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APPLICATIONS OF CLASSICAL MODELS TO TROPICAL PEAT

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SUMMARY

Current models of peat accumulation and degradation were developed with an emphasis on temperate and boreal peat. This work tests the relevance of standard analytical models to tropical peat. Specifically, it tests the ability of models developed by Ingram (1982), Clymo (1984) and Winston (1994) to describe nine peat dome profiles from Sarawak, Malaysia. Models are run using values of a hydrologic parameter calculated based on morphological data, water balance data and an unconstrained best fit to the peat domes. The models were unable to reproduce the dome profiles using parameters derived from empirical water balance data. Water balance parameter values were two orders of magnitude larger than morphometric and best fit values, and predicted much higher dome curvature than found in profile data. These results suggest that either models or parameter formulations need to be adapted to better describe the hydrologic controls on tropical peat dome curvature.

KEY WORDS: Tropical peatland; Analytical Model; Dome profile; Hydrology

INTRODUCTION

Tropical peatlands account for 8% of global peatlands (Andriesse, 1988) and have been poorly studied. They are being rapidly destroyed by logging, plantation development and human settlement (Page *et al.*, 2009) resulting in large CO_2 emissions which are responsible for up to 30% of global emissions from land use, land use change and forestry (Hooijer *et al.*, 2006). Better understanding of the processes limiting tropical peat formation and degradation may improve peatlands management and reduce emissions. Given the need to better understand the processes governing tropical peatlands, this paper assesses the applicability of classic analytical models of peat dome formation to data from tropical peatlands.

Two classic models, developed by Ingram (1982) and Clymo (1984) describe different fundamental controls on peatland development. They share a two layer conceptualization of the peat bog (Ingram, 1978). A thin layer, the acrotelm, sits above a permanently waterlogged catotelm. Aerobic decomposition is possible in the seasonally oxic acrotelm, while the catotelm experiences only anerobic decay. The acrotelm has a high hydraulic conductivity, allowing high shallow subsurface flow, while the catotelm has a low hydraulic conductivity. In Ingram's model, the peat dome is maintained by impeded drainage, which causes the water table to mound. In turn, the lowest position of the water table level controls the level of the peat surface as organic matter accumulates below the water table but rapidly decays above the water table. Thus, the peat dome's profile is determined by flow from the acrotelm into the catotelm and its hydraulic conductivity. In Clymo's model, a peat dome's height is limited by vegetation growth and decay rates. Peat is transferred to the catotelm at a constant rate but is lost through anaerobic decay as a proportion of the total mass of the catotelm. As a result, catotelm growth declines over time, reaching an asymptotic limit to peat depth equal to p/α where p is the rate of new litter added to the catotelm (LT^{-1}) and α is the anaerobic decay rate of the catotelm (T^{-1}).

Different models may predict taller maximum heights or different curvature profiles. This paper compares dome profile predictions of Ingram (1982) and Clymo (1984) as well as a later model by Winston (1994) that includes aspects both hydraulic and vegetation growth controls. When fitting profile data, the models have the following free parameters:

Ingram:	C, L
Clymo:	$C, t, p/\alpha, \alpha$
Winston:	$C, t, p/\alpha, R, T$

The hydrology parameter, C is defined as follows:

$$C = U/k = H^2/L^2 \qquad (1)$$

This parameter controls dome curvature, and plays a central role in each of the models, even where vegetation controls the maximum dome height. It results from treating the peat as an aquifer into which all recharge is from precipitation, then using Darcy's law and the Dupuit assumptions to solve for the shape of the water table. A morphometric C value can be calculated directly based on observed characteristics such as the dome length and maximum height (Equation 1). Alternatively it can be calculated from water balance data based on the ratio of recharge to hydraulic conductivity (Equation 1).

α	anaerobic decay rate [T^{-1}]
H	maximum dome height [L]
L	radial length of bog [L]
k	hydraulic conductivity [LT^{-1}]
p	rate of addition of peat to the catotelm [LT^{-1}]
R	initial peat accumulation rate [LT^{-1}]
t	age of dome [T]
T	thickness of initial peat layer [L]
U	recharge rate [LT^{-1}]

Fig. 1. Definition of Symbols

METHODS

Peat dome heights from three analytical models (Ingram, 1982; Clymo, 1984; Winston 1994) were compared against nine peat dome profiles from two coastal sites in Sarawak, Malaysia: the Rajang River Delta and the Baram River Delta, compiled in Anderson (1964).

