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THE IMPACT OF HUMAN DISTURBANCE ON LOCAL CLIMATE IN THE YUCATÁN, MEXICO

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Abstract
Human activity is a major cause of environmental change in natural ecosystems. Geographic information systems (GIS) make possible the evaluation of the relationship between spatial changes in land cover and other variables, such as temperature, vegetation and moisture. 21% of the landscape of southern Yucatan in 2000 was disturbed, and these areas were 4.3 C warmer than the “natural” landscape towards the end of the dry season. The residual temperature, the difference between actual and expected temperature after removal of the lapse rate (elevation effect), was calculated. Early secondary growth (0-3 years) residual was significantly warmer than forest residual; early secondary forest was 3.7 +/- 2.1° C, compared with forest, which was -0.6 +/- 1.4° C. Areas in close proximity to disturbed areas appeared to be affected by the increase in residual temperature of disturbed areas. The residual temperatures of areas surrounding deciduous forest, however, were also warmer.

LAND SURFACE TEMPERATURE, DISTURBANCE, LANDSAT THERMAL BAND 6, DRY TROPICAL FOREST

I. Introduction

Forests provide many hydrological services to human and wildlife populations. Quantifying these services at the meso-spatial scale improves understanding of services as a subset of ecosystem or earth system services (Daily and Söderqvist 2000). Recently, the global environmental change research community has demonstrated that regional-scale land changes can affect regional climates, especially temperature and precipitation (IGBP 1999). Demonstration that these types of change follow from tropical deforestation provide important insights about coupled human-environment systems, complete with implications for biotic diversity and cultivation.

The research presented here explores the relationship between region-wide land clearance in a dry tropical forests and associations with changes in surface temperatures in the region. The case study addresses the southern Yucatán peninsular region of southeastern Mexico. This region, the location of a long-standing research project of land-use and land-cover change, centers on the karstic rolling uplands (100 m to 370 m elevation) that form the spine of the peninsula and was home to an old growth dry tropical forest that began to incur significant human disturbances in the middle of the twentieth century. The region is dominated by a semi-arid climate and experiences a north-south precipitation gradient of 900 mm to 1500 mm. Everywhere a distinctive dry season is encountered, the length and intensity of which follow the precipitation gradient. Mean temperatures are high throughout the year, ranging from 20 to 30 degrees Celsius (CNA 1926-2002). Specifics about the physical geography of the region, land dynamics, and the larger project examining land-cover change there can be found in various sources (Turner et al. 2001; Turner, Geoghegan and Foster 2004).

Karst topography, shallow soils (outside of *bajos*), and an intensive dry season compound water availability for vegetation (Lugo et al. 1978). Various studies demonstrate that based on tree leaf litter, deciduousness in the southern Yucatán relates to water stress. When deciduous trees drop their leaves, this in turn should have a significant impact on temperature, because evapotranspiration decreases when leaf surface area decreases. Transpiration is one mechanism whereby temperatures are moderated, so a decrease in transpiration results in an increase in temperature.

Human activities since 1950 have resulted in most of the current disturbed land in the southern Yucatán defined here. Human activities which have contributed to this disturbance include the shifting cultivation or *milpa* and commercial chili cultivation by smallholder farmers, failed large-scale agricultural projects, and small cattle ranches. At least 409 km^2 of mature tropical forests have been opened in larger region (<19,000 km^2 in analysis) since 1987 (SYPR project data).

Temperatures of second growth forest may be significantly different than old-growth forest. In one study in the Yucatán, mature forest has the lowest temperature and cleared areas had the highest temperatures overall. Second growth forest temperatures decrease as the forest matures (Southworth 2004). The effects of an increase in local temperature could include significant ecological effects. With the increase in temperature of 2-3° C predicted by global climate change models, the result would be the disappearance of temperate forests and the expansion of dry tropical forests in Mexico (Villers- Ruíz 1997). An increase in dry tropical forests and a decrease in tropical rainforests would have the effect of reducing biodiversity, since dry tropical forests support fewer species (World Biomes 2004). Finally, reduced soil water availability in deforested areas or areas of degraded forest increases susceptibility to fires and burning (Nepstad 1999), and make decrease crop productivity as well..

The effect of disturbed land on local climate (and the hydrological cycle) in the southern Yucatán has not been well-studied. This research employs a first order assessment of some of these consequences. Specifically, thermal satellite images are used to estimate surface temperature (using a GIS), and the effect of converting forested land to cleared (disturbed) land on land surface temperature can therefore be evaluated.

