Rainforest Expansion in Far North Queensland

A Preliminary Analysis of the Windsor and Carbine Tablelands

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The four-year term of the Australian Government's Marine and Tropical Sciences Research Facility (MTSRF) officially concluded at the end of June 2010. The Commonwealth Environmental Research Facilities (CERF) Transition Program for the MTSRF aimed to deliver new and additional synthesis products based on the contemporary information needs of the primary end users through the synthesis and analysis of pre-existing MTSRF outputs. In addition, the MTSRF Transition Program extended research that is highly relevant to the future CERF key investment areas of the Great Barrier Reef and Torres Strait, northern Australia and terrestrial biodiversity.

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Acronyms Used In This Report

AIC .... Akaike Information Criterion
BIC .... Bayesian Information Criterion
BOM .... Australian Bureau of Meteorology
CRC .... Cooperative Research Centre
CSIRO .... Commonwealth Scientific and Industrial Research Organisation
DEM .... Digital Elevation Model
ECW .... Enhanced Compressed Wavelet
GIS .... Geographic Information System
MTSRF .... Marine and Tropical Sciences Research Facility
RMS .... Root Mean Square
TPI .... Topographic Position Index
WTMA .... Wet Tropics Management Authority

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Introduction

Tropical rainforests across northern Australia fall under a range of structural and floristic types (Webb 1959, 1968, 1978; Webb and Tracey 1981a, 1981b), which include structurally complex vine forest developed on relatively nutrient rich, moist but well drained soils, to structurally simple rainforest types on oligotrophic moist soils. In the Wet Tropics of Queensland, tropical rainforest covered an estimated 965,000ha prior to European settlement of the area during the nineteenth and twentieth centuries. Subsequent human impacts resulted in a reduction in the area of rainforest to approximately 750,000ha. Some small areas of wet tropical rainforest are privately owned, although most of the remaining rainforest areas in northern Queensland were declared the Wet Tropics World Heritage Area in 1988 (Kanowski *et al.* 2003).

A distinctive feature of rainforest in the wetter parts of northeastern Queensland is the often abrupt boundary between the rainforest and eucalypt dominated vegetation or grassland (Harrington and Sanderson 1994). The vegetation dynamics of the rainforest boundary has been the subject of immense scientific interest, with studies targeting various aspects of the rainforest boundary, including environmental gradients (Turton and Sexton 1996); vegetation-climate response modeling (Hilbert *et al.* 2001); mammalian assemblages (Williams and Marsh 1998); vegetation structure (Duff 1987; Ash 1988; Unwin 1989); and fire susceptibility of species (Unwin *et al.* 1985).

While rainforest boundaries may appear abrupt and stable, pollen records suggest that these boundaries have been expanding and contracting throughout geological history (Walker and Chen 1987; Haberle 2005). Possible reasons for rainforest expansion include climatic amelioration (Hopkins *et al.* 1993) and/or release from fire suppression (Bowman 2000; Hill *et al.* 2000)

In the region between Ingham and Cooktown, wet sclerophyll forest dominated by tall (>40m) eucalypts typically forms a narrow fringe ranging in width from around 300m to 4km along the rainforest margin (Harrington and Sanderson 1994; Harrington *et al.* 2000) (Figure 1). A number of authors report that rainforest in far northern Queensland is expanding at the expense of eucalypt dominated vegetation (Unwin *et al.* 1988; Stocker and Unwin 1989; Unwin 1989; Harrington and Sanderson 1994; Harrington *et al.* 2000, 2005), touting changed fire regimes since European colonisation. These studies are built on a ‘pyrocentric’ perspective and treat rainforest and wet forest as alternate stable states occurring along a gradient of abiotic factors, where fire encourages the fire-dependent (sclerophyll) vegetation whilst limiting rainforest (Warman and Moles 2009). Such a paradigm emphasises the role of fire, and has given rise to some modern management conundrums, propagating the view that rainforest needs to be curtailed by fire to conserve or maintain adjacent biotas or habitats. In particular, Harrington and Sanderson (1994) paint the invasion of rainforest in a negative light, predicting further loss of wet sclerophyll habitats without adequate management, and endangerment to endemic native mammals like the Yellow-bellied glider (*Petaurus australis*) and Brush-tailed Bettong (*Bettongia tropica*).

On the other hand, the actual area of rainforest in Australia is extremely small in comparison to eucalypt dominated vegetation, and the threat posed to wet sclerophyll vegetation at a landscape scale may have been overstated. As argued succinctly by Walker (1990), an understanding of rates associated with such landscape-scale processes is essential for informing ecosystem management at scales ranging from years and decades, to hundreds and thousands of years to accommodate longer-term regional climatic fluctuations.

Study Aims

Here we explore the rates of landscape change and landscape conditions associated with rainforest expansion in the Wet Tropics World Heritage region of northeastern Queensland. We assess change in rainforest in a 270.19 km^2 study area within the Wet Tropics Bioregion with reference to available aerial photography (1951-1955 and 2008) and landscape coverages (geology, elevation, slope, aspect, proximity to streams), and ask to what extent rates of rainforest change were similar for both time periods and mediated by climatic and landscape conditions.

Methodology

Study Area

The study area was situated in and around the Wet Tropics World Heritage Area (Figure 1) of far northern Queensland. The Wet Tropics contain many different vegetation types which form a complex and dynamic mosaic (Hopkins *et al.* 1993; Hilbert *et al.* 2001). The region covers approximately 1.8 million hectares (Williams 2006) and is characterised by a fragmented band of humid tropical rainforests interspersed with fire-prone sclerophyll vegetation (e.g. grasslands, open woodlands and eucalypt forests) (Unwin 1989; Hopkins *et al.* 1993; Hilbert *et al.* 2001).

