as management restrictions frequently ignored. By the mid-2000s some primary forests nearby converted to chamkar with good quality timber becoming largely unavailable due to the removal of large trees.</td>
</tr>
<tr>
<td>Skun</td>
<td>In the late 1990s, the period when the last of the Khmer Rouge soldiers joined forces with the government, forest resources begin to decline as larger operators arrived and military involvement in clearing occurred. Stricter rules on access to the nearby Phnom Kulen National Park came into place in the beginning of the 2000s impacting forests located along the foothills closer to the village.</td>
</tr>
<tr>
<td>Tuol Kralanh</td>
<td>Some areas nearby were cleared of forest by the Cambodian military in the late-1990s. Land grabbing and associated forest clearing since the late-1990s.</td>
</tr>
<tr>
<td>Prei Thmei</td>
<td>Extensive clearing in the early to mid-2000s, with ongoing issue of illegal clearing near the village.</td>
</tr>
<tr>
<td>Thmor Chul</td>
<td>Significant clearing of forest in the early-2000s.</td>
</tr>
<tr>
<td>Ommnas</td>
<td>Clearing of forest in the mid to late 1990s commonly for use as firewood by local people. Clearing and burning by villagers in the early 2000s for boundary demarcation. Clearing associated with land grabbing since the mid to late 1990s.</td>
</tr>
<tr>
<td>Popel</td>
<td>Interviews revealed that forest in the immediate vicinity of the village had remained relatively intact until the early-1990s with only local use for NTFPs and firewood collection. Since that time larger high value forest trees had been targeted by those linked to the Cambodian military.</td>
</tr>
<tr>
<td>Sasei</td>
<td>Forest clearing in the early 2000s. Repeated clearing and burning to establish plantations such as cashews.</td>
</tr>
</tbody>
</table>

The approach to improving interpretation of the changes observed is to examine the correlation of the MAD variates with the original spectral bands of the input images, spectral plots, used in this research, provide an alternative approach.

Spectral plots were created at areas containing distinct image tones, from the ASTER 2002 to 2004 and Landsat 1990 to 2002 change imagery (Table 2). Separate plots were created from time 1 and time 2 of each set of original input images to MAD. The steps required to create the spectral plots is illustrated in Figure 5 (for demonstration purposes only one site is shown). For each category of change, plots were created from multiple sites. The pixel values for all bands of the two MAD input images at the locations identified were extracted and used to generate the spectral plots. By interpreting the spectral pattern of each pair of plots acquired at identical locations within the two input images, the type of change that occurred between the two dates could be better understood. Statistics including mean and standard error (SE) were derived based on the range of
values at each location. SE effectively accounted for the number of data points used in the calculation. Error bars on all plots allowed the variability across the range of data points used in each plot to be observed.

Plot category numbers described in Figures 6 and 7 relate to each change category number, by sensor type, described in Table 2. The result of this process is plots that show differences in the pattern of reflectance that represent different types of land cover such as vegetation, soil and water. For example, Figure 7(b) shows the spectral pattern at the same
site in the ASTER 2002 to 2004 change imagery. The plots are spatially related, but temporally different. Each shows a vegetation pattern with a higher reading in the near-infrared band (band 3) than in the red band (band 2). However, the reduction in the reflectance value in band 3 of the second plot suggests a decline in the abundance of vegetation in 2004.