II. Methods

Study Area. The study area constitutes the western scene (path 20, row 47) of the Landsat imagery covering the southern Yucatán. This scene covers most of the center peninsula ridge or *meseta*, a limestone hill zone between the eastern and western coast of the peninsula. The scene covers approximately 3.3 million ha centered on Highway 186 cutting east-west across the base of the peninsula. The vegetation in this area of the southern Yucatán is dry tropical forest (Lundell 1934; Miranda 1959). Forests are most deciduous in the northwestern part of the study area, extending in a thumb-shaped pattern from the northwest towards the center of the region (see Figure 3).

As noted, the southern Yucatán is the study region for the SYPR (Southern Yucatán Peninsular Region) research project, headquartered at Clark University (www.clarku.edu/departments/geography/research/sypr.shtml). The study area for this research encompasses most of the 22,000 km^2 region of that project and includes all of the Calakmul Biosphere Reserve. The Landsat (path 20, row 47) scene used in this study also includes areas to the north and west that are included in the SYPR project analysis. These areas include considerable large-scale mechanized agriculture and more extensive areas of intensive disturbance than that observed in the large project's study.

Images used. The first image used in this analysis was taken on 12 February 1999 (path 20, row 47), and the second was taken on 27 March 2000. The 1999 thermal image (Landsat 5) has a resolution of 120m, and the 2000 thermal image (Landsat 7) has a resolution of 57m. Fortunately, atmospheric effects are minimized for the two Landsat scenes used in the analysis as both are cloud-free. There were no precipitation events approximately 2 weeks before the March 2000 image was collected, and precipitation before the February 1999 image was collected was minimal. All analysis was done using Idrisi Kilimanjaro GIS (Eastman 2003) and all seven bands of data from georeferenced Landsat images in the Universal Transverse Mercator (UTM) coordinates; data were acquired from the SYPR (Southern Yucatán Pensinsular Region) research group at Clark University.

Land-Use classification. The 2000 land use classification was completed using the MAXLIKE module. Representative training sites for each land cover type were digitized and spectral signatures for each land cover type were created. The 12 February 1999 image was classified into 5 land cover classes: water, cleared, second growth, forest, and burned (Figure 5). At this time in February of 1999, moisture was plentiful and forest and other vegetation was a healthy green, as it is before the deciduous trees lose many of their leaves towards the end of the dry season. The 2000 image was classified by the SYPR (Southern Yucatan Peninsular Region) project at Clark University into 25 land cover classes. These 25 land cover classes were grouped into water, cleared, successional growth, burned, and deciduous forest classes.

Land Surface Temperature Estimation. The surface temperature for the 1999 Landsat TM image was estimated using the THERMAL module, which gives the at-satellite "brightness" temperature using a look-up table approach described in the IDRISI Kilimanjaro Help THERMAL Notes (Eastman 2003). This brightness temperature would be the correct temperature if land cover types were blackbodies. Blackbodies are theoretical perfect emitters and absorbers of thermal energy, so in reality, land cover types emit less thermal energy than a blackbody. Water behaves most like a blackbody (emissivity=1.0), and its maximum emissivity is 0.99. Temperature was estimated using the equation in Step 3 (see below) in IMAGE CALCULATOR. 11.5 µm (the average between the range of 10.4 µm and 12.5 µm) was used. Finally, 273.15 degrees was subtracted from the result in Kelvin to get a final result in degrees Celsius.

The 2000 Landsat ETM+ thermal band 6 presented more of a challenge for calculating surface temperature, because the THERMAL module does not yet have an option to estimate brightness temperature from the Landsat 7 satellite thermal data. Therefore, temperature was derived from the low-gain band thermal band 6 to surface temperature in five steps, using the method described by Weng (2004), and using IMAGE CALCULATOR.

*Step 1: Conversion of thermal band 6 digital numbers (*DN*) to radiance temperature(*L_λ*).* The conversion of thermal band 6 to radiance temperature involved using the following equation, and substituting band 6 (low-gain) for DN (digital number).

Equation 1: $L_\lambda = 0.0370588 \times DN + 3.2$

Step 2: Conversion of radiance temperature(L_λ*) to brightness temperature(*T_B*).* The conversion of radiance temperature to brightness temperature used the following equation, and the result of step 1 was substituted for L_λ.

Equation 2: $$T_B = \frac{K_2}{\ln((K_1/L_\lambda)+1},$$

where T_B is effective at-satellite brightness temperature in K, L_λ is spectral radiance in W/ (m^2 ster µm) and K_2 and K_1 are pre-launch calibration constants. For Landsat-7 ETM +, K_2 = 1282.71 K, and K_1 = 666.09 mW cm^{-2} sr^{-1} µm^{-1}.