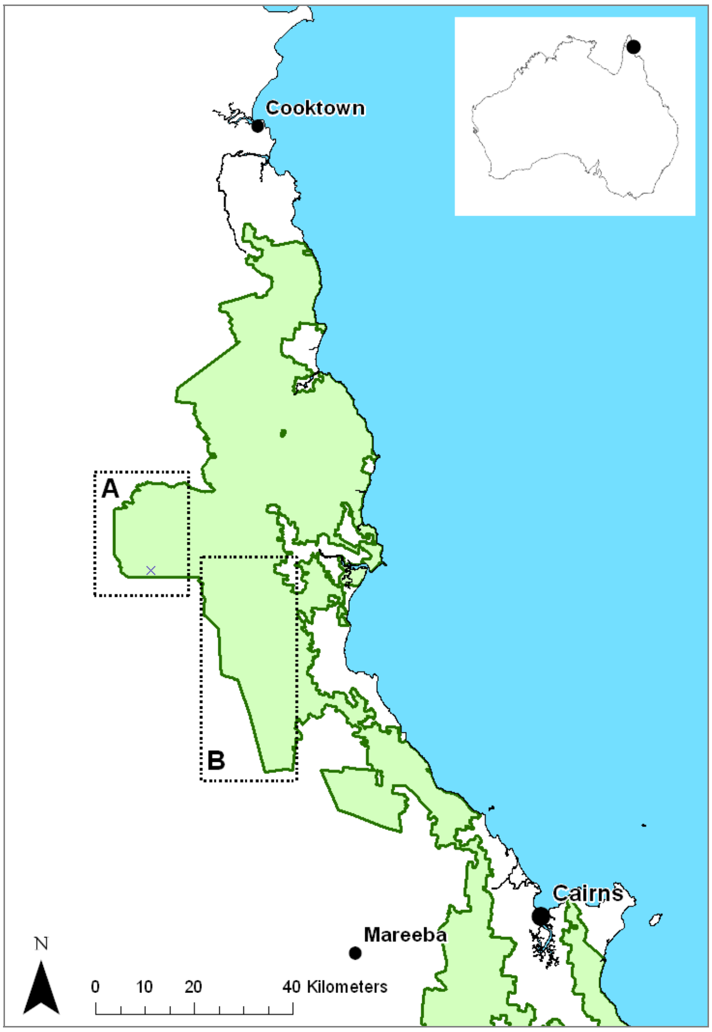

Figure 1: Selected sites for mapping of rainforest change, denoted in enclosed rectangles representing Mount Windsor (A) and Mount Carbine (B). Green shaded areas denote the boundaries of the Wet Tropics World Heritage Area.

The regions selected for the current study are within and surrounding the Mount Windsor and Mount Carbine National Parks (Figure 1). Vegetation in the two study regions comprises a mosaic of formations, including rainforest and a range of vegetation types on drier facies. Based on recent mapping (Goosem *et al.* 1999), and applying the terminology of Webb (1959, 1968), regional rainforest assemblages fall under notophyll vine forest and microphyll rainforest and includes microphyll vine thickets on cloudy windswept summit areas (Table 1). The remainder of the terrestrial vegetation comprises mostly eucalypt-dominated open-forests and woodlands occupying a broad range of freely draining substrates; heaths restricted to shallow, infertile soils; and *Syncarpia* and *Lophostemon*-dominated forests.

Mount Windsor is a granitic massif with a broadly domed summit where elevations exceed 1,000m. Similarly, Mount Carbine is a granitic massif with an elevation exceeding 1,000m, but has a summit area 35km long and up to 15km wide. The geology of the region consists of Palaeozoic granite batholiths and metamorphics of the Hodgkinson Formation and the physiography of the area describes a complex series of plains and low to high ranges.

Precipitation data for the study period (1950-2008) was obtained from the Mossman Central Mill weather station (Station no. 031044; Coordinates 145.38°E, 16.46°S; Australian Bureau of Meteorology) (Figure 2). Mean annual rainfall at the Mossman Central Mill weather station exceeds 2,300mm, mostly falling between December and April, with the highest rainfall occurring in January and the lowest in July. Climate data obtained from the next nearest weather station at Low Isles (Station no. 031037; Coordinates: 145.56°E, 16.38°S) show that the mean annual temperature of the region ranges between 27.4°C (lowest) and 30.1°C (highest) over the annual cycle and monthly relative humidity at 1,500 h ranges between 64% and 84%.