6. Findings and discussion

A key purpose of this research was to understand whether categories of change identified from MAD can be translated to that observed in the field or ‘real world’. Categories of change evidenced in the Landsat 1990 to 2002 MAD and ASTER 2002 to 2004 MAD change imagery are identifiable as distinct image tones. Samples of the distinct tones, showing homogenous areas at each location are shown in the corresponding change images (Figure 8), with a description of each given in Table 2. This data was compared with qualitative information, obtained from semi-structured interviews, to provide insight into management practices, issues surrounding forest resource use, and access constraints faced by local residents (Table 3).
Table 3. Summary of responses from semi-structured interviews by village

On seven occasions (approximately 12% of cases), responses were received from interviews that conflicted with observations identified from MAD. In addition, at 12
sites (approximately 20% of the time) there was no obvious relationship between field observations and information from interviews. Access restrictions during fieldwork meant that some sites were only observed from afar, often hundreds of metres away from the site identified from MAD. Access was most commonly restricted where there was the risk of landmines (mainly in Phnom Kulen), private property boundaries, or natural landscape barriers associated with forest cover, topography or water. By drawing on a range of data to interpret the MAD change images these constraints were able to be limited.

6.1. Landsat 1990 to 2002 MAD change image – category 1

This category of change, which dominated an extensive area north-east of the study site (Figure 8), is seen as a homogenous purple class which covers a considerable geographic area and is associated with primary and secondary forests that have experienced minimal disturbance during the change period 1990 to 2002 (Table 2). This is supported by the corresponding spectral plots which show little change in the abundance of vegetation in 2002 compared with 1990, as indicated by the consistent pattern observed between band 4 and band 3 across both sets of plots (Figure 6(a)).

Interviews with villagers from Thmei in February and April 2008 indicated that at category 1a (Figure 8(a)) primary forest had existed up until circa 2005. At the time of fieldwork some areas nearby contained remnant stands of forest with valuable timber species such as Anisoptera glabra (Phdiek) and Mesua ferrea (Bos niek). Multiple respondents from Anglong Thom village indicated that forest located near category 1b had been converted to chamkar in the early to mid-2000s (Figure 8(a)). During interviews two respondents described restrictions on local people’s access to forests due to controls established by the management authority in the mid-1990s. Despite this, local people continued using forests at this time, for fuelwood, small areas of chamkar (mostly rice), and for NTFPs such as fruit, resin and medicine. The spatial scale of such activities may not have been detected in the change imagery, and this may explain why the area maintained relatively stable forest cover during the change period.

Considerable change to forest cover began to occur after 2000 when the area was cleared of landmines by the non-profit organization The HALO Trust, and people began to access these areas for more intensive purposes such as timber-getting. Change to forest cover in areas that had been de-mined occurred despite the restrictions that had been put in place by APSARA, prior to this date. Interviewees reported that management restrictions were commonly ignored after 2000 as the risk associated with landmines decreased. By the mid-2000s good quality timber had become largely unavailable due to the removal of large trees.

Field observations and interview findings indicate that the subtle difference observed in category 1 of the Landsat 1990 to 2002 and the same category in the ASTER 2002 to 2004 MAD change images is possibly linked to the activities of local people managing these forests for non-timber forest products (NTFPs) including fruit and medicine, timber, and regrowth of areas that were previously swidden agriculture (Figure 9).
6.2. Landsat 1990 to 2002 MAD change image – category 2

Common across the study site, at different spatial scales, this category represents change from vegetation to nil or dead vegetation. The 2002 spectral plots indicate significantly less vegetation compared with the 1990 plots. This change is associated with conversion of forest to non-vegetation, or dead vegetation possibly as a result of fire (Figure 6(b)). Absorption in band 4 of the 2002 plots suggest burning has occurred. Fire is commonly used to remove remaining vegetation after clearing by villagers for ricefield expansion. Charcoal or burnt vegetation decreases NIR reflectance, as observed in the 2002 plots. Field visits to category 2a and 2b provided some insight into possible contributing factors (Figure 8(a)). Interviews with villagers from Skun suggested that numerous locations along the base of the escarpment, and with the same characteristic pattern as category 2, were cleared of forest in the late 1990s by the Cambodian military, or those connected to the military. Interviews with villagers from Omnas, located in the vicinity of category 2b, indicated that this area, similar in pattern to category 2a was cleared of forest between 1995 and 2000, for use as firewood by local people. Villagers indicated that as early as 2000 boundary demarcation had been common at category 2b. Boundary demarcation usually involves clearing and burning prior to establishing boundary markers. Evident occurrence of this practice appears to support the data.