Step 3: Conversion of brightness temperature to surface temperature (S_t) *by adjusting for emissivity.* The equation given below was used, and the result of step 2 was substituted for T_B. (The estimation of emissivity (ε) is described in the next section.)

$$S_t = \frac{T_B}{1 + (\lambda \times T_B/\rho) \ln\varepsilon}$$

where λ= wavelength of emitted radiance (peak response and average of limiting wavelengths is 11.5 µm), $\rho = h^*(c/\sigma)$ (1.438 X 10^{-2} m K), σ = Boltzmann constant (1.38 X 10^{-23}J/K), h= Planck's constant (6.626 X 10^{-34} Js), c = velocity of light (2.998 X 10^8 m/s, and ε is emissivity.

Step 4: Determination of Residual Temperature After Removal of Lapse Rate (skip this step for surface temperature map). An image of the lapse rate was created in IMAGE CALCULATOR from the digital elevation model and the equation from the regression of temperature with elevation. The lapse rate image was subtracted (using IMAGE CALCULATOR) from the surface temperature image (from step 3), to yield a residual temperature image.

Step 5: Determination of average temperature with standard deviation. The EXTRACT module was used to calculate the average temperature and standard deviation for each land use from the surface or residual temperature map from step 3 or step 4.

III. Results

1999 land surface temperatures estimated from the thermal imagery are 21-24° C (averages by land cover class), which compares to a average air temperature for the month of February 1999 of 23-25° C reported at two weather stations in the region (CNA 1926-1952). Land surface temperature in 1999 was highest for cleared and lowest for forest and water. Second growth forest was the second coolest, followed by burned. Surface temperature in 2000 was highest for cleared and burned areas, followed by secondary growth. Temperature was lowest for water, followed by forest. Deciduous forest had mid-range temperatures (Figure 1). Overall, disturbed land had higher than average temperature in 2000 (35.8 °C as opposed to 32.5 °C). Consequently, average temperature was higher in 2000 than in the pre-disturbance landscape (Table 1).

In 1999, residual temperature after removing the lapse rate (effect of elevation) was highest for burned and cleared, and followed the same pattern as surface temperature in 1999 (Figure 2). Second growth had the next highest residual temperature. Water was coolest,

Figure 1. **Land surface temperature for 1999 and 2000. The ranges for temperatures in 2000 were greater than for 1999.**

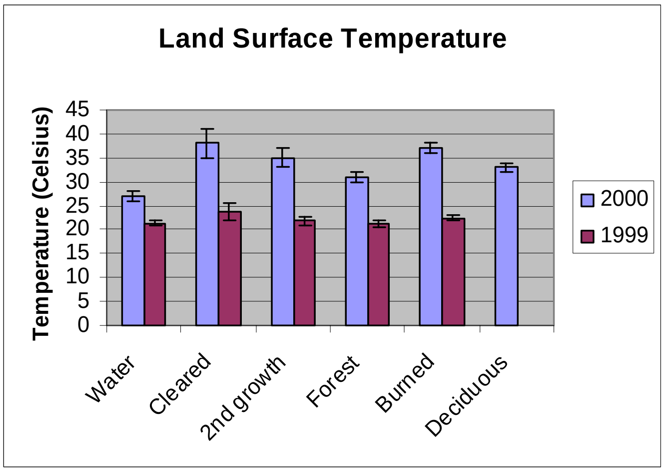


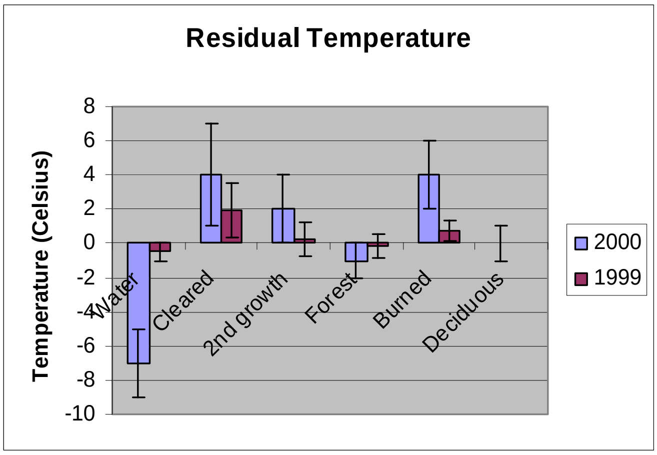
Table 1. Pre-Disturbance Land Use Classification: The pre-disturbance temperature of the "natural" landscape was calculated based by assuming that all of the land area disturbed by humans in 2000 was originally forested.