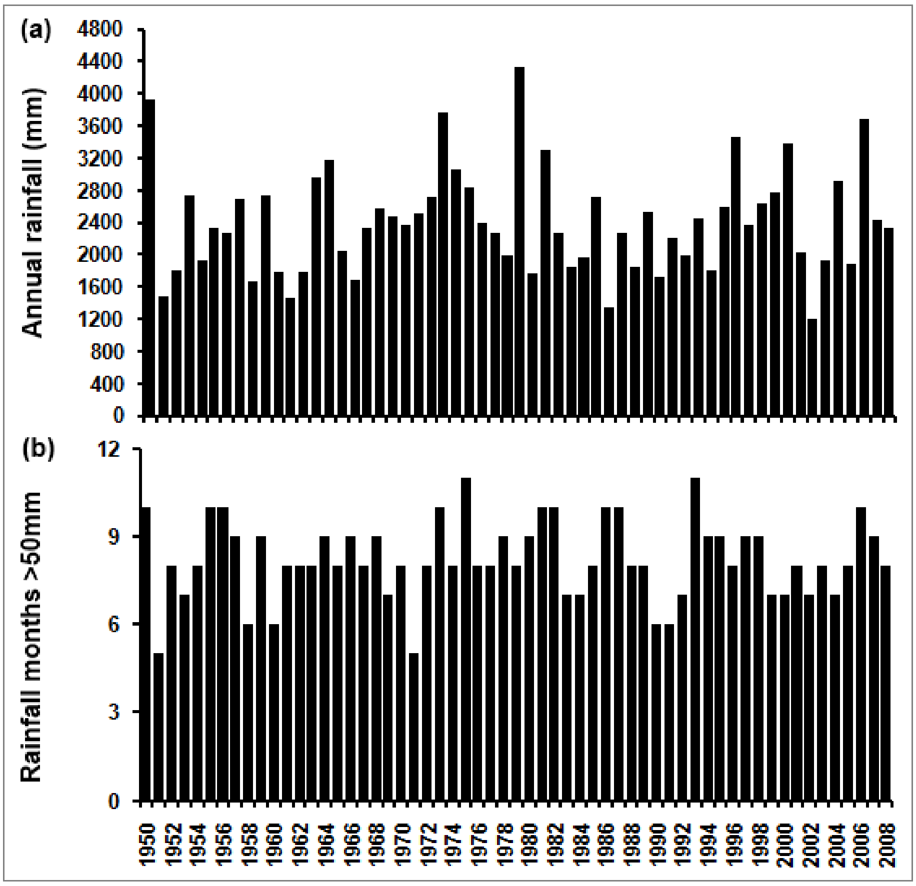

Figure 2: Rainfall data from the Mossman Central Mill weather station, the weather station nearest to Mount Windsor and Mount Carbine, 1950-2008, showing annual rainfall (a) and number of months where rainfall >50mm (b).

Mapping rainforest change

Available black and white aerial photos (scales ranging from 1:24,000 to 1:30,000) for the two areas, Mount Windsor (1951-1955 composite) and Mount Carbine (1955) were scanned at 1,690 dots per inch, ortho-rectified and stitched to create ortho-mosaic compressed GeoTIFF images at 0.5m pixel size using Landscape Mapper v1.4.56 (Myriax Software Pty Ltd, Hobart). Images were subsequently converted to compressed ECW format using ER Mapper 7.2 for faster viewing as a GIS layer in ArcMap 9.3. A 30m resolution digital elevation model (DEM) (Shuttle Radar Topographic Mission Level 2 data, licensed for use by Geoscience Australia) provided the rectification surface. A colour 2008 orthomosaic covering the entire Wet Tropics Bioregion was provided by the Wet Tropics Management Authority (WTMA). In addition to its use as a comparison image for vegetation change, this orthomosaic provided a 0.5m resolution control layer for spatial referencing and adjustment of the 1950s photography. Features such as drainage lines, rock outcrops, buildings and occasionally the centrepoint of a single tree canopy were aligned to corresponding features in the 2008 orthomosaic. Root mean square (RMS) errors for each orthorectification after final stitching were:

- **Mount Windsor:** 8 photos, 103 control points, 42 bond (stitch) points, RMS error 12.3 m;
- **Mount Carbine:** 12 photos, 80 control points, 32 bond (stitch) points, RMS error 16.0m.

To estimate temporal change, we employed a grid approach in ArcGIS whereby we layered 50x50m grid cells over each of the two areas for both time periods and attributed each grid cell for vegetation and environmental attributes. Collectively, both grid areas encompassed an area of 270 km^2. These grid cells were positioned to include both savanna and rainforest vegetation across vegetation boundaries. The vegetation for each grid cell was attributed by assigning a status of being either rainforest or savanna (eucalypt forest and other open forest types) (Table 1) based on canopy openness (closed canopy = rainforest; open canopy = savanna) and visible understorey components. To facilitate this process, we layered a 2008 vegetation map provided by the WTMA over the orthomosaics as an approximate guideline for determining vegetation type. Grid cells in which both rainforest and savanna occurred were attributed based on the dominant vegetation type. Grid cell areas which covered bare rock, roads, water bodies, built-up areas or plantations were excluded from the subsequent analysis.

Table 1: Relationship of final vegetation mapping classes as used in GIS analysis, with respect to original codes used in the WTMA vegetation map.

Vegetation mapping codes in pre-existing vegetation map	Vegetation classes used in current study
Notophyll rainforest	Rainforest
Microphyll rainforest	Rainforest
Microphyll thickets	Rainforest
Sclerophyll-rainforest transitions	Rainforest
Closed *Acacia* forest	Rainforest
Closed *Lophostemon* forests	Rainforest
Acacia forest and woodland	Savanna
Eucalyptus forests and woodlands	Savanna
Syncarpia forests and woodlands	Savanna
Shrubland and heathlands	Savanna

To determine the linear distance of vegetation change, we selected 100 points in a shape (.shp) file on the rainforest edge at random locations on the 1950s mosaics. These 100 points were paired with points on the rainforest margins for the 2008 mosaic and the linear distance between each paired point (Figure 3) was measured using the measure function in ArcGIS.