Examination of spectral plots, together with information from interviews, indicates that clearing and subsequent burning likely occurred at category 2a and 2b. This is reflected in the observed change in category 2. In addition, examination of a 2004 SPOT image reveals linear features, indicating boundary demarcation, at both locations (Figure 10).

This example demonstrates the variability evident within the MAD categories of change, and the challenge in defining boundaries that clearly distinguish change.

6.3. Landsat 1990 to 2002 MAD change image – category 3

This category appears to represent conversion from forest to bare ground. The corresponding plots indicate a considerable loss in vegetation in 2002 compared with 1990 (Figure 6(c)). The 2002 plots have a reflectance pattern consistent with soil, showing a slight increase between band 3 and band 4 and a large increase between bands 4 and 5. Compared with vegetation, soil has little absorption in the red band (as it contains no
Figure 10. Land cover at category 2a (Figure 8(a)) Landsat change. (a) 2004 SPOT image with evidence of linear boundaries; and (b) land cover in 2008 from fieldwork photographs showing structures and complete removal of vegetation.

chlorophyll) and usually reflects in the NIR and mid infrared bands (Figure 6(c)). Soil reflectance is also usually greater where less organic materials are present. This category predominantly occurs on the sandstone plateau of Phnom Kulen to the north-east of the study site (Zone 5), with soils containing high amounts of sand, silt and clay, further accounting for the pattern observed in the spectral plots.

Interviews with villagers from Anglong Thom and Kla Kmum village, located in the vicinity of category 3a and 3b (Figure 8(a)), indicated that primary forest had been converted to swidden agriculture at both locations between the mid to late 1990s until the early 2000s. This observation corresponds to the pattern observed in the corresponding plots, described above. During interviews held in Popel village, near Kla Kmum, one respondent described how forest in the immediate vicinity of the village had remained relatively intact until the early 1990s, and since that time higher value forest trees had been removed.

6.4. Landsat 1990 to 2002 MAD change image – category 4

Category 4 of the Landsat 1990 to 2002 MAD change image occurs on the foothills of Phnom Kulen, on the plains, and in the north of the study site in Zone 5. This category largely represents conversion from vegetation to non-vegetation. The 2002 spectral plots indicate a decline in vegetation when compared with the 1990 plots (Figure 6(d)). According to villagers from Omnas, clearing associated with land grabbing began near category 4 c in the mid to late 1990s, and continued after that time (Figure 8(a)). This observation corresponds temporally with World Heritage listing of Angkor in 1992, when land became increasingly valuable at locations beyond the boundary of zones 1 and 2, which includes the villages of Omnas and Tuol Kralanh.

Interviews held with villagers from Prei Thmei, located in the vicinity of category 4a indicated that these areas were cleared approximately five years prior (Figure 8(a)), and extensive clearing had occurred north of this location circa 2000. During interviews villagers discussed the ongoing problem of illegal clearing and land use conflict at this location, and in nearby areas. Conflict over land in Cambodia more broadly is well documented (Chann 2019).

Interviews with villagers from Thmor Chul, near category 4b (Figure 8(a)), established that the area was cleared of forest circa 2001. This corresponds with the pattern observed in the
spectral plots in 2002 which indicate a loss in vegetation compared with the earlier 1990 date (Figure 6(d)). Findings from interviews with villagers from Omnas indicated that location 4 c was cleared of forest in the mid to late 1990s and the site has experienced ongoing clearing since. Given that most respondents did not live in this area prior to the late 1990s, knowledge of land cover prior to this time, as sourced from interviews, was incomplete.