Land Cover Class	Est. Hectares Before Disturbance*	Hectares 2000	Average Temperature (^oC) Before Disturbance**	Average Temperature (^oC) 2000
Forest	32854634-	2577662	31.5 (32 +/-1)	31.5 (32 +/-1)
Sedge	23377 +	23377	39.1 (39 +/-2)	39.1 (39 +/-2)
Water	6692	6692	26.8 (27 +/-1)	26.8 (27 +/-1)
Disturbed	0	707801	NA	35.8 (36 +/-3)
Total	3315532	3315532	31.5	32.5

*The actual hectares of forest before disturbance may be less beceause the actual hectares of sedge may be higher.

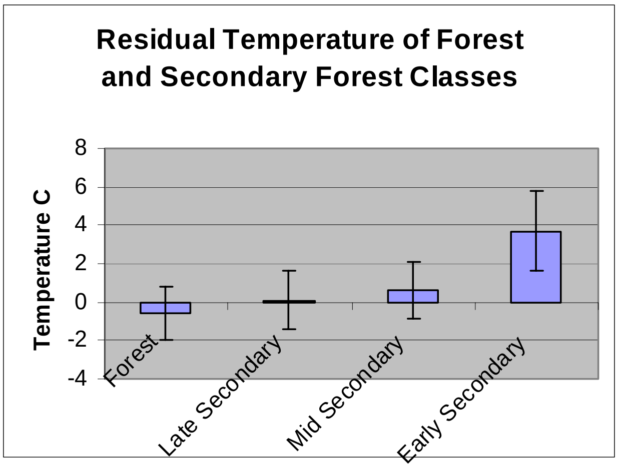
**Hypothetical temperature used for comparison purposes only, to show the effect of disturbance on absolute temperature.

Figure 2. Median Residual Temperature and Standard Deviation, 1999 and 2000. The residual temperature after the removal of the lapse rate (elevation effect) for each of the major land cover types is shown below. Residual temperatures for 2000 had a higher range than for 1999, but exhibited a similar variation by land cover type as in 1999.



followed by forest. In 2000, residual temperature followed the same pattern as in 1999, and deciduous forest was slightly warmer than forest (Figure 2). As the age of secondary growth increases, temperature decreases, but the greatest drop in temperature was between early secondary growth and middle secondary growth (Figure 3).

Figure 3. Median Residual Temperature and Standard Deviation of Secondary Growth Forest and Forest*, 2000. The residual temperatures of medium and tall stature forest types are compared with the temperatures of secondary forest in various stages of regrowth. Early secondary is 0-3 years, mid secondary is 4-9 years, and late secondary is 10-15 years of age (Eastman 2004).



* Includes medium and tall stature forest classes only.

The difference in temperature between areas close to disturbance and far from disturbance appears to be up to 12 °C over a distance of 5km in 2000(Figure 4). The regression for distance from disturbance in 1999 was similar to 2000. In 2000, increasing distance from deciduous forest is significantly correlated with a decrease in residual temperature (r=-0.33) (Figure 5). This correlation was not evaluated for 1999 because less trees had lost their leaves in the middle of the dry season of 1999 compared to the end of the dry season in 2000.

Figure 4. Residual Temperature After Removal of Lapse Rate vs. Distance from Disturbance, 2000. The temperature after removal of lapse rate is correlated with distance from disturbance. All land cover types were included in the regression.