Figure 3: Illustration of the methodology used to determine change in linear distances in rainforest boundaries on Mount Windsor in the 2008 orthomosaic. The unbroken line represents the rainforest boundary in 2008 and the dotted lines represent the boundary in the 1950s orthomosaic, which has since moved. The yellow triangular and red dot points denote random sampling points chosen for measuring rainforest boundary distances in the 1950s and 2008 repestively. Change in linear spread is measured by determining the distance between the yellow triangle and the corresponding red dot.

Correlates of rainforest change

The grid cells used for attributing vegetation type were also attributed for environmental variables including elevation, geology, proximity to water bodies or drainage systems and distance to rainforest (Table 2). A topographic position index (TPI; Jenness 2005) was calculated from a DEM with a resolution of 30m provided by the WTMA, using a search radius of 500m. A TPI provides a measure of the difference in elevation of a location and the mean elevation of the surrounding area, and is therefore useful for classifying locations as ridges, valleys, etc.

We examined the association of rainforest change with landscape features by applying the modelling approach for analysing spatially autocorrelated non-normal data developed by Murphy *et al.* (2010). All 50x50m grid cells were included in the analysis. Potential explanatory variables generated are given in Table 2. Thus our statistical model constitutes an exploration of the landscape features that may influence the probability of a previously non-rainforest site becoming (and remaining) dominated by rainforest.

Table 2: Environmental correlates deemed to have an influence on rainforest change.

Variable	Description	Hypothesised effect
Aspect	Aspect was incorporated as a composite variable consisting of 'northness' [cosine(aspect)*%slope] and 'eastness' [sine(aspect)*%slope]. Thus, 'northness' and 'eastness' were indices ranging from -1 (steep south or west-facing slope) to 1 (steep north or east-facing slope).	Lower probability of expansion on steeper slopes due to increased fire intensity and reduced moisture trapping, and greater probability of expansion on steeper slopes correlated with topographic protection.
Distance from rainforest	Distance (m) from the nearest rainforest patch margin as mapped in the earlier time period (1950s) from both Windsor and Carbine orthomosaics. For analysis purposes, this correlate was confined to cells within 1,000m of pre-existing rainforest patches.	Declining probability of invasion at points distant from pre-existing rain forests.
Elevation	Height (m) above sea level.	Greater probability of expansion at lower elevations due to more favourable moisture regimes.
Geology	Broad classes extracted from Australian Geological Survey 1:250,000 map for the region.	Expansion rates will vary with geology due to differences in fertility and water holding capacity.
Slope	In degrees, determined for each grid cell of a 30m digital elevation model (DEM).	Lower probability of expansion on steeper slopes.
TPI	Topographic Position Index (Jenness, 2005) determined for each grid cell of a 30m DEM by calculating the difference between the elevation of the grid cell and the mean elevation calculated from all grid cells in a circular window of radius 250m centred on the cell of interest.	Lower probability of expansion on ridges.
Water	Proximity (m) to water bodies or drainage systems. Calculated for each grid cell in ArcGIS using the 2008 orthomosaic.	Greater probability of expansion close to water due to higher water availability, fire protection and propagule dispersal in water.

Modelling rainforest change

We treated our response variable as binomial (i.e. 0 = savanna remained savanna; 1 = savanna changed to rainforest), using a binomial error family with logit link. Models representing all combinations, without interactions, of the seven environmental correlates (Table 2) considered to be relevant to rainforest change were constructed as generalised autoregressive error models (GAR_{err}). This type of model was recently developed by Murphy *et al.* (2010) to analyse spatially autocorrelated non-normal data. It is similar to the simultaneous autoregressive error model for normal data (Cressie 1993) but can cope with non-normal data types like a generalised linear model. This type of spatial model is limited to 4,000 observations, so we chose a random sample of our total dataset. Because virtually no conversion from savanna to rainforest occurred >1km from a rainforest boundary, we selected 4,000 points from within this distance. We confirmed that the GAR_{err} models successfully accounted for residual spatial autocorrelation using correlograms based on Moran's I (Dormann *et al.* 2007; see Figure A1 in Appendix, this report).

Models were evaluated using the Bayesian Information Criterion (BIC), a model selection index favouring both model fit and model simplicity (Burnham and Anderson 2002). BIC is analogous to the more widely used Akaike Information Criterion (AIC), but tends to penalise complex models more heavily than AIC. Hence, it tends to be more appropriate for large datasets where the main underlying drivers are of primary interest (Link and Barker 2006). Lower values of BIC indicate greater support for a model, relative to other models in the same candidate set. From BIC, evidence weights (w_i) were calculated for each model, and these are equivalent to the probability of a given model being the best in the candidate set. The importance of each variable was evaluated by calculating $w+$, the sum of w_i for all models in which that variable occurred. For each variable, $w+$ is equivalent to the probability of the best model containing that variable, and is a useful expression of the weight of evidence for the importance of the variable. We considered that $w+$ values of <0.73 were indicative of substantial model selection uncertainty, and that a relationship between the response and the explanatory variable in question was not well supported by the data. A $w+$ value of 0.73 is equivalent to a BIC difference of two units between the models containing the variable under examination and those not containing it. A difference of two units is a common 'rule of thumb' used in ecological studies to assess evidence of an effect (Richards 2005).

Results

Changes in rainforest area and linear spread

Our results point to net rainforest expansion on both the Windsor and Carbine Tablelands (Table 3; Figure 4). The extent of net rainforest expansion was greater on the Windsor Tableland (368.25ha) than on the Carbine Tableland (81.25ha).