Hydrologic parameter values (*C*) were calculated according to three methods. First, a morphometric value was calculated for each dome using profile topography (Equation 1). Next, a water balance value was calculated using the ratio of flow from the acrotelm to catotelm to hydraulic conductivity (Equation 1) based on empirical data from two water balance studies (Table 1) from the Rajang River Delta region: the Kut catchment (Ritzema and Wösten, 2002) and the Jemoreng catchment (Hooijer, 2005). Groundwater flow values were used to approximate flow from the acrotelm to catotelm. We ignored shallow subsurface flow to estimate a low recharge value, as Ingram (1982) suggested using recharge data (precipitation – evapotranspiration) from a drought year as a lower bound on average flow to the catotelm. A hydraulic conductivity value of 0.5m/day was selected based on Wösten *et al*.'s (2008) model of a two layer tropical peatland. This value represents the low hydraulic conductivity of the catotelm, which is the focus of these models.

Finally, best fit parameter values were calculated for each dome. Peat dome profiles were calculated with each model and set of parameters. Residuals and mean squared error were calculated to evaluate the models' ability to fit the dome profiles. For each set of *C* values, all other parameter values were optimized within constrained ranges, as follows: t (3000-6000 yrs), p/α (2-10 m), α (0-0.01 yrs^{-1}), R (0-0.01 m/yr), T (0-1m), L (data value ± 300m). Parameter values were optimized using Matlab's "lsqcurvefit" function, which is based on the Levenberg-Marquardt algorithm for nonlinear least squares. A multi-start global optimization technique used 100 starting points.

RESULTS

Morphometric and best fit values of *C* were similar. Model runs with these two sets of parameters reasonably reproduced dome profile data. Water balance parameter values differed dramatically from morphometric and best fit values, and were unable to reproduce the peat dome profiles. Performance was similar across the three models.

Morphometric *C* values calculated for each of the nine domes (Equation 1) ranged from 2.5×10^{-6} - 1.0×10^{-5} for Baram River Delta domes and 3.9×10^{-7} – 2.7×10^{-6} for Rajang River Delta domes. Higher values at Baram reflect the steeper curvature of the dome margins of domes at the site. Model fits with these parameters were a reasonable fit to the profile data. On the other hand, hydrologic parameter values calculated from regional water balance data (Table 1) were two orders of magnitude larger than the mean morphometric value (Table 2). When models were run with these parameter values they were unable to fit dome profile data. Instead fits had much steeper curvature, predicting domes which were either much taller or of a much smaller radius than real domes. For example, Ingram's model predicted domes as tall as 200m rather than 2.9m - 9.1m as captured in the data (Fig. 1).

Fig. 2. Ingram (1982) Projections for Sungei Assan Profile, Naman Forest Reserve, Rajang River Delta. Three Ingram fits with different parameter values. Plotted points: profile data values; Dotted line: C = 3.3 x 10-4 (Kut catchment water balance data); Dashed line: C = 5.5 x 10-4 (Jemoreng catchment water balance); Solid line: C = 2.7 x 10-6 (Morphometric value)

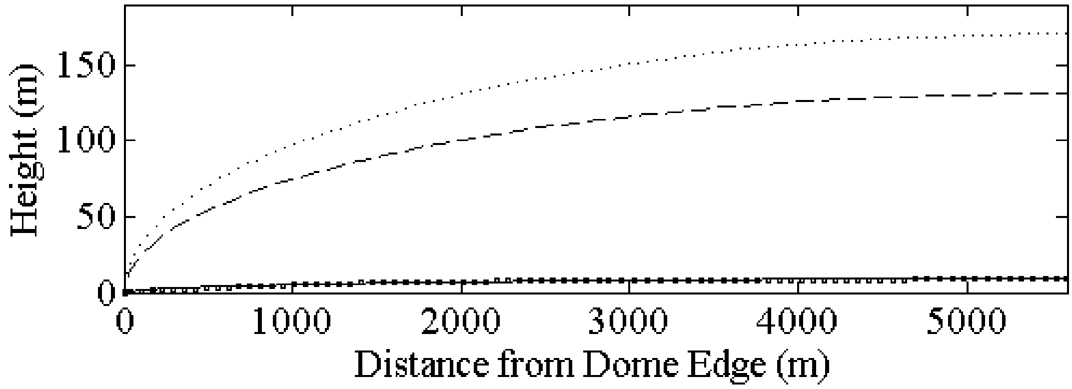

Table 1. Water Balance Components for catchment studies from the Rajang River Delta, Sarawak

Flux Density (mm/yr)	Jemoreng Catchment	Kut Catchment
Precipitation	3400	2769
Evapotranspiration	1073	1248
Surface runoff	950	1031
Shallow subsurface flow	800	340
Groundwater flow	100	170

Best fit *C* values for the nine domes were in close agreement with the morphometric values but very different from water balance values (Table 2). Using best fit parameters models successfully reproduced the dome profiles, resulting in an average mean squared error of 0.08 m^2, 0.12 m^2, and 0.18 m^2 for the Winston, Clymo and Ingram models respectively when run for nine profiles. Winston’s model best matched the profiles and best reproduced the central bog plain, a dominant feature in half of the profiles modeled. Winston’s formulation explicitly accounts for the central bog plain and his piecewise functional form allows greater flexibility in fitting the data.