6.5. ASTER 2002 to 2004 MAD change image – category 1

This category of change is similar in character to that observed in the Landsat 1990 to 2002 category 1 change image with relatively stable forest vegetation cover between the two dates. The ASTER spectral plots indicate a vegetation pattern with strong reflection of light in band 3 and, conversely, strong absorption in band 2 (Figure 7(a)).

Interview respondents from Anglong Thom, in proximity to category 1a (Figure 8(b)) described how regulations introduced in the early 2000s placed restrictions on local access to forests. Secondary forests continued to be used for extraction of NTFPs. By the mid-2000s some primary forests nearby had been converted to chamkar agriculture, resulting in a decline in good quality timber with the removal of large trees. The result of this may be reflected in the second change category which is evident as small areas of distinct change within category 1.

6.6. ASTER 2002 to 2004 MAD change image – category 2

This category is associated with swidden agriculture where vegetation has experienced cycles of forest removal and regrowth. Swidden agriculture was established at category 2a (Figure 8(b)) between 2002 and 2004. Other neighbouring areas associated with this category are managed by local villagers for timber, firewood collection and household gardens at fine spatial scales. The pattern observed in the ASTER plots (Figure 7(b)) indicates a reduction in vegetation between 2002 and 2004. The shifting nature of swidden agriculture, practiced at these locations at different time periods, likely explains the main differences in observed pattern. One villager reported during interviews in Thmei that forests in the vicinity of these locations are frequently cut and sold by outsiders and wealthy individuals from neighbouring villages. The consequent decline in good quality timber has altered the forests here and has forced locals to rely on poorer quality timber for their own needs.

6.7. ASTER 2002 to 2004 MAD change image – category 3

This category occurs predominantly on the foothills and escarpment in the north and north-east of the study site in Zone 5. The latter 2004 plots indicate a decline in vegetation. Both the 2002 and 2004 plots show a vegetation pattern, indicated by strong reflection in band 3 and strong absorption in band 2. However, reduced absorption in band 2 of the 2004 plots indicates less abundant vegetation (Figure 7(c)). Background reflectance from exposed soil, common in shrubland environments, is likely also contributing to the reduction in green vegetation in 2004 (Figure 11(d)).

Interviews with villagers from Skun, located in the vicinity of category 3a (Figure 8(b)) suggested that this and nearby areas were cleared of forest, on a large scale, in the late
1990s, with further clearing and the boundary demarcation beginning to occur in the early 2000s. In addition, a policy of forest exclusion in neighbouring Phnom Kulen National Park directly impacted nearby forests, including those located along the foothills. The pattern of landscape fragmentation at this location four years prior to 2008 is shown in Figure 11(a). Boundary demarcation and young cashew plantations, identified at this location during 2008 fieldwork, are shown in Figure 11(b). Remnant forest species, identified on the boundary of these categories of change, are shown in Figure 11(c). Regrowth shrubland, with exposed soil, is shown in Figure 11(d).

6.8. **ASTER 2002 to 2004 MAD change image – category 4**

Category of change 4 is found in Zone 5 and represents conversion from vegetation to a different type of vegetation between 2002 and 2004. Interpretation of spectral plots, together with information from interviews in Thmor Chul and Sasei village appears to support this observation.

The 2004 spectral plots indicate a decline in vegetation compared with those from 2002. This is largely associated with conversion from forest to shrubland vegetation. Both plots show a vegetation pattern, indicated by strong reflection in band 3 and strong absorption in band 2. However, reduced absorption in band 3 of the 2004 plots indicates less abundant vegetation in 2004 (Figure 7(d)). Background reflectance from exposed soil
has likely also contributed to the reduction in green vegetation in 2004. Interviews with villagers from Sasei indicated that this area, coincident with category 4a (Figure 8(b)), was cleared of forest circa 2002, corresponding with the pattern observed in the spectral plots. Tall grasses, and stumps showing evidence of past burning, were identified at this location during fieldwork in 2008 (Figure 12). In addition, one respondent from Thmor Chul stated that significant clearing of forest occurred at this location sometime in the early 2000s.