Figure 4: Illustration of change in extent of rain forest on Mount Windsor as mapped on the original 1950s orthomosaic (a) and the corresponding area in the 2008 orthomosaic (b). The 2008 orthomosaic was desaturated for comparison. Note, general vegetation thickening by 2008, including in areas of savanna vegetation. Each grid square represents a 50x50m area and the grid squares in red have been attributed for rainforest occurrence. Note the additional red grid squares (thickened borders) attributed for rainforest in the 2008 mosaic. The remaining grid squares in black represent savanna.

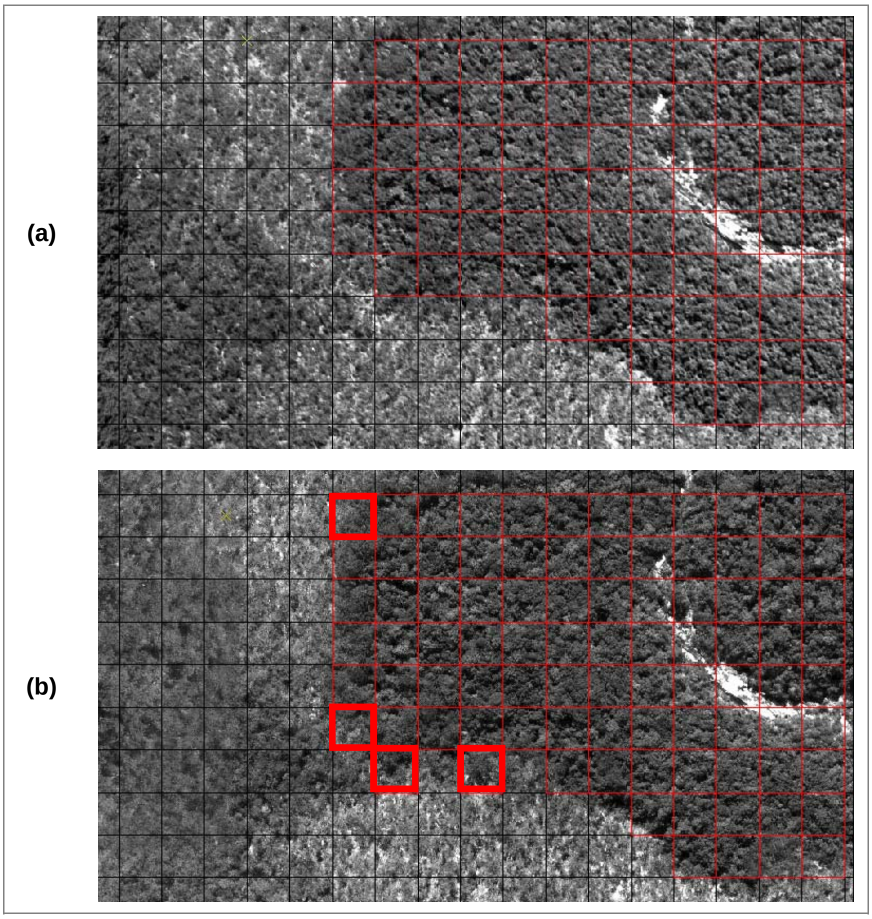

Table 3: Change in area extent of rainforest and savanna on the Windsor (1951-1955 vs. 2008) and Carbine Tablelands (1955 vs. 2008) (total area of grid cells given in parentheses).

	Windsor (12,137 ha)		**Carbine (14,882 ha)**	
	1951-1955	**2008**	**1955**	**2008**
Rainforest area	4,356 (35.9%)	4,724 (38.9%)	5,232 (35.2%)	5,313 (35.7%)
Savanna area	7,781 (64.1%)	7,413 (61.1%)	9,650 (64.8%)	9,569 (64.3%)
Percentage of change (Rainforest to Savanna)	0.8		0.8	
Percentage of change (Savanna to Rainforest)	5.2		1.3	

In terms of linear boundary shifts, 49% and 32% of the paired sampling points on Mount Windsor and Mount Carbine respectively showed some change in the location of rainforest boundaries (Figure 5). In both areas, most of the boundaries showing rainforest expansion had moved less than thirty metres. Likewise, where savanna expansion occured, most boundaries had typically shifted less than thirty metres, with the exception of Mount Carbine, in which one point exhibited a linear spread of 43m (Figure 5).

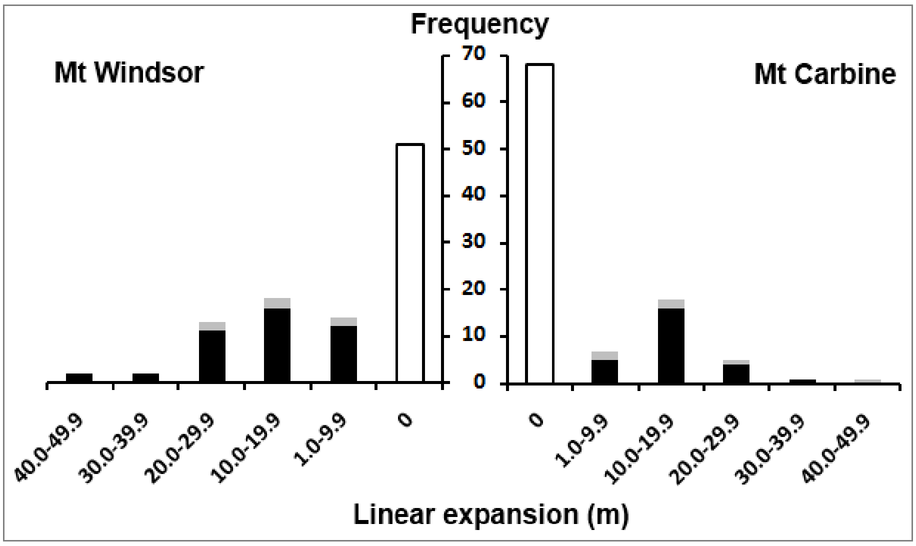

Figure 5: Linear expansion of the rainforest margins on Mount Windsor and Mount Carbine as measured from 100 random paired points. White bars denote points that have not exhibited boundary movement; black bars denote points where the rainforest boundary has expanded; and grey bars denote points where the savanna boundary has expanded.