Table 2. Comparison of *C* Values

Site	Morphometric *C*	Ingram Best Fit *C*	Clymo Best Fit *C*	Winston Best Fit *C*
Baram River Delta Domes				
Lubok Pasir	8.4×10^{-6}	1.2×10^{-5}	9.6×10^{-6}	1.4×10^{-5}
Tanjong Jabai	1.0×10^{-5}	7.8×10^{-6}	1.6×10^{-5}	1.3×10^{-5}
Tanjong Jaye	2.5×10^{-6}	4.2×10^{-6}	3.1×10^{-6}	3.0×10^{-5}
Pagalayan Canal	6.2×10^{-6}	6.5×10^{-6}	8.0×10^{-6}	7.0×10^{-6}
Rajang River Delta Domes				
Sungei Assan	2.7×10^{-6}	2.9×10^{-6}	2.7×10^{-6}	2.7×10^{-6}
Sungei Sawai	4.8×10^{-7}	3.9×10^{-7}	4.3×10^{-7}	4.3×10^{-7}
Rantau Panjang	3.9×10^{-7}	4.1×10^{-7}	3.9×10^{-7}	5.7×10^{-7}
Daro Forest	9.4×10^{-7}	7.4×10^{-7}	9.1×10^{-7}	8.7×10^{-7}
Pulau Bruit	1.0×10^{-6}	6.8×10^{-7}	1.4×10^{-6}	1.5×10^{-6}
Sarawak Water Balance *C*				
Jemoreng catchment *C*	5.5×10^{-4}			
Kut catchment *C*	9.3×10^{-4}			

DISCUSSION AND CONCLUSION

The Ingram, Clymo and Winston models were unable to reproduce the dome profiles using empirical water balance parameter values. These *C* values were two orders of magnitude larger than mean morphometric and best fit values and resulted in much steeper predicted dome curvature than found in profile data. There are several possible reasons for the discrepancy between empirical water balance *C* values and the best fit values.

First, the lack of seasonality in tropical peat may strongly influence which hydrologic variables are relevant to the models. These models focus on the catotelm, defined by the lowest level of the water table, assuming that the maximum peat height is limited by high rates of aerobic decay of peat above the level of the water table in the driest season or year. However, this may not be the dominant limitation on dome height in coastal Sarawak, where rainfall is much more constant. Rainfall along the coast of Sarawak averages approximately 3600mm/yr, ranging from 2800-4700 mm/yr (Ritzema and Wösten, 2002). While there is some seasonality to rainfall, monthly precipitation exceeds evaporation year-round. As a result, low water table periods may not control the system to the extent they do in more seasonal climates. Instead it may be more important to consider processes in the acrotelm, which these models ignore, assuming they do not play a role in limiting the long-term peat dome surface.

Another possibility is that these domes have a much higher effective hydraulic conductivity than typical catotelm values suggest, resulting in their low curvature. This may be due to spatial heterogeneity and vertical gradients in catotelm hydraulic conductivity, which may be more pronounced in woody peat and are not captured in any of the models. Holden and Burt (2003) reached similar conclusions, noting that acrotelm-catotelm models rely heavily on measurements of hydraulic conductivity in the peat, which can vary widely over short distances. Instead, we may need to consider flow in the high conductivity surface zone rather than only the low conductivity catotelm. Additionally, it is possible that the aerobic/anaerobic divide does not correspond to the high-conductivity/low-conductivity divide as suggested by the simplistic acrotelm-catotelm model. If these two interfaces occur in different places, then more of the catotelm flow may be happening in a region of high hydraulic conductivity. These observations suggest a need to better understand the vertical profile of hydraulic conductivity in tropical peatlands.

The inability of these models to reproduce profile data from coastal Sarawak suggests the focus on average characteristics of the catotelm is too simplistic to describe the evolution of these systems. While a more complex model would more accurately capture spatial trends and processes within the dome, simple analytical models remain valuable in their ability to relate processes to basic topographic and hydrological parameters. Thus, adapting these simple models to tropical peat would be a useful tool which could allow more accurate predictions of peat depth across the tropics. This may require the use of a different hydrologic parameter C which better captures the lack of seasonality and woody structure of the peat. Future research to identify such a parameter may allow these models to better describe tropical peatlands.

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