7. Conclusions and limitations

The MAD remote sensing method (Canty and Nielsen 2008; Nielsen, Conradsen, and Simpson 1998; Nielsen 2007), in combination with interview data and spectral plots was effective in detecting vegetation cover change at the Angkor World Heritage Site, Cambodia at different spatial and temporal scales. The method was particularly well suited to this research because ground-truthing and incorporation of field data to interpret MAD categories supported the integration of qualitative data, thus providing more robust interpretation. This research improves on much of the existing applications of MAD through the process of verification of the types of change observed using interview data and field observation.

Although MAD results provide an indication of change at specific locations, the results of field investigations carried out during this research suggest, however, that the different forms of change identified are not always clearly understood. Integrating multiple forms of knowledge and understandings using different methods has provided insight into the forms of vegetation change, and some of the contributory drivers operating in a World Heritage setting. While this is true, it was not the intention or within the scope of this research to consider all possible drivers of change. For example, the expansion of cashew plantations at locations identified during fieldwork cannot be explained by a single factor but by a number of factors such as market demand, climate and land tenure arrangements.

The trend across all MAD categories is one of change from vegetation cover of one type to another or to less or nil vegetation. The MAD categories have provided some insight into the often subtle differences between the changes observed in the remote sensing. While interviews have provided further insight into such changes this research does not purport to establish a direct cause-effect relationship between the two data types. It does

![Figure 12. Land cover at category 4a (Figure 8(b)) ASTER change. (a) 2004 SPOT image; and land cover in 2008 from fieldwork photographs showing (b) grasslands; and (c) exposed soil and evidence of past burning.](image-url)
however provide a useful method which could be improved upon by using more recent field observations and higher resolution image data to give insight into change at the site since 2004.

Linking interview data with the change imagery based on spatial and temporal correspondence was fundamental to this research. The difficulties some interview respondents had in accurately relating processes or events to time, particularly when compared with other data sources such as spectral plots initially presented research challenges. However, uncertainties in the sequencing or timing of change processes also provided important insight into local perceptions of, and response to such processes.

Where there was a contradiction between MAD findings and field data this illustrated the inherent complexity in understanding change processes. For example, field observations and interview data in some instances suggested little commonality between the different category locations, despite shared patterns in the spectral plots. Such contradiction may reflect the limitation of using information from interviews which relied on respondents interpreting prior events occurring a considerable time in the past (drawing on memory). Data scale including the variable spatial scales of vegetation clearing and other change processes also potentially impacted on interpretation of the change imagery.

Despite the limitations, the results demonstrate the benefits of extending satellite-based interpretation of landscapes beyond scientific field survey to include observations from interviews. Future research may benefit from a comparison of the outputs from MAD with outputs from other well established remote sensing change detection methods such as supervised classification and PCA.

Notes

1. A concept adopted by UNESCO to describe the interaction between culture and nature in the context of World Heritage.
2. Landsat images were obtained from the United States Geological Survey (USGS) Earth Resources and Science Centre (EROS) (http://glovis.usgs.gov). ASTER images were obtained from the Earth Remote Sensing Data Analysis Centre (ERSDAC) Japan (http://www.ersdac.or.jp/eng/index.E.html).
3. At the time of image acquisition only bands 1, 2 and 3 were freely available, hence no additional ASTER bands were used.
4. A 2% linear histogram colour stretch was applied to all change images for display purposes.
5. Identified as regions of interest (ROIs) in ENVI™.
6. Location of villages, and their proximity to change categories can be seen in Figure 8.
7. Forest that has experienced successional change a long time in the past.
8. A complete list of trees identified during the course of this research are available directly from the author. Text in brackets are plant names in the Khmer language.
9. Swidden is a form of chamkar agriculture which is typically not permanent.
10. Location of villages, and their proximity to change categories can be seen in Figure 8.

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