Correlates of change

There was a very strong effect of distance from the original rainforest boundary on the probability of conversion from savanna to rainforest. The probability (*w*+) of 'distance to rainforest' appearing in the best model of savanna conversion was >0.99 at both Windsor and Carbine (Table 4). Very little savanna situated more than one hundred metres from a rainforest boundary became rainforest (Figure 5). No other variables had any clear effect on the probability of conversion from savanna to rainforest (Table 4).

The best models of savanna conversion explained 32% and 23% of residual deviance at Windsor and Carbine, respectively, and 32% for the two sites combined.

Table 4: Importance values (*w*+) of environmental predictors of expansion at Mount Windsor and Mount Carbine, based on the Bayesian Information Criterion (BIC). '*w*+' can be interpreted as the probability of that variable being in the best model. As a 'rule of thumb', values of *w*+ ≥0.73 can be interpreted as clear evidence of an effect (Richards 2005), and such values are shown in bold.

Variable	***w*+**		
	Windsor	**Carbine**	**Combined**
Distance to rainforest	**>0.99**	**>0.99**	**>0.99**
Topographic position index	0.06	0.57	0.04
Elevation	0.14	0.02	0.03
Slope	0.06	0.03	0.04
Geology	0.04	0.02	0.02
Distance to waterbody	0.02	0.02	0.02
Aspect	0.00	0.00	0.01

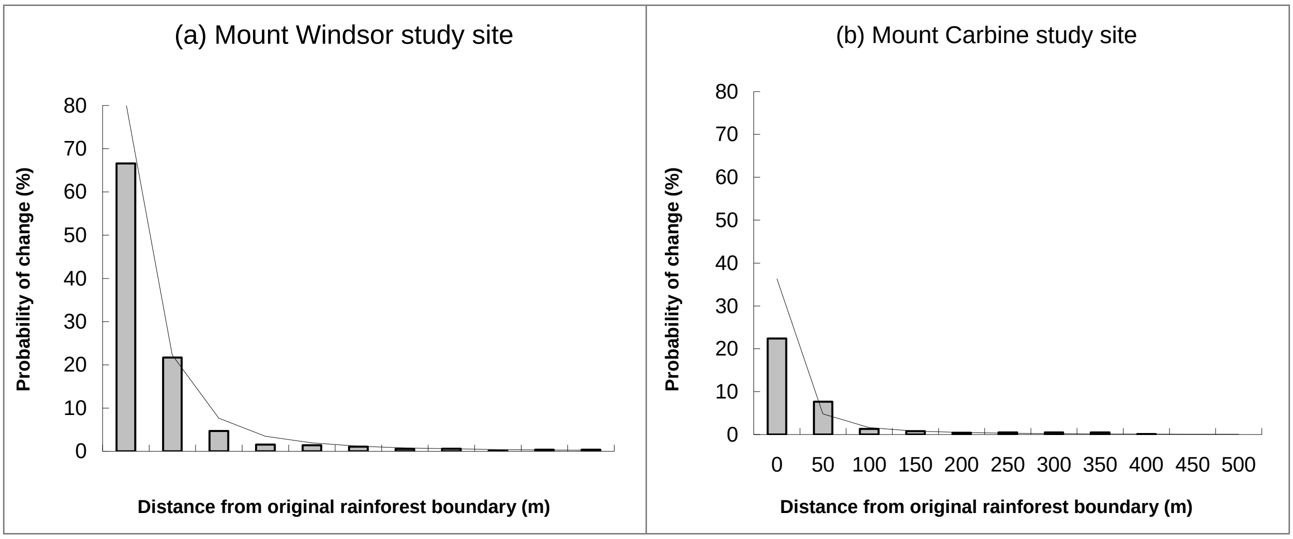

Figure 6: The observed (bars) and predicted (line) probabilities of conversion of savanna to rainforest in relation to distance to the original rainforest boundary, at the Mount Windsor (a) and Mount Carbine (b) study sites. The model predictions are based on multimodel averaging of the entire candidate set of models, weighted according to w_i and assuming mean values for all other variables.

Discussion

Our results suggests a net expansion in the extent of rainforest into savanna dominated vegetation. Our statistical models suggest that over a period of several decades, rainforest expansion occurred on all geologies and at all elevations in sites that would be described as savanna on Mount Windsor, and to a lesser degree on Mount Carbine.

The reasons for the different extent of rainforest expansion between Windsor and Carbine are unclear. However, it is known that Mount Windsor has had a history of logging (Crome *et al.* 1992), while Carbine Tablelands has remained unlogged since European colonisation. The greater expansion of rainforest in the Windsor region may then in part represent rainforest that is expanding back into areas that were previously logged.