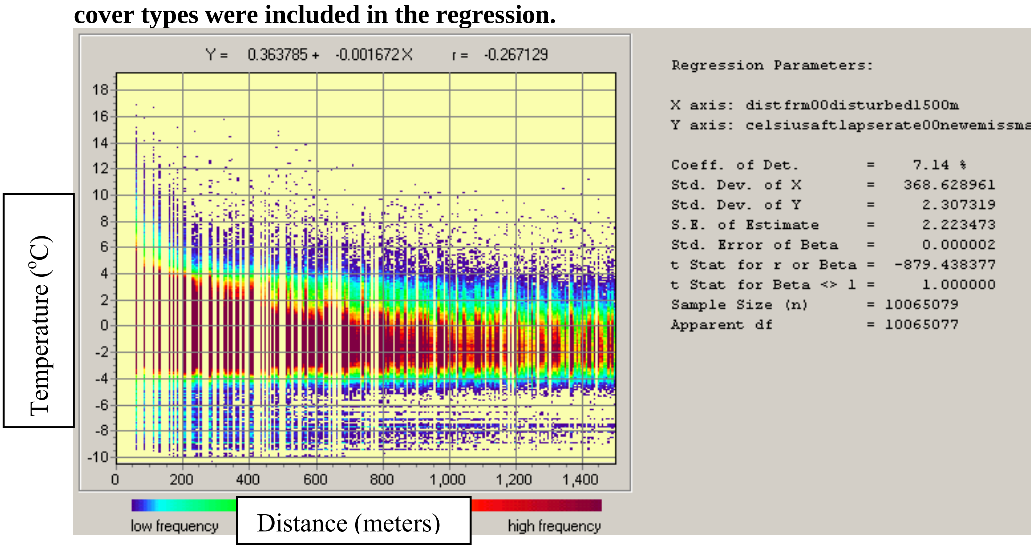
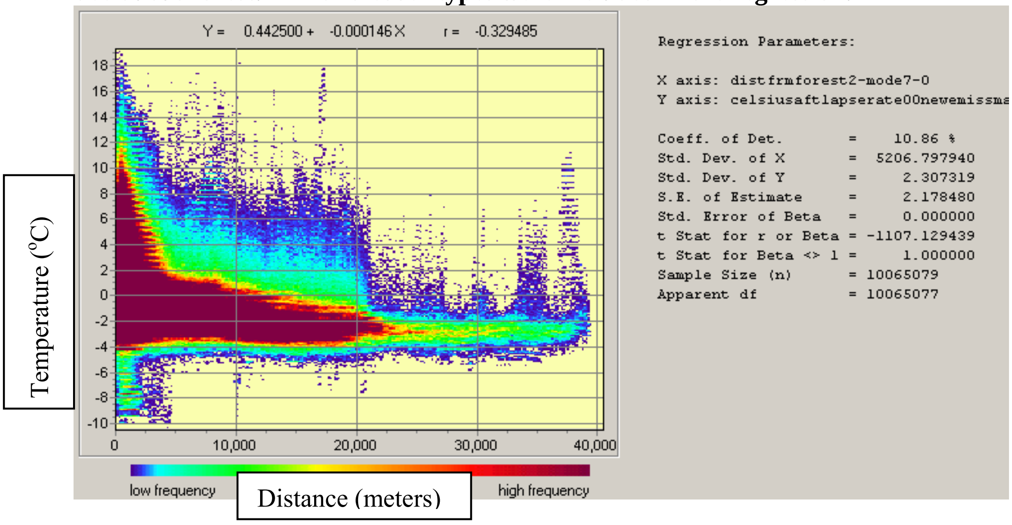


Figure 5. Residual Temperature vs. Distance from Deciduous, 27 March 2000. The residual temperature after removing the effect of elevation had a negative correlation with distance from deciduous forest. All land cover types were included in the regression.



IV. Discussion and Conclusion

Disturbance appears to affect temperature in the Yucatán, but the impact appears greater when moisture is scarce and temperatures are high. In 2000, on a warm (32.5° C) day at the end of the dry season, residual temperatures in disturbed (cleared and burned) areas were significantly higher than in natural areas (forest and water). In contrast, on a cooler, wet day in the middle of the dry season in (mid-February 1999), residual temperatures were less extreme but followed the same pattern as in late March 2000. When moisture is scarce and temperatures are high, such as in the March 2000 image, the effect of land cover change on temperature appears to be at a maximum. In order to evaluate whether this is the case, a study comparing results from the end of the dry season to the rest of the year could be undertaken.

When disturbance causes an increase in temperature, then this increased temperature may, in turn, impact the wider landscape. For example, residual temperature may decrease with increasing distance from disturbance; a negative correlation was observed within 1.5km for 1999 and 2000, although the effect was much smaller or nonexistent at greater distances. Deciduous forest had a stronger effect on temperature than disturbance, as shown by the relationship between distance from deciduous forest and residual temperature.

Determining temperatures of various land cover types, and the associated temperature change as a result of changes in disturbed land area is essential for understanding, appreciating, and using hydrological data in the Yucatán, Mexico and in other areas of the world. Temperature change with disturbance in the Yucatan, and related factors, could be investigated further. This data and information will allow researchers to eventually model the hydrological cycle in the region and help model how human and wildlife populations are affected by changes in temperature, rainfall, and evapotranspiration as a result of land cover change.

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