In far northern Queensland, Harrington and Sanderson (1994) reported that rainforest had expanded in the Mount Spurgeon area; part of the Mount Carbine region in the current study. The results in that study are not directly comparable to those of our study due to different coding of vegetation types. However, Harrington and Sanderson (1994) report a much greater extent of rainforest expansion than has been documented in our study. For instance, they documented an increased of 720ha in a mixed species wet sclerophyll forest type with a young rainforest understorey (coded as 'rainforest' in this current study) on Mount Spurgeon, suggesting that rainforest had invaded what was once wet sclerophyll forest with a grassy ground layer. By comparison, our results for the Carbine region only showed an increase of 81ha of rainforest (Table 3).

Unwin (1989) reported that rainforest had expanded in the Herberton highlands over a ten-year study period, and suggested that rainforest was expanding at an estimated 1m year^{-1}. Our results are in agreement and show that at certain localities rainforest linear expansion may expand at a similar rate. For instance, the fastest rate of linear expansion measured using our paired points system was 45m in 53 years (equivalent to ~0.8m year^{-1} rainforest expansion). The balance of the results (Figure 5) suggest that rainforest expansion is more likely to occur at a much slower rate. It is apparent also that rainforest expansion occurred along drainage lines at Mount Windsor and Mount Carbine, even if not exclusively so. In another study, rainforest expansion was documented in riparian rainforest in the Mossman region between 1944 and 2000 (Lawson *et al.* 2007), just east of the study sites in this study. Meave *et al.* (1991) have highlighted the importance of riparian habitats as refugia for rainforest vegetation in savanna landscapes; a point also implicit in Ash's (1988) descriptive model of rainforest expansion for northeastern Queensland.

An additional observation made, but not quantified in the observation of the aerial photographs of the two time periods was that the vegetation exhibited general thickening in many areas (e.g. Figure 3). This is in agreement with the findings of Johansen and Phinn (2005) who analysed vegetation change in the Wet Tropics Bioregion using Landsat TM/ETM+ imagery from 1988 and 1999. They detected vegetation thickening in the transition zone between rainforest vegetation and woodland vegetation in remote inland areas.

Rainforest expansion has been documented in other studies throughout tropical regions in Australia. For instance, Russell-Smith and others (2004b) reported rainforest expansion in the monsoon tropics of Iron Range National Park. Likewise, a similar phenomenon has been reported in the Northern Territory, in Kakadu National Park (Bowman and Dingle, 2006; Banfai and Bowman, 2005, 2006, 2007), Litchfield National Park (Bowman *et al.* 2001) and the Gulf of Carpentaria (Brook and Bowman 2006).

Russell-Smith *et al.* (2004b) found rainforest expansion in Iron Range across all geologies sampled, but they also detected a higher probability of rainforest expansion on certain geologies. By contrast, our results show that the only significant driver of rainforest expansion on Mount Windsor and Mount Carbine was distance to pre-existing rainforest (Figure 6). Additionally, by using a spatially explicit modelling approach, we can be confident that we have avoided spurious relationships between rainforest expansion and environmental factors, such as geology. Previous attempts to model rainforest expansion (e.g. Russell-Smith *et al.* 2004b) have not adequately dealt with spatial autocorrelation, so the true relationships with environmental variables are uncertain.

As with the current study, Banfai and others (2007) found that monsoonal rainforest expansion in Kakadu was most strongly correlated with distance to pre-existing rainforest. This supports the view that the rainforest boundary dynamics in Kakadu National Park have primarily been incremental on the rainforest boundary, as has been observed in other regions of northern Australia such as at Weipa, northern Queensland (Bowman and Fensham, 1991). Our results through measuring linear spread (Figure 5) and modelling (Figure 6) are in agreement with incremental expansion on the rainforest margins. It is likely therefore that rainforest expansion at Mount Windsor and Mount Carbine has occurred primarily through the process of margin extension, rather than other successional processes such as nucleation and irruption (Russell-Smith *et al.* 2004a). Nevertheless, the effect of geology on rainforest expansion in far northern Queensland remains to be assessed on a larger spatial scale, as the rainforest regions south of the study area have very different geologies.

The lack of clear local environmental correlates driving rainforest expansion neccessitates an examination of additional factors. It has been suggested that European colonisation and related pastoral activities may have altered the fire regimes previously effected by aboriginal management and lightning strikes (Unwin, 1983, 1989; Ash, 1988). Unfortunately, there is no reliable information available about the fire regimes of aboriginal people or of European pastoralists. It is clear however that sclerophyll forest containing rainforest was already apparent before the 1950s (Harrington and Sanderson, 1994), which indicates that the shifting of rainforest boundaries was occurring well before the 1950s. Cast under a palaeoecological persepective, there is clear evidence from charcoal (Hopkins *et al.* 1993, 1996) and pollen studies (Kershaw 1994; Haberle 2005) that rainforest-savanna margins have indeed been oscillating throughout geological time. *Eucalyptus* woodland was apparently much more widespread in far northern Queensland, and possibly occured even in the wettest areas which now contain rainforest (Hopkins *et al.* 1993). The rainforest re-expansion apparently started ca. 8,000 yr BP and coincided with a period when conditions were particularly favourable for rainforest; the climate being considerably wetter and less seasonal than it is today (Kershaw and Nix, 1988). Banfai and Bowman (2005, 2006, 2007) attribute rainforest expansion in Kakadu to CO_2 increases and a general wetting trend, and Bowman and others (in review) suggest that rainforest expansion is a signal of global climate change that is so strong it is overwhelming the hostile fire regimes that are degrading the surrounding savannas. Further, recently Warman and Moles (2009) suggested the paradigm of wet sclerophyll forests being converted into rainforest because the drivers that maintained savanna had shifted toward the regime that would be more favourable for rainforest. It is not therefore unreasonable that CO_2 increases or wetting trends may be the drivers of rainforest expansion in the current study.

Given the sensitivity of the predominant rainforest type however to change in temperature, it is highly unlikely that rainforest expansion of the same rainforest type will proceed below a certain altitude. Hilbert and others (2001), for instance, predicted that notophyll vine forest types are likely to experience a decline with the incumbent increase in temperature to accompany climate change.

Conclusion

Rainforest in upland areas of the northern part of the Wet Tropics Bioregion has been exhibiting a net expansion in extent between the period spanning the 1950s to 2008. This expansion is not strongly correlated with any local environmental correlate other than distance to pre-existing rainforest. The magnitude of rainforest expansion however does not appear to be as great as some earlier reports. A comparison of aerial photography of more southerly areas, including Clohesy, Koombooloomba and Paluma, are in the works and is anticipated to provided a more complete picture of the environmental drivers of vegetation change across the Wet Tropics Bioregion.

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Appendix

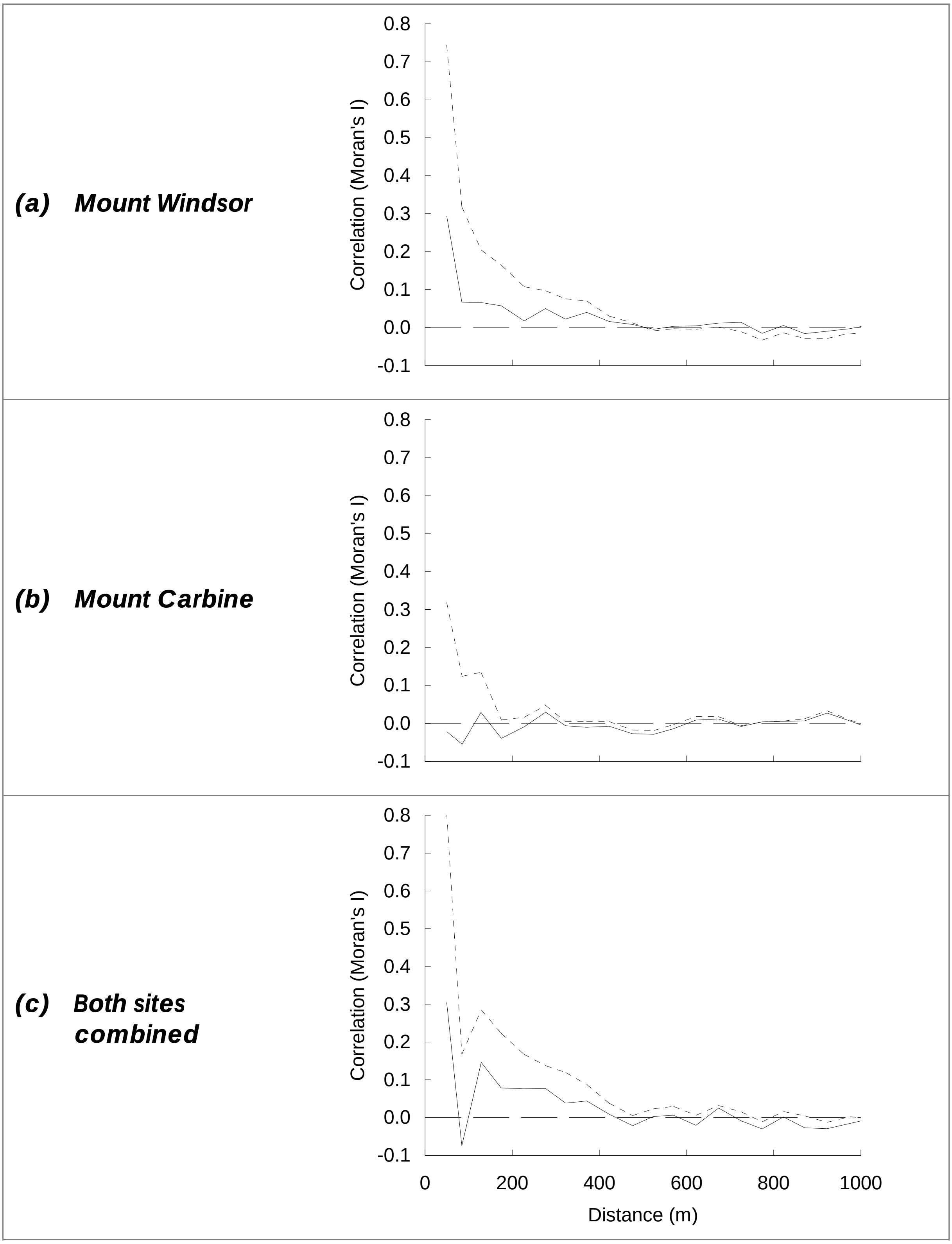

Figure A1: Correlograms of residuals of non-spatial Generalised Linear Models (dashed lines) and spatially explicit Generalised Autoregressive Error (GAR_{err}) models (solid lines), at Mount Windsor (a), Mount Carbine (b) and both sites combined (c). The residuals relate to the global model (i.e. including all explanatory